High-Point Rendel

Borough of Telford & Wrekin Council

Ironbridge Gorge Instability

The Interpretation of Ground Investigations at Jackfield and the Lloyds

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EXECUTIVE SUMMARY

Slope movement within the Ironbridge Gorge is primarily the result of the continued development of a valley system resulting from the incision of the River Severn into a geological sequence of relatively weak materials. River processes have eroded the riverbanks removing toe support of the valley sides and combined with high groundwaters following heavy rainfall ground movement occurs. In addition, the effects of the industrial revolution and continued industry into the twentieth century has resulted in the loading of the slopes with tile and mine waste and the overlying strata subsiding into the voids created by mining. Within the area of study mineral extraction has included coal and, clay for brick and tile manufacture.

The study area has been divided into three main sites: Lloyds Head, Lloyds Coppice and Jackfield. Within these areas three sites have been identified to be at high risk from landslide and subsidence. Both the slopes on Lloyds Coppice and Jackfield have a history of landsliding and two areas in particular at these sites are currently showing active ground movement. Subsidence and bank erosion by river action is currently affecting the Lloyds Head area. Ground movement at all three sites is threatening the integrity and socio-economic structure of the Ironbridge area and the Ironbridge Gorge World Heritage Site. The sites of immediate concern are **Lloyds Head Road,** Lloyds Cottage area at **The Lloyds** and Salthouses Road at **Jackfield**. Ground movement and subsidence at these sites has been observed and confirmed by survey and the recent ground investigation. The remaining slopes of the study area have all been subject to ground movement in the past and there is no reason why these slopes will not be reactivated in the future. Although the extraction of mineral in parts of the Gorge cannot be substantiated as being a major contributory factor to slope failure, it is considered that the mining of clay, in particular, at Jackfield is likely to have had more effect on the stability of this slope due to thicker horizons of extraction compared to the coal. Mining records do not show the presence of mineral extraction in the areas of Lloyds Cottage and Lloyds Head, however, borehole data suggests that coal mining probably associated with the extraction of other minerals was undertaken at these sites.

The areas of current movement have been identified as sites that require remedial works ranging from **urgent** (The Lloyds in front of Lloyds Cottage) to **within 2 years** (at Lloyds Head and Jackfield) based on a relative risk assessment undertaken as part of the study. Further deterioration and neglect of all these sites will result in loss of the road network at Lloyds Head, The Lloyds and Salthouse Road, and the potential loss of property. The severance of any these roads would result in re-routing traffic and possibly threaten public safety as emergency vehicle access is restricted. In the case of the Tuckies there is no alternate vehicle access other than Salthouse Road. In addition, this would significantly affect the local socio-economic structure and potentially damage World Heritage Site status.

Stabilisation works would maintain communication and emergency vehicle access between Coalport and Ironbridge and, the Tuckies and Coalford. Prior to the implementation of remedial works an automated telemetry early warning system should be installed comprising slope movement instrumentation, which would be able to inform the Council of rapid movement likely to threaten public safety and assets.

The recommended remedial works for each of the three sites of concern are substantial, comprising riverbank protection, mechanical stabilisation of the slopes and drainage. All three sites require riverbank protection which is considered the primary trigger of landslides. Both the Lloyds Cottage and Jackfield sites require drainage to reduce the level of the groundwater below the sliding ground mass. Mechanical stabilisation by, for example piling, is required to prevent mass movement of the ground and loss of the road at Lloyds Cottage. Further stabilisation studies for Lloyds Head and Jackfield are required given the potential further deterioration of the ground until remediation measures are employed.

In addition to the slope stabilisation works it will be necessary to continue monitoring the borehole instrumentation already installed in the area and undertake addition ground investigations and inspections on a periodic basis. Recommendations have been made for a strategic approach to manage the slope instability. This is discussed in the main report along with other recommendations for slope stabilisation at various sites, further ground investigations and action plans should road access be severed along The Lloyds, Salthouse Road and Lloyds Head.

It is recommended that the Borough of Telford & Wrekin proceed with immediate effect to pursue funding for the stabilisation of The Lloyds at Lloyds Cottage and install real time monitoring on this and the Salthouse Road slope. Further studies have been recommended for the Lloyds Head area.

NON-TECHNICAL SUMMARY

High-Point Rendel were commissioned by Borough of Telford & Wrekin Council to undertake The Ironbridge Gorge: Lloyds and Jackfield Landslide Study in May 2003 in accordance with their 'Scoping Statement for the Interpretation of Ground Investigation Results at the Lloyds and Jackfield' (November 2002, ref. GISCOPE/HM009). The project comprised a desk study of the recent ground investigations at Lloyds Coppice, Lloyds Head and Jackfield areas (see Figure 1), and reviewing previous studies including ground instability, archaeology and mining. The objective of the study was essentially to identify the interrelationship between ground movement across the gorge and the potential for betterment of the slopes by future remedial schemes. This involved identifying the causes of the instability and the mechanisms causing ground movement, and establishing a ground model for the area in a format which will enable the assessment of remedial scheme proposals on a locality wide basis.

This project has been funded by English Partnerships, Advantage West Midlands, Shropshire County Council, Bridgnorth District Council, Ironbridge Gorge Museum Trust and the Borough of Telford & Wrekin Council.

The Ironbridge Gorge has a history of landsliding. The oversteepened slopes of the Gorge have been formed by incision and erosion by the River Severn. Ground movement is essentially the consequence of the processes of valley development whereby the slopes attempt to reach a natural state of stability. Slope instability has been exacerbated by the aftermath of the last glaciation which caused rapid erosion and down cutting through relatively incompetent geological strata which form the flanks of the gorge. The situation has been further complicated through the human influence of mining, which has created voids at depth causing ground subsidence, plus the loading of the slopes with mine waste. The groundwater regime would undoubtedly have changed during the mining and more significantly following the cessation of mining in the area when the dewatering of mines would have also ceased. A further consequence of the industrial revolution in the area has been the disposal of tile and brick waste along the river banks and slopes. These deposits, due to their deposition in a non-compacted state, are susceptible to river erosion and slope instability. Furthermore, there has been an increase in the frequency of flooding of the

Ironbridge Gorge over the last decade and heavy periods of rainfall have increased the levels of groundwater within the slopes; climatic change may already be affecting the area.

The slopes within the area of study show evidence of recent ground movement: in the Salthouse Road area of Jackfield and the area between Wesley Road junction and to the east of Lloyds Cottage. In these areas the slopes are currently active, potentially causing damage to property, disruption to infrastructure, and, to some degree, threatening public safety. It has been determined that as a consequence of ground movement significant historic buildings will be damaged and ultimately demolished in order to comply with Health & Safety requirements. This may affect the current integrity of World Heritage Site.

The study area has been further divided into smaller more-manageable units which are identified on Figure 2. The areas of current active movement include the Wesley Road/ Lloyds Cottage sub-unit (the Lloyds), Lloyds Head sub-unit, and Salthouse Road (Jackfield). Figure 3 identifies the areas of historic and current ground movement.

The Jackfield and Lloyds Coppice slopes comprise previously failed ground at shallow level and can be considered as material consisting of residual shear strength. The slopes exposed in the study area have the potential to reactivate and fail in the future. Monitoring of the slopes by ground survey and borehole instrumentation show that some areas are moving at a greater rate than others. The areas of short term concern are discussed below. However, it should be emphasised that the areas, which are not currently showing significant trends of movement have the potential to fail.

Presently, traffic flow into Ironbridge is reduced to one lane along a section of The Lloyds as a result of ground movement. Failure of the ground in front of Lloyds Cottage will almost certainly result in the loss of road in this area. Tension cracks and localised subsidence are spreading upslope and laterally, expanding the current footprint of ground movement. Severance of the road would ultimately result in road diversions, possibly through the residential area of Madeley, disruption to traffic between Coalport and Ironbridge, and, more than likely, damage to property. Further failure of the slope may result in the narrowing of the River Severn and a shift of stream flow to the southerly bank; this would undoubtedly result in accelerated erosion of the Lloyds Head area with consequential increase in instability upslope in this area. It has been recommended that urgent remedial works should be undertaken at this site including further ground investigation, ground behaviour mapping and the detailed design of a slope stabilisation and riverbank protection works.

A further area of concern is in the Jackfield site, where a section of slope previously failed in 1952-53. The major failure zone lies within 5m of the surface where the slope materials comprise weathered clay and mine spoil. Although, the slope is relatively gentle in inclination, erosion at the toe of the river bank by river flow is removing downslope support. This combined along with prolonged periods of rainfall, cause the material in the upper part of the slope to become weaker and failure of the slope occurs as a reactivation of the previously failed slope. The slopes at Jackfield, in the Salthouse Road area, are likely to continue moving downslope. Although movement is slow, the constant motion of the ground will continue to damage structures and the road. The consequences will also result in continued maintenance of the services which presently run over ground and are in regular need of repair. The concern at this site is if Salthouse Road is made impassable or severed, emergency vehicles will not be able to access the Tuckies area which has permanent residents. Furthermore, the residents and the public will not be able to access property and businesses. Further ground movement will also push the river northwards towards the Lloyds House area of Lloyds Coppice and possible accelerate toe erosion on this slope.

The Lloyds Head site is located on the southerly bank some 300m downstream of the Freebridge at Coalford and lies on made-ground consisting of mine and tile waste underlain by worked coal measures. The steep slopes of tile waste form a river bank, approximately 5m above river level, which is actively eroding. In addition subsidence, from uncompacted tile waste, is threatening the integrity of property and infrastructure in the area.

Across the study area future ground movement is likely to accelerate as a result of climate change, which predicts wetter winters and a consequential increase in groundwater. Of further concern is the relatively recent increase in frequency of flooding. Flooding events have been recorded nearly every year over the last decade which may be a result of climatic change already being experienced.

The human influence on the natural slopes in the study area is significant: spoil has been deposited on the slopes and riverbanks, and mining has created voids at depth resulting in disturbance to the overlying strata. The industry and properties located on the lower slopes throughout the study area may have contributed to instability through water pipe and drain leakage. This leakage may be due to ground movement dislocating pipes or simple age related deterioration in condition. Furthermore, any road drainage appears to discharge onto the lower slope beneath the road.

The landsliding evident on the valley sides corresponds to areas where the relatively incompetent Coal Measure Formations are exposed and is restricted to areas where the geological structures and/or mine workings make the slopes additionally susceptible to movement. Any influence mining has had on current slope instability cannot be substantiated. However, the effects of mining and the likely resulting bed separation and subsidence of the overlaying horizons cannot be disregarded, especially as not all mine workings have been recorded. Furthermore, the active lower slopes of the Salthouse Road area of Jackfield coincide with the mining for coal and clay at shallower levels than elsewhere along the slopes. The effect of at least two minerals being mined at shallow depth may have resulted in the overlying bedrock being more susceptible to slope failure.

Within the study area it is probable that the incidence of instability has shifted from one side of the valley to the other as the debris of the failure area ‘toes’ out into the river. This results in lateral erosion to the opposite slope as the river is ‘nudged’ towards this slope. This may account for the variation in stability on each side of the Gorge, where sections of the slope appear stable where there is more toe support (eg Jackfield Area B, Salthouses and The Tuckies on the south bank) and the converse is true where instability is identified on the opposite banks (eg School House area and to the west of Lloyd’s House). This is also true for the Lloyd’s Head and Lloyd’s Cottage areas.

In addition, the Tuckies and Doughty Faults have been identified to delineate areas of instability from slopes more stable. Jackfield Area B (Jackfield Tile Museum) has been identified to be more stable than its adjacent slope of Jackfield Area A (Salthouse Road). Without further investigation it cannot be determined whether the instability is a result of the Coalport Beds being thrown down to the east of the fault exposing less competent strata or whether the fault provides a ‘slip’ surface facilitating bed release. This can be applied to the northern bank where the Jackfield and Lloyds Coppice border the area of instability at Lloyd’s Cottage.

Slope stability analysis has been undertaken of some of the slopes in the study area that are currently affected by ground movement and this has identified factors of safety of less than 1 when ground water levels are simulated.

Not all the slopes within the study area have been modelled using computer slope stability analysis. Therefore, it is possible that the remaining slopes may be affected by ground movement in the future.

In an attempt to review the main findings of the desk study and the slope instability sections all relevant data found during the course of this study has been summarised for each site.

Borehole locations identified in the text can be located on Figure 4.

Lloyds Head

- The made ground is uncohesive in nature and was possibly uncompacted during placement.
- The made ground is subject to subsidence (as groundwater washes out finer material) and is more susceptible to river erosion.
- The site is prone to flooding during high river levels which have become more frequent.
- Monitoring along Lloyds Head identifies that the ground surface has moved nearly 2m to the North-North-West (ie riverwards) and subsided over 1m since 1994.
- Inclinometer BH RA (RO1) suggest possible shear at the base of the borehole with downslope movement comprising a component of bedding dip (having said this further readings are required to confirm any movement).
- Any ground slippage is likely to involve the made ground slipping over the in situ weathered clay of the Middle Coal Measures or possibly, at depth, along slide facilitating beds.
- The continued erosion of the banks caused by river action is likely to accelerate during high river levels and thus promoting riverbank failure.
- The extent of mining for coal within the Middle Coal Measures may have been significant given the relatively shallow exposure at this site. Dependent upon the

method of mining (eg pillar and stall, longwall etc; of which no records are available) mining subsidence may still be affecting the site.

The principle cause of ground instability is considered the erosion of the slopes by river action and the washout of fines in the uncompacted made ground resulting in slope recession and subsidence. The consequences of mining in the area may also be affecting the site.

Jackfield (Area A)

- This slope has been subject to rapid degradation by meltwaters during the last glacial period and the high groundwater levels associated with post glacial conditions.
- Currently river erosion is undercutting the valley sides and removing support at the toe of the slopes along the subunit Salthouse Road.
- Valley development has and will continue to initiate a cycle of landsliding activity as slope processes strive to reach equilibrium (ie a state of stability)
- Accelerated degradation of the slopes is aided by the relatively incompetent geology comprising interbedded clays, mudstones, sandstones and coals, and the geological dip of the beds.
- The dip of the strata is shallow (~4^o) towards the east which could facilitate ground movement towards the river
- The geological structure in the form of faulting may be providing conduits for groundwater and backsarps for slope movement, for example The Doughty and Tuckies Faults.
- The ground movement observed from the geomorphological mapping identified land units of multiple rotational back tilted blocks of various stages of degradation and translational (or debris) failures with secondary rotational failures.
- The presently active translational failure in the Salthouse Road sub-unit is a reactivation of the 1952 slip. Ground movement of this area is currently occurring, evidenced during a recent walkover.
- Road drainage appears to discharge directly onto the lower slope.
- The failure in 1952 was triggered by heavy rainfall and subsequent high groundwater levels, this is likely to have been the trigger for the most recent ground movement, although no data is available for actual rainfall in this period.

- The failed area of the lower slope (riverwards of Salthouse Road) contains substantial made ground deposits where the slip plane lies at the interface with the underlying clay and further upslope the slip plane can be observed at ~5m depth within the weathered clay.
- The areas of instability coincide with areas that have been mined at shallower depths than Area B for Red Tile Clay and Sulphur Coal. The combined effect of more than one seam being mined may have involved greater bed separation of the overlying strata and subsidence, which has reduced the integrity and strength of the material resulting in the localised instability along the Salthouse Road subunit.
- The area of the 1952 slip is located on the outside bend of the river where more turbulent water erodes the toe and removes support of the ground upslope.
- Borehole instrumentation has identified that the Salthouse Road sub-unit is currently active and areas outside this sub-unit are relatively stable.
- Groundwater levels are 5m bgl on the lower slope of the Salthouse Road sub-unit and 2m to 3m bgl outside this unit. This suggests that given the slopes are currently active, slope stability is very sensitive to increases in the groundwater level.
- The sensitivity of groundwater was analysed using slope stability software and found that areas of the slope are prone to failure with a rising water table.
- Furthermore, perched water tables may occur above the in situ clay material within the relatively more permeable made ground which will further reduce the strength of the material.
- Slope stability analysis has been undertaken for typical slope profile across the Jackfield site. Analysis has required the residual soil parameters values to be used to promote ground failure at representative groundwater levels. Residual values allow for possible bed separation as a result of mining.
- Slope stability analysis identified that discrete sections of the slope had a factor of safety of less than 1 and that the whole slope was unlikely to fail en masse.
- Analysis identified that the majority of failures were relatively shallow and deep rotational failures could not be realistically modelled.
- The area of the 1952 slip was analysed to have a factor of safety near to 1 when groundwater was 2m bgl.

- Survey monitoring has identified up to 5m NNW movement since 1994 and almost 850mm of settlement in the slipped area. The average rate of movement is ~0.5m/ year.
- Outside of this area there is negligible lateral and vertical movement.

The principle cause of ground instability is considered the erosion of the slopes by river action and the high groundwater levels following periods of heavy or prolonged rainfall. The consequences of mining in the area may also be affecting the site.

The movement of the debris slide in the area of the Salthouse Road sub-unit is slow with accelerated periods of movement following high water infiltration. Figure 5 shows the ground failure model for the site.

<u>Jackfield (Area B)</u>

This area contains the Jackfield Tile Museum sub-unit of the Jackfield site.

- Slope stability analysis identified that this slope had a factor of safety greater than 1 for all realistic soil and groundwater parameters computed.
- This sub-unit has been extensively undermined for Red Tile Clay and has substantial made ground cover comprising mining and tile waste.
- Survey monitoring, during 2003, has identified lateral ground movement to the NE (towards the river) of up to 0.2m and settlement of up to 15mm.
- Part of this sub-unit failed in 1984 around the lower slope.
  - Part of this slope is also located on the outside bend of the river which may have contributed to the 1984 failure, otherwise this subunit has more toe support than the adjacent slopes (ie Area A).
- Inclinometer monitoring (CP 14) identifies made ground to be slipping on in situ material, which may be subject to sub-artesian water pressures. Ground displacement is ~20mm downslope, all other boreholes show negligible displacements.
- Groundwater data suggests a uniform water table of ~2.5m bgl.
- It is possible that the Jackfield Tile Museum walls may be acting as a retaining structure to the toe of the slope.
- Furthermore, mining subsidence may have resulted in a shallowing of the slope.

Although there appears to be little evidence of significant ground movement in the area, ground movement has occurred in the past and further data collection may confirm ground movement which may presently be developing.

<u>Lloyds Coppice</u>

- This slope has been subject to rapid degradation by meltwaters during the last glacial period and the high groundwater levels associated with post glacial conditions.
- Currently river erosion is undercutting the valley sides and removing support at the toe of the slopes.
- Valley development has and will continue to initiate a cycle of landsliding activity as slope processes strive to reach equilibrium (ie a state of stability)
- Accelerated degradation of the slopes is aided by the relatively incompetent geology comprising interbedded clays, mudstones, sandstones and coals, and the geological dip of the beds beneath Lloyds Coppice Fault.
- The dip of the strata is shallow (~4^{o}) towards the east which could facilitate ground movement towards the river. Above the Lloyds Coppice Fault the bedding dips into the slope.
- The geological structure in the form of faulting may be providing conduits for groundwater and backsarps for slope movement.
- The Lloyds Coppice Fault may also be providing a surface or acting as a backsacrp facilitating ground slippage.
- The ground movement observed from the geomorphological mapping identified land units of multiple rotational back tilted blocks of various stages of degradation.
- The only recorded mining in the Lloyds Coppice area is for Red Clay from the Blists Hill pit. Geomorphological mapping identifies a graben feature, which coincides with and area of relatively shallow mining.
- Ground movement at Lloyds Cottage appears to have commenced following the period of heavy rainfall during the winter of 2002/03 which more than likely raised groundwater levels.
- The failed area contains substantial made ground deposits although the slip plane lies above a river gravel horizon.

- There are no records to suggest that mining has taken place beneath Lloyds Cottage, however, borehole logs suggest that ground has been worked ~20m bgl at a depth of a coal seam.
- The effects of mining may possibly involve bed separation of the overlying strata and subsidence, which is reducing the integrity and strength of the overlying material.
- This area is located on the outside bend of the river where more turbulent water erodes the toe and removes support of the slope above; toe erosion has been observed.
- Borehole instrumentation has identified that the Lloyds Cottage sub-unit is currently active, with ground movement also observed in boreholes upslope of the New Houses sub-unit (near The Pond); areas outside these sub-units show no significant trend in ground movement.
- Two distinct shear surfaces can be observed from the inclinometer plots: shallow and relatively deep (~4m and 13m bgl dependent on borehole location).
- Groundwater levels at Lloyds Cottage show groundwater level near surface level (one reading only received to date). It is considered that the near surface level of water is a major factor in slope movement.
- Road drainage discharges directly onto the lower slope. The culvert east of Lloyds Cottage discharges directly onto the lower slope. The outlet is in an area with localised failures, which have probably been triggered by high groundwaters.
- Furthermore, perched water tables may occur above the in situ clay material within the relatively more permeable made ground which will further reduce the strength of the material.
- Slope stability analysis has been undertaken for typical slope profile across the Lloyds Coppice site. Analysis has required the residual soil parameters values to be used to promote ground failure at representative groundwater levels. Residual values allow for possible bed separation as a result of mining.
- Slope stability analysis identified that the Lloyds Cottage slope has a factor of safety near or below 1 with conservative groundwater levels.
- Analysis identified that the majority of failures were relatively shallow and deep rotational failures that could be modelled would fail against the dip of the bedding.

- The other section analysed, towards the east of the site, calculated factors of safety above 1 even with relatively high porewater pressures.
- Survey monitoring has identified significant lateral and vertical movement along The Lloyds in the Lloyds Cottage and Old School sub-units. Up to 2.2m and 1.2m has occurred since 1994, respectively. Average rates of movement for the respective sites are 244mm/yr and 138mm/yr. Outside of this area there is negligible lateral and vertical movement.
- Remedial measures were undertaken in 1995 comprising soil nails and gabion retaining walls. Although, this may be arresting movement of the road it is unlikely that the soil nailing extends beyond the rear of the current slipping mass, failure of this block may result in a rapid en masse failure.

The principle cause of ground instability is considered the erosion of the slopes by river action and the high groundwater levels following periods of heavy or prolonged rainfall. The consequences of mining in the area may also be affecting the site.

Furthermore, the Lloyds Coppice Fault maybe acting as a backscarp or a sliding surface facilitating ground movement. Figure 6 shows the ground failure model for the area.

To maintain World Heritage Site status and to retain the current infrastructure it has been determined on the basis of this study that remedial action should be implemented. This has been initiated in the first instance by setting out the guidelines for a slope management strategy for the area. The management strategy has been developed by assessing the hazards and risks across the study area and prioritising the need for action in order to either prevent further ground movement or protect persons/ property from ground movement. The management strategy has recommended a number of actions ranging from continued monitoring in less critical areas to urgent remedial works. These remedial actions for the site areas have been summarised into the table at the end of this executive summary. Figure 7 shows the areas of recommended remedial works and actions.

The slope strategy for the whole study area is identified below and is followed by site specific recommendations for the **Jackfield, Lloyds Coppice** and **Lloyds Head** areas:

- Updating and expanding the geomorphological map of the study area at a larger scale to confirm the ground behaviour of the slopes;
- Undertake a quantitative risk assessment in conjunction with the updating of the ground behaviour mapping
- Continued monitoring of existing inclinometers, piezometers and monitoring pins on a regular basis to confirm current and identify any future trends of movement;
- More regular existing piezometer readings in the active zones of the study area;
- A thorough review of the inclinometer data;
- Frequent inspections and structural surveys of retaining structures and buildings (i.e. Jackfield Tile Museum) in areas of current and potential landslide activity;
- The consideration of using an automatic data gathering system as an interim measure prior to the construction of slope stabilisation works at Lloyds Cottage and the Jackfield slip area. This would enable data to be downloaded to the Council office remotely and free the survey teams currently visiting the site;
- Liaison with utility services to identify date and exact location of damage to services;
- The installation of a weather station to monitor effective rainfall;
- Co-ordination with the Environment Agency to identify hydraulic processes of the River Severn with particular emphasis to the study area and its susceptibility to river erosion and the options for potential remedial works;
- Co-ordination with land owners over riparian ownership of the riverbanks;

- Develop a contingency and emergency action plan in the event that a major failure or blockage of roads occurs, i.e. to ensure access for emergency vehicles and utility companies, short-term rehousing, meeting health & safety requirements etc.

With regard to the **Jackfield** slopes, the slope strategy specifically recommends:

- The installation of real-time monitoring instrumentation to identify and measure the rate of movement and groundwater levels in the Jackfield slip. This can then be compared with weather data (i.e. effective rainfall);

- Further ground investigation and the installation of borehole instrumentation up slope of the recent site of investigation in the Salthouse Road area in order that potential retrogressive failures and lateral ground movement can be identified and to identify the properties of the faults within the site area;

- Co-ordination with the utility authorities who have services within and above Salthouse Road and other roads, to ensure any maintenance carried out does not have any adverse effects on slope instability;

- Develop an emergency remedial works strategy should failure occur and sever the Salthouse Road and its services.

With regard to the **Lloyds Coppice** site, the potential for road failure and loss of access between Coalport and Ironbridge requires urgent remedial works at Lloyds Cottage. During the finalisation of this report, TWC commissioned further studies in the Lloyds Cottage area including additional ground investigations, topographic survey and the design of a remedial scheme. However, for the purpose of this report, the urgent actions recommended, and now completed, have been listed below for completeness. The ground movement observed and current rate of displacement is considered critical. There is a serious threat that the road might be severed in this location in the near future particularly with the onset of winter following a particularly dry summer. Therefore, the site specific requirements are:

- **URGENT** updating of the geomorphological map of the Lloyds Cottage area to confirm the ground behaviour;

- **URGENT** further ground investigation and the installation of borehole instrumentation up slope of the recent ground investigation in the area of Lloyds Cottage to allow shear surfaces and the lateral extent of ground movement to be determined, and to understand the faulting in the area;

- **URGENT** undertaking of a topographic survey of the Lloyds Cottage area;

- **URGENT** undertaking of detailed design of the remedial works to the Lloyds Cottage area of failure, including river bank protection and slope stabilisation measures, which could include mechanical stabilisation (e.g. piles and shear keys etc) and drainage;

- Regular monitoring of the failed sheet pile wall at the Lloyds House riverbank with remediation/ replacement of the sheet pile wall as required by the monitoring results;

- Develop a contingency and action plan for areas where major failure or blockage of roads may occur, to ensure access for emergency vehicles and utility companies, short-term re-housing, meeting health & safety requirements, road diversions, etc.;

- Co-ordination with the service companies who have services within The Lloyds, to ensure any maintenance carried out does not have any adverse effects on slope instability; and,

- Develop an emergency remedial works strategy should failure occur and sever the Lloyds before any comprehensive stabilisation scheme is installed.

With regard to **The Lloyds Head** the site specific details required as part of the strategy include:

- Continued monitoring and the implementation of a regular programme of crack mapping and spot levels to monitor ground movement and subsidence;

- Further ground investigations to identify the extent of any slip upslope by using inclinometers and mapping;
- Subsurface investigation into the extent of tile waste deposits (i.e. by trial pits and boreholes);
- Investigations into the most suitable method of river bank protection;
- Development of a design strategy for the prevention of further subsidence by the uncompacted tile waste (i.e. grouting);
- Develop an action plan: emergency vehicle access, utility services, etc;
- Develop a remedial works strategy; and,
- Develop contingency plans for a failure event: i.e emergency works.

SUMMARY TABLE OF REMEDIAL ACTIONS

Section No.	Location	Remedial Recommendation	Basis for Recommendations	Timeframe for Remediation
Lloyds Coppice	Lloyds Cottage	Further ground investigations to identify slip surface profile and local ground conditions and detailed topographic survey. Surface crack and ground behaviour mapping. A combination of river bank toe protection, mechanical slope stabilisation (eg piles) and drainage to maintain present road alignment and infrastructure.	The rate of ground movement is significant and the loss of The Lloyds is considered highly likely to occur in this area. The loss of The Lloyds in this area would be detrimental to the local infrastructure and tourism, with a major impact on the World Heritage Site. It is recommended that works should be undertaken **URGENTLY** before failure occurs.	Urgent
	Old School	Further ground investigation to identify subsurface condition. Continued monitoring, ground behaviour mapping and site inspections.	Movement in this area is considered localised to the area of The Lloyds where the road traverses to the lower reaches of the slope. There is no apparent evidence of ground movement observed within the road and it is necessary that further borehole instrumentation be installed to monitor any potential deeper-seated ground movement.	Complete Within one year
	Lloyds House	Continued monitoring and updating of ground behaviour map Commence a programme of monitoring of the failed sheet pile wall area, where risk may change following acceleration of movement	Movement of the sheet pile wall is evident. Should failure occur in totality there is the potential for loss of The Lloyds and access between Madeley/ Coalport and Ironbridge. Without evidence for signs of ground movement in the area and no significant trend of movement from the monitoring pins it is recommended that continued monitoring and updating of the ground behaviour plan be implemented.	Complete Within one year
Jackfield	Jackfield Tile Museum	Continued monitoring and updating of ground behaviour map. Structural survey of retaining walls and building.	Currently there is no evidence to suggest significant ground movement in the area. However, this area is adjacent to Jackfield landslip area and further expansion of this failure to the west could affect the Museum. Furthermore, the structural integrity of the retaining walls needs to be established with regard to the slope above the Museum area. Monitoring is required to identify any transgression of the landslip into the Museum area.	Complete Within one year
	Salthouse Road (Jackfield Slip Area)	Ultimately, this area will require remedial works to arrest downslope movement. The rate of movement is slow, but may accelerate with time. This area requires interim real-time ground instrumentation prior to the remedial works likely to comprise toe protection and slope drainage. Should the area be untreated for some time, mechanical stabilisation may be required in addition as the failure retrogresses. Continued monitoring and updating of ground behaviour map	Ground movement can be currently observed. Past movement has resulted in the realigning of Salthouse Road and the placing of utility pipes above ground level. The loss of Salthouse Road is highly likely to occur in this area without active intervention. Although movement is slow and funding for any works may not be forthcoming it is recommended that interim subsurface instrumentation be installed to monitor the rate of ground movement in real time which can be conveniently downloaded without the necessity for infrequent inclinometer and surveying.	Installation of site specific subsurface instrumentation within **6 months**, preferably before the Winter 2003/4. Remedial works within 2 years.
	Salthouses	Continued monitoring and updating of ground behaviour map	Currently there is no evidence to suggest significant ground movement in the area. However, this area is adjacent to Jackfield landslip area and further expansion of this failure to the east could affect the road and Salthouses. Monitoring is required to identify any transgression of the landslip into the Salthouses area.	Complete Within one year
	Tuckies	Continued monitoring and updating of ground behaviour map	There is no evidence to suggest any trend of significant ground movement and therefore, it is considered only necessary to undertake monitoring and updating of the ground behavioural map.	Complete Within one year
Lloyds Head	Lloyds Head	A combination of river bank protection and ground stabilisation to prevent further subsidence. Continued monitoring, crack mapping and sub surface investigation to the extent of tile waste deposits	The combination of subsidence and river erosion is currently threatening the short to medium term integrity of Lloyds Head road and the property between the road and the river. Subsidence is likely to damage property and erosion of the riverbanks threatens the safe use of property by persons.	Studies within one year and Remediation required within c.2 years

Glossary

Alluvial material	Material transported and deposited by a river. Usually comprising sands and gravels
Angle of friction	Is the compressive forces that hold particles together
Anticline	A fold of geological strata in the form of an arch
Aquifer	A water bearing bed of strata
Arenaceous	A group of detrital sedimentary rocks, typically comprising granular material, eg sandstones
Argillaceous	A group of detrital sedimentary rocks, typically comprising cohesive material, eg clays, shales, mudstones, siltstones and marls
Artesian	An aquifer, confined by impermeable strata, holding water under pressure, which can rise to the surface through a borehole
Bedding	Relating to sedimentary rocks, a surface parallel to the surface of deposition
Carboniferous	A period in geological history named after the widespread occurrence of carbon in the form of coal in these beds (c345my to 280my before present)
Coal Measures	The Lower, Middle and Upper Coal Measures are formations within this geological group of the Carboniferous Period
Cohesion	Is the force that holds particles in a soil or rock together.
Colluvium	Weathered material transported by gravity, eg failed slope material accumulating lower down on the slope
Debris	Material resulting from ground slippage, landslide or rockfall
Debris slide	For the purposes of this report see *translational slide* below
Degradation	The general lowering of the land through the processes of weathering, transportation and erosion
Detrital	Particles of minerals or rocks which have been derived from pre-existing rock by processes of weathering or erosion
Dip	The angle of the bedding
Downthrow	The downwards displacement of a faulted block along a fault plane
Drift geology	All the glacial deposits left after the retreat of glaciers and ice sheets. For the purposes of this report drift also includes the superficial geology comprising alluvial deposits and made ground
Equilibrium (limiting)	The angle of the slope at the point at which the block starts to move downslope (ie when the downslope force just exceeds the upslope resistance)
Escarpment	For the purposes of this report a vertical rocky face where ground is displaced downslope
Factor of Safety	The ratio of resisting forces to destabilising forces; a factor of safety of less than 1 defines failure of the slope.
Facies	Features which characterises a sediment as having been deposited in a given environment
Fault	A fracture in a rock which there has been an observable amount of

	displacement
Gabions	Generic name to revetments consisting of stone contained in stell or polymer mesh
Geology	For the purposes of this study the nature of the processes which have given rise to its present state
Geomorphology	The description and interpretation of land forms
Glacial deposits	The results of erosion, transportation and deposition of material related to ice sheets and glaciers
Gouge zone	Rock material that has been ground to a fine particle size of clay/silt during the process of faulting
Graben	A downthrown block between two parallel faults or in the case of this study a downthrown block occurring as a result of subsidence and bed separation
Groundwater	Water contained in and flowing through the pores and fissures of soil and rock
Hade	The angle a fault plane makes with the vertical plane
Hanging wall	The block thrown down of a fault plane
Hydraulic gradient	The change in total hydraulic head between two points, divided by the length of flow
Hydrogeology	The study of groundwater or underground waters
Hydrology	The study of water and for the purposes of this study, the study of surface waters
Inclinometer	A method of obtaining the borehole angle from the vertical, thus enabling measurement of the ground displacement
Inclinometer torpedo	The instrument used to measure ground displacement
Lithology	Generally relates to descriptions of sediments/ rocks based on their outcrop
Loading	The added force (weight) from, for instance, human influence of depositing mine spoil, etc to the ground surface
Made ground	Material deposited by unnatural processes (eg mine spoil, factory waste, etc)
Meltwaters	Waters originating from the thawing of ice sheets or glaciers
Multiple rotational failure	A sequence of rotated blocks sharing a common basal shear surface
Normal fault	Formed under tension, downthrow is on the downdip side
Periglacial	A region adjacent to an ice sheet
Permeability	Is the measure of the ability of water to move through a soil or rock mass
Permafrost	Permanent frost or permanently frozen ground associated with ice sheets and glaciers
Piezometer	An instrument installed within a borehole to measure pore water pressure or, in the case of this study, to measure groundwater level (*a*

	standpipe piezometer)
Pore water pressure	The pressure of groundwater in the pores of a soil, rock and other material
Retrogressive failure	Where ground movement occurs at the base of the slip and the destabilising effect riffles back up slope
Reverse fault	Form under compression, downthrow side is opposite to dip
Rock fall	The failure of a block or blocks of rock due to possible undercutting, weathering or structural condition and loading
Rotational failure	Where ground movement takes place by sliding over a curved basal shear surface, with the result that the moving mass becomes tilted or rotated as it moves
Run off	Surface water flow into streams or rivers
Scarp	A near-vertical face forming the back face of failed downslope block
Scree	The accumulation formed by the fragments resulting from the mechanical weathering of rocks
Seatearth	A type of fossil soil associated with coal seams
Shear strength	The amount of maximum shear stress that a material can withstand before failure occurs
Shear stress	The force acting to rupture a material so that it deforms by one part sliding over another: *see cohesion and angle of friction*
Silurian	A geological period preceding the Carboniferous Period, extending from 435my to 395my before present
Spoil	Waste material derived from mining extraction
Strata	Rocks which display layering or bedding
Subsidence	The downwards displacement of material into underlying voids
Surcharge	See *loading*
Syncline	A basin shaped fold of strata
Tension crack	An aperture that opens upslope of a failure as the intact ground relaxes
Toe	The base of a riverbank or slope
Toppling	The failure of blocks of rock through a forward rotation due to gravity
Translational slide	A moving mass of a coherent body, remaining in contact with the ground on an inclined slip surface or shear plane sub-parallel to the slope
Uncomformity	Is the plane or break between two sequences of rocks with different dips. It indicates a period of earth movements or tectonic deformation between the times of sediment deposition.
Water table	For the purposes of this study the level at which groundwater lies below the surface. The level at which pore water pressure is aero (the *'phreatic level'*)
Weathering	The process by which rocks are broken down and decomposed by the action of external agencies such as wind, rain, temperature changes, plants and bacteria
Young	The orientation of the rock in which deposition occurs.

Notations

bgl	Below ground level
m	Metres
mm	Millimetres
my	Million years
γ	Unit weight
c'	Drained effective stress shear strength - cohesion
c'_{peak}	Peak strength
c'_r	Residual strength
ϕ'	Drained effective stress shear strength - angle of friction
ϕ'_{peak}	Peak strength
ϕ'_r	Residual strength

IRONBRIDGE GORGE INSTABILITY
LLOYDS AND JACKFIELD LANDSLIDE STUDY

1 INTRODUCTION

The Ironbridge Gorge has a history of landsliding and the slopes within the area of study show evidence of recent ground movement. Part of the slopes at Jackfield and the area around Lloyds Cottage are currently active and the riverbank at Lloyds Head and throughout other parts of the study area are actively eroding. All three areas are currently at threat from damage to property, disruption to infrastructure, and to some degree, public safety. All three sites lie within the boundary of the World Heritage Site.

The oversteepened slopes of the Gorge have been formed by incision and erosion by the River Severn which combined with the susceptibility of the geology has led to slope failure and landsliding. The situation has been complicated through the human influence of mining, which has created voids at depth, resulting in ground subsidence, and the surcharging of the slopes with mine waste. The groundwater regime would undoubtedly have changed during mining and more significantly following the cessation of mining in the area when the dewatering of mines would have also ceased. A further consequence of the industrial revolution in the area has been the disposal of tile and brick waste along the river banks and slopes. These deposits, have loaded the potentially unstable slopes and due to their deposition in a non-compacted state, are susceptible to river erosion and subsidence.

Furthermore, there has been an increase in the frequency of flooding of the Ironbridge Gorge over the last decade and heavy periods of rainfall have increased the levels of groundwater within the slopes; climatic change may already be affecting the area and the consequences of climatic change may be expected to cause further deterioration of the slopes in the future.

Ground movement within the area of study and the resulting damage and threat to public safety will continue unless remedial measures are undertaken to arrest ground movement.

1.1 Terms of Reference

The Ironbridge Gorge Landslides study was commissioned by Telford & Wrekin Council in order to interpret results of the recent ground investigation at The Lloyds and Jackfield landslides. This report completes the assignment in accordance with the Scoping Document sent under cover of Telford & Wrekin Council's letter dated 10 December 2002 (ref, HM

009intech). High-Point Rendel's (HPR) proposal was sent under cover of their letter dated 22 January 2003 (ref. Gen/S2003-004/EP3107/ARC/mlf); a revised proposal was submitted by HPR and sent under cover of their letter dated 13 February 2003 (ref. Gen/S2003-009/EP3107/CFS/mlf).

Telford & Wrekin Council awarded HPR the Ironbridge Gorge Landslides project in their letter dated 8 April 2003 (Ref. HM009-Interaward).

1.2 Objectives

The objectives of the study are stated in the Scoping Statement for Interpretation of Ground Investigation Results at The Lloyds and Jackfield, dated November 2002 (Ref. GISCOPE/HM009). The objectives of the study were:

- To identify the interrelationship between ground movement across the gorge and how this could be influenced by remedial schemes
- To establish the speed and extent of instability on each side of the gorge in the area identified on the plan attached to the Scoping Statement (ref. HM009/SCO_PLAN)
- To identify the causes of the instability and the mechanisms causing ground movement.
- To come to a greater understanding of geological, hydro-geological and hydrology structure in the area based on the investigation results.
- To produce a ground model for the area identified on the plan HM009/SCO_PLAN and to make available this data to inform the design process.
- To produce a comprehensive interpretative report for the whole area identified on plan HM009/SCO_PLAN.
- To produce a ground model for the same area in a format which will enable the assessment of remedial scheme proposals on a locality wide basis.

This report has considered all areas within the study boundary both as individual areas and considering any inter-relationship between areas in order that a ground model can be determined for each site. The study has concentrated on areas where subsurface data has been provided.

Representatives of HPR and TWC undertook a visit to the study area on the 20 & 21 May 2003. A further site visit was made by HPR and TWC which was site specific to Lloyds

Cottage following significant reactivation of ground movement in the area. It should be noted that the study area visits to key sites, undertaken by HPR, were for site familiarisation only and no detailed walkover survey, or mapping was required to be carried out by HPR as part of this scope of works.

During the course of this project High-Point Rendel have employed our retained sub-consultant Professor Edward Bromhead as a specialist advisor.

Professor Bromhead is Head of Civil Engineering at the University of Kingston and is a world renowned authority on unstable slopes. Professor Bromhead is the author of The Stability of Slopes and has written many technical papers on the subject.

1.3 This Report

This report comprises two volumes, Volume 1 includes the main body of the report and Appendices and Volume 2 comprises the figures only.

2 DESK STUDY

2.1 Background and Previous Studies

The study area encompasses the north and south valley side of the Ironbridge Gorge between the Freebridge and the footbridge down stream of the River Severn near The Boat Inn (see Figure 2.1). TWC has divided the study area into three main sites: Lloyds Coppice on the northern bank of the Severn; and the Lloyds Head and Jackfield sites both located on the southern bank.

Substantial information has been provided by TWC. Data provided included recent ground investigation studies, previous slope instability reports, archaeological reports and mining studies. A list of the information provided is presented in Appendix A. This project has been, essentially, a desk study and has relied on data determined by previous studies supplemented by HPR observations on site, and their interpretation of the recent ground investigation data and familiarity of other landslides sites across the UK. Given the amount of data provided, this report has endeavoured to include as much relevant data as possible, however, time constraints to meet the required programme may have prevented some of the less relevant information from being included.

Extensive ground investigations were undertaken immediately prior to this study in the three areas of interest. The investigations included cored and open hole drilling and the installation of borehole instrumentation, namely, inclinometers and piezometers. Laboratory testing was also carried out on soil samples from most sites. Ground investigation data has also been provided for the studies undertaken at Lloyds Cottage (1995) and either side of the Freebridge, also undertaken in 1995.

The ground movement within the study area has resulted in the need for frequent maintenance to repair cracked and damaged roads (The Lloyds, Salthouse Road and Lloyds Head) and substantial stabilisation works have been undertaken at Lloyds Cottage and Lloyds Head. The stabilisation works across the site are described later within this report.

The Lloyds Coppice site rises from ~40mAOD at river level to ~140mAOD on the plateau at Madeley. The valley side is bounded by two small valleys containing Coalport Road to the east and Madeley Road to the west. The valley side is densely wooded with minimal areas that have no tree growth. The slope itself comprises a series of ‘slope and bench’ profiles along the entire length. At the top of the slope a scarp some 10m to 30m high is observed running the entire length of this section of the valley comprising thickly bedded sandstone. A minor road, The Lloyds, traverses the lower part of the slope and is frequently used by residents and tourists. It is the main communication route around the gorge and is presently at threat from failure in the area between Wesley Road and Lloyds Cottage.

The Lloyds Head site is located on the southerly bank some 300m downstream of the Freebridge at Coalford and lies on made-ground consisting of mine and tile waste underlain by Coal Measures. The steep slopes of tile waste form a river bank, approximately 5m above river level which is actively eroding. Subsidence, from uncompacted tile waste, is threatening the integrity of property and infrastructure in the area.

The Jackfield site is bounded by the River Severn to the north, the Jackfield Tile Museum to the west and the footbridge across the Severn near The Boat Inn to the east; the southern boundary runs approximately NW-SE through Woodhouse Farm. The slopes on this side of the river are used for pasture and have little or no trees except for either side of Salthouse Road and the lower valley sides which are situated towards the westerly and easterly boundaries. The undulating slope forms an average angle of 10 degrees and rises from river level at ~40mAOD to ~115mAOD at Woodhouse Farm. Part of the slope shows evidence of recent ground movement, observed during the site walkover. Salthouse Road has a history of ground movement, and in parts, has a temporary flexible surfacing to accommodate such ground movement. In the early 1950’s substantial ground movement resulted in property being damaged and subsequently demolished. Ground movement also caused progressive movement of the banks into the River Severn, encroaching some 15m into the river area.

The study area has a recorded history of landsliding dating back to the 1700’s when the industrial revolution began in the area. However, landsliding would have commenced earlier during the rapid incision of the natural slopes by the River Severn following the last glacial period. The period of landsliding from the 1700’s to the present day reflects the period in which the area has been populated and hence the recording of landslides that have affected properties and industry. During this industrial period the natural slopes were loaded, in places, by mine spoil and tile waste. The slope processes of naturally formed slopes is to achieve equilibrium following the loss of support from the toe of the slope. In the case of the Ironbridge Gorge, which is, in geological terms, still in the early stages of development, lateral erosion of the river banks is removing the toe of the slopes and the slopes are in a continual state of movement in an attempt to achieve equilibrium. This will continue until the gorge reaches maturity or remedial measures are undertaken to increase the factor of safety of the slope either by protecting the river banks and stabilising the slopes or a combination of both.

Ground movement is currently occurring at all three sites and is likely to continue while erosion of the river banks occurs. The risk for ground movement in areas of population is currently high, however, landslides outside these areas could occur and potentially temporarily dam the river threatening areas upstream and downstream. Some areas (ie Lloyds Coppice) are threatened by the loss of road resulting in damage and disruption to property and infrastructure.

For the purposes of this report the study area sites have been further subdivided into more manageable units. The areas are located in Figure 2.2. The areas are defined by the following boundaries and are considered necessary for the lower slopes only.

Jackfield Site:

- Jackfield Tile Museum: which contains the western part of the study area up to approximately 50 metres east of the museum.
- Salthouse Road or the Jackfield (1952-53) Slip Area: which comprises the area from the eastern edge of the Museum Area to the western edge of Salthouses.
- Salthouses: from the western edge of Salthouse to Jackfield Mill
- Tuckies: which forms the remaining area of the eastern part of the study area

Lloyds Coppice Site:

- Lloyds Cottage: the western part of the site
- Old School (also known as School House): the mid-section of the site
- Lloyds House: the eastern part of the site

Lloyds Head Site is considered as one unit.

2.2 Geology and Geological Structure

2.2.1 Solid Geology

The geology of the area of study is described in the Geology of Telford and the Coalbrookdale Coalfield Memoir (BGS, 1995) and is shown on the Telford 1:25000 scale geological map sheet supplied by TWC. It comprises the outcrop of the Lower, Middle and Upper Coal Measures of the Carboniferous period. Silurian age rocks do occur in the west of the valley, but are outside the area of study for this report.

Lloyds Coppice and the Jackfield valley sides comprise material of the Upper Coal Measures (UCM), namely the Coalport and Hadley Formations. The Middle Coal Measures (MCM) are exposed in the western part of the study area towards the base of the valley. Table 2.1 summarises the geological sequence. The general description of each unit is also shown in Table 2.1 along with notable horizons and thickness of the units within the study area. The geology of the area is shown on Figure 2.3.

The geology is discussed further in Section 2.7 with regard to the recent ground investigation.

TABLE 2.1 SUMMARY OF GEOLOGICAL SEQUENCE IN STUDY AREA

Unit	Sub-Division	Description	Notable Horizons	Thickness (m)
Upper Coal Measures	Coalport Formation	Great thicknesses of red and grey strata, mainly argillaceous material, in which sandstones and coal seams are rare.	Main Sulphur Coal at the base of the formation is thin and sulphurous compared to the productive measures in the LCM & MCM – widely worked south of the R Severn. The Thick Rock is the most persistent sandstone in the Coalport Fm.	~85[1]
	Hadley Formation	Lies uncomformably on MCM, which outcrops at river level near the New Buildings and comprises approx. equal amounts of sandstone and argillaceous strata of varying colours: red, purple, and greenish grey.	Brick and tile clays worked	~15m
Middle Coal Measures		Dominant lithology grey mudstone, with subordinate sandstones	The Pennystone Marine Band (known to be mined for ironstone) lies at the base of the MCM. The Big Flint Coal widely worked throughout the area	~40
Lower Coal Measures		Comprises mudstones, ironstones, coals and seatearths, and more significant sandstone beds than the MCM	The New Mine Coal/Viger lies immediately below the MCM. Major coal seams worked include, in descending order; Ganey Coals, Best, Randle and Clod and Little Flint	

Ref. BGS, 1995
[1]Observed from borehole data taken at Lees Farm (IGS, 1973)

2.2.2 Geological Structure

The area around Ironbridge includes two unconformities; one between the Silurian and Lower Coal Measures and the other between the Middle and Upper Coal Measures. The Lower and Middle Coal measures have been gently folded into synclines and anticlines which trend southwest-northeast and plunge gently to the northeast.

The geological structure within the study area can be conveniently divided between the faulting evident on the geological map. Two sets of faults can be observed trending approximately west-north-west to east-south-east and north-east to south-west.

Generally, the dip of the beds is 4° to the east-south-east south of the 'Lloyds Coppice' Fault (see Figure 2.2), although this varies between 3° and 6° locally. North of this fault the strata dips 7° to the north-east.

The geological structure is presented in Table 2.2, the boundaries of which, and their locations, are shown in Figure 2.3.

TABLE 2.2 SUMMARY OF GEOLOGICAL STRUCTURE (FAULTED)

Area of Faulted Block	Geology Present	Downthrow of Block	Dip of Strata Dip/ dip direction
Jockey Bank Fault to Jackfield Fault	The Lower Coal Measures are exposed at lower valley level, on both sides of the Severn, where strata youngs upslope on the southern bank to the Coalport Formation. This block forms a hanging wall of a reverse fault with the ground to the west and the hanging wall of a normal fault with the Lloyds Coppice Fault.	The Jockey Bank Fault has a downthrow approx. 5m to 10m to the northwest in the Hadley Formation, but the throw reduces within the Gorge	5/ESE
Jackfield Fault to Doughty Fault	Both the Lower and Middle Coal Measures are exposed in the lower valley, where the strata youngs to the east, down stream and upslope.	The Jackfield Fault downthrows to the southeast and reduces from approx. 40m to 15m to the northeast in the Hadley Fm at Jackfield	6/ESE (Taken from Tile Mine)
Doughty Fault to Madeley Fault	The Coalport Formation is evident both north and south of this fault	The Doughty Fault throws down to the southeast, the throw has been estimated at 40m from mine tile plans*	4/ENE (Taken from Tile Mine)
North of 'Lloyds Coppice' Fault	Normal faulting has resulted in this block exposing the Coalport Beds in the upper valley of the north side of the gorge; with the LCM & MCM outcropping in the lower western side of the valley.	Downthrow is to the south (approx. 30m*)	7/NE (Lees Farm boreholes)
North of the 'Tuckies' Fault	The Coalport Formation is evident both north and south of this fault	A cross-fault between the Doughty and Madeley Faults shows downthrow to the south, ~10m	18/SE North of the Tuckies fault

Refs. BGS,1995

* Downthrow taken from, Halcrow, 1990.

In addition to the faults shown on 1:25000 scale geological map, mining records have identified two inferred faults both trending northeast-southwest and bounding the Lloyds Coppice fault to the south. These faults have also been shown on Figure 2.3 as dashed fault lines.

The geological structure and in particular the effects of faulting in the study area are discussed in more detail in Section 2.7.

2.2.3 Superficial Geology

Extensive areas of active rotational slips have been identified at both the Lloyds Coppice and Jackfield sites. These deposits are described and discussed in greater detail within Section 2.7 and 3.

Glacial deposits are evident on the plateau areas around Madeley and have been found to be up to 17m in thickness within the Lees Farm boreholes (IGS, 1973). Small isolated pockets of glacial deposits are identified on the drift geological map on the north western side of Lloyds Coppice.

Deposits of colluvium are described as being present on both the Jackfield and Lloyds Coppice slopes, mainly consisting of debris from old landslide events which may have originated from solid or drift deposits (Babtie, 2003).

River gravels are present at depth in one of the boreholes on the Lloyds Coppice site, but no river deposits are present at the surface.

The lower slopes at all three sites have deposits of waste from mine workings and, in particular at Lloyds Head, extensive deposits of tile waste.

2.3 Geomorphology and Landsliding

2.3.1 General

The geomorphological processes in the Lloyds Coppice and Jackfield study areas have been predominantly influenced by slope instability: a natural process of valley development. Therefore, it is considered appropriate to discuss the geomorphology of the site along with the landsliding.

Formation of the Ironbridge Gorge began during the end of the Last Glacial period as an overflow channel from ice-dammed lakes centred around the Cheshire - Shropshire plain. A full description of the development of Ironbridge Gorge can be read in Wills (1924).

It is currently considered that initial meltwater flows caused rapid erosion of the Ironbridge Gorge and all the meltwaters were diverted via the Gorge into the Severn system. Accelerated erosion by river action combined with the accelerated periglacial and permafrost slope processes would have resulted in ground failures due to toe removal of the valley sides and high groundwater levels during seasonal melting of the ice within surface layers. These two processes would have resulted in rapid degradation of the valley sides.

More recently the Ironbridge Gorge has developed by river incision eroding and undercutting the valley sides resulting in slope steepening and, subsequently, slope instability. The progressively deepened and steepened valley and the creation of pronounced escarpments has proved conducive to slope failure. This is evident, in places, where swathes of slipped ground have been observed. Valley development initiates a cycle of landsliding activity involving both shallow and deep seated landslides. This has been aided at Ironbridge by the high initial rate of incision (ie meltwater flow towards the end of the last glacial period), the geology and geological structure (ie orientation of the relatively incompetent coal measures) and groundwater conditions (eg periglacial and possible permafrost conditions). The Gorge is considered immature in age and is still in the process of developing.

It is generally considered that the river initially flowed on its present alignment from overflowing the col at Ironbridge and following the line of the Lloyds Coppice Fault, where preferential erosion occurred, although BGS (1995, p105) shows the Lloyds Coppice Fault to terminate against the Jockey Bank fault and is not in evidence to the west of this fault. The river was restricted from flowing north of the crest of Lloyds Coppice by the Thick Rock Sandstone horizon, which was higher than the level of the col at 100m.

Skempton (1953) proposes a three stage relationship between valley development and slope instability, as follows:

- Stage 1: downcutting and undercutting by a river generates shallow surface slides, once critical slope angles have been attained.
- Stage 2: the attainment of critical slope heights due to continued incision results in the development of deeper slides.

- Stage 3: when downcutting slackens or ceases and/or the river ceases to erode the valley side-slopes, the slopes degrade through shallow landsliding to a relatively stable angle.

It is considered that the area of study in the Ironbridge Gorge, based on Skempton's work, is currently in an early phase of Stage 3.

The action of river incision has exposed strata having a component of dip towards the Jackfield valley side, allowing the potential for sliding blocks and water to flow preferentially towards the river. At Lloyds Coppice the dip of the strata is into the valley sides, which favours the ingress of water into the slopes.

The Stage 2 deeper seated failures would have been structurally driven by the dip of the strata, although it is considered that initial incision of the river resulted in stream migration south due to the Thick Rock preventing northerly flow and the river migrating down dip of the Lloyds Coppice Fault.

2.3.2 Previous Geomorphological Mapping

Morphological mapping of the study area was undertaken by Babtie for their 2003 report and by Halcrow for their 1990 report. Halcrow (1990) subdivided the slopes into geomorphological units based on their landforms indicative of the landslide processes involved in their formation (see Figure 2.4). The following units have been based on Halcrow's ground behavioural descriptions, albeit undertaken in 1990, rather than the 'break of slope' geomorphological mapping used by Babtie (2003) which do not classify the different landforms according to the slope processes. From the rapid walkover undertaken in May 2003 and the study of aerial photographs of the site High-Point Rendel concurs in principle with Halcrow's landform classifications, although boundaries for each morphological unit have undoubtedly changed since 1990.

2.3.2.1 Jackfield Site

The Jackfield site is described as follows:

- The slopes of Jackfield rise from river level at ~40m and form an undulating generally uniform 10^{o} slope up to the Woodhouse Farm at approximately 110m AOD

- The slope from Salthouse Road level up is used for agricultural use (eg pasture)
- The area downslope of the road to the river contains properties and buildings
- The slopes in places have been 'loaded' by mine waste
- The river banks contains tile waste deposited from the Jackfield and Benthall Tile Works
- During the recent walkover, there was evidence of recent ground movement in the area where slippage occurred in 1952

Halcrow (1990) have identified six different morphological units for Jackfield:

Unit I: Near Woodhouse Farm, an area of gently sloping surfaces separated by low steep scarps and tension cracks of moderate relief. The downslope edge is formed by a steep continuous scarp some 5 to 10m high, which is considered to be the main backscarp of the Jackfield landslide. The broad fissured scarp is believed to represent an incipient retrogressive extension of the landslide by relatively deep rotational displacements within the bedrock.

Unit II: the downhill edge of Unit I is marked by an abrupt break in slope which marks the upslope edges of Units II and III. This unit is an area of a series of backward sloping surfaces and steeper downslope faces, well vegetated and used for pasture. This unit represents an area of degraded back tilted blocks derived from multiple rotational landslides relatively deep in bedrock.

Unit III: Adjacent to Units I and II, immediately north-east of Woodhouse Farm, Unit III comprises a series of gently sloping benches on platforms, some backtilted. These rotated blocks are oblique to the general trend of ground movement and are sharper in appearance suggesting movement occurred more recently than in Units I and II.

Unit IV: The area immediately upslope of Salthouse Road and downslope to river level; is an area of generally subdued relief, highly degraded, well vegetated and being wooded in parts. It contains areas of made ground which extends down to river level. The morphology suggests that translational sliding is dominant with subsidiary rotational elements. The material slipping is derived from the landslide blocks upslope. Recent and past site investigations identify movement ~5.0m below ground level. The 1952-53 investigation identified that much of the upper slope comprised made ground, the lower part appeared to comprise seatearth and some coal, suggesting failure occurred through in situ rock adjacent to the river.

Units V and VI: These units represent areas of moderately deep rotational landslides with some translational elements, all within bedrock. The direction of movement of these landslides units is directly towards the tributary valleys, east and west, respectively, of the Jackfield landslide.

2.3.2.2 Lloyds Coppice Site

The Lloyds Coppice site is described as follows:

- Lloyds Coppice rises from river level at ~35 to 40m AOD to approximately 145m AOD and has an slope gradient between 15^{o} and 26^{o}.
- The slopes are heavily vegetated with immature and mature tree growth.
- The upper valley slope is dominated by the sandstone escarpment which runs the entire length of the study area increasing in height from west to east.
- The slope and bench profile of the slope, across much of the site, suggests that this is an area of multiple rotational landslides.
- The benches commonly show saturated ground and ponding.
- The lower part of the valley has been used to dump mine waste.

Halcrow (1990) have identified seven different morphological units for Lloyds Coppice:

Unit I: Forms the main scarp observed across the crest on the northern slope. The unit is ~1200m long and up to 30m high, and beyond it lies the gently south-easterly sloping plateau comprising the residential area of Madeley. It forms a steep cuspate scarp trending west to east and north-west to south-east direction. Bedrock comprising sandstones, siltstones and mudstones are exposed locally in cliff faces between which the scarp comprises very steep slopes where the bedrock is obscured by the accumulation of scree. There is little evidence of active instability. Boulders are present locally at the base of the scarp indicating rockfall; in places degradation of the scarp has resulted in debris sliding. In parts of the backscarp there is a narrow bench feature 3 to 5m below the crest and is believed to have been caused by the sliding of a less resistant capping layer, either of superficial deposits or weak mudrock.

Unit II: lies beneath Unit I and in the eastern part of Lloyds Coppice. A series of ridges or tilted platforms up to 30m wide and separated by short steep scarp slopes aligned approximately parallel to the backscarp sloping downslope away and towards it. Several small ponds and waterlogged ground occur within hollows of this area. This unit is considered indicative of multiple rotated blocks with no significant active movement taking place at present.

Unit III: forms a section of the central cliff from mid-slope upwards to Unit I. This unit is a ridge-like area of ground. Unlike Unit II, individual blocks cannot be recognised and the morphology is more degraded and subdued. It is believed to represent a mass of bedrock detached from the main landslide backscarp, probably by rotational movement. There is no indication of active or recent ground movement.

Unit IV: forms the eastern upper section of Lloyds Coppice beneath Unit I. This unit has similar morphology to Unit II but has more pronounced topography which includes several rocky cliffs. Mature tree growth and ponding, in its central section occupying a graben-like feature, are evident. The backtilted blocks are considered indicative of predominantly rotational failure of the bedrock although the presence of the graben-like feature suggest subsequent translational movement. Rock failures, by toppling, are apparent from a rock face in the northwest of the area.

Unit V: extends across the mid-slope length of Lloyds Coppice. This unit is characterised by a more subdued, well vegetated topography which descends the slope in a series of irregular lobes, benches and gentle scarps and ridges; generally, slope directions are downhill but several backward sloping areas were mapped. The ground is notably wet in the upper part of the unit with ponds and waterlogged areas in its northwestern part. Numerous discontinuous fresh small scarps and tension crack development aligned both along and down the slope and the upslope edge of the unit is marked by a fresh scarp in which disrupted roots and remnant rock debris are exposed. Fallen trees and several small mud and debris slides are evident. Landslide processes include both rotational and translational, affecting the degraded material originating from the disruption and weathering of displaced blocks upslope. Movement is clearly active in much of this unit and recently active or quiescent in the remainder.

Unit VI: extends across the mid-slope length of Lloyds Coppice beneath Unit V. This unit is characterised by a mainly degraded, gently undulating series of lobes, cusps, gullies and ridges. The landsliding in this unit is probably translational movement of degraded landslide debris from upslope. The depth of sliding is likely to be shallow, although there is no evidence of active movement, however, the area near School House, shows sharper features giving the appearance of a more recently disrupted area.

Unit VII: from the western extent of Lloyds Coppice to east of School House between Unit VI and the River Severn. This unit forms the toe area of the landslide complex. In the central and western part of the unit substantial areas of colliery spoil have been deposited. A small area of natural ground is preserved between the toe of the spoil and the river bank in this area and also to the extremity of the unit. Bulging and fissuring are evident along much of the length of The Lloyds. One particularly notable area is the vicinity of its junction with Wesley Road and the area of made ground between these two roads. A slip scarp and sub-vertical slip surface are also observed in the spoil material adjacent to Telford Canal Club [*presumably the Canoe Club*]. The natural ground, where observed, is hummocky and fissured between the spoil and the river. There are several issues and a tendency for water to collect in a depressed area at the toe of the spoil, there being a backward slope of the natural ground in places. The river bank which is some 2 to 3m high is being actively undercut by the river. There are several failures of the river bank comprising rotational failures which in some instances are accompanied by flows of saturated sands and silts forming the river bank. This has resulted in the disruption of footpaths and the toppling of trees into the river. The sheet pile wall downslope of School House has been severely dislocated by ground movement (Plate 1). The main slip surface is believed to be observed just above low water mark level. On this basis the landslide debris is only 2 to 3m thick immediately adjacent to the river but probably increases upslope. The landslide displacements affecting this area are probably mainly translational sliding of debris and overlying made ground along the failure surface at rockhead.

2.3.2.3 Lloyds Head

Lloyds Head is an area of relatively flat ground adjacent to the river upstream from the Jackfield site. The river banks comprise up to 5m thickness of tile waste deposits underlain by the Middle Coal Measures, which have been mined in the area. Stream action is currently actively eroding this section of riverbank (see Plate 2).

TWC's (2000a) desk study of Lloyds Head identifies a former cart track, which ran parallel to the old Severn Valley rail line to the Jackfield Tile Works. Between the 1830's and the 1930's tile waste and furnace slag, from the Jackfield Works, was deposited along the river bank; tile waste ceased to be dumped in the 1930's. The frequency of maintenance undertaken on the road resulted in remedial repairs being constructed in 1995 (see Section 2.9). The area containing tile waste was observed to be moving in 2000, resulting in subsidence and causing damage and cracking to sections of road.

The tile waste was unlikely to have been compacted before being placed. The relatively high permeability of the material has enabled washout of the fines, resulting in the ground subsidence and the continued regular maintenance of the road (Plates 3 & 4).

TWC's (2000a) report also describes the ground movement on the privately owned land at Railway Crossing cottage that has lost 4m width of riverside land.

No mapping was undertaken by Halcrow of the Lloyds Head area.

2.3.2.4 Landslide Events

Babtie (2003) identify ground failures as early as 1728, and both Babtie and Halcrow (1990) record the locations and events which have occurred across the Lloyds Coppice and Jackfield sites between 1925 and 1990. The records relate only to the recorded effects without reference to their failure mechanism, magnitude or specific location. The location of recorded landslides are shown on Figure 2.5.

The earliest recorded landslide event occurred in 1728. Up until 1925 no further landslips were recorded in the study area, although a landslide resulted in the temporary damming of the River Severn at The Birches, Buildwas in 1773. The Halcrow report refers to a general trend of narrowing of the river as a result of the northerly migration of the southern bank in the Jackfield area. This has been described as consistent with ground movements in the area, but may also be the result of tipping from tile works along the southern riverbank. It is considered that the overall migration of the river is southwards from the Lloyds Coppice Fault, however, recent ground movements (since the 18^{th} Century) and the surcharging, by mine spoil, of the natural slope has resulted in a recent trend of the river northwards. Further landslips in the Jackfield area occurred in 1925, northwest of the Tile Museum, and in 1931.

The best documented landslide occurred in 1952, and continued into 1953, between the Jackfield Tile Works and Salthouses. In early 1952, a ‘catastrophic’ landslide occurred damaging six houses, which were later demolished. Salthouse Road was closed to traffic and the railway was maintained daily as the track continued to slew and subside. Henkel and Skempton (1954) and Skempton (1964) report that the maximum downslope displacement reached 18m and the southern river bank was displaced northwards approximately 14m beyond the previous river bank line. The slip is said to have occurred on a 10.5^{o} sloping hillside in the exposed Coalport Beds of the Upper Coal Measures which near the surface are composed of stiff fissured clays. Ground movement was relatively slow moving following heavy rainfall. Horizontal movement was of the order of 20m in the centre of the moving mass, while the displacement at the foot of the slide was ~10m. The difference in relative movement resulted in undulation and cracking of the ground between the road and the river, bringing about the demolition of property and disruption to the utility services. The upper limit of the sliding was marked by a 1.5m clay backscar. In 1952 boreholes were sunk to identify water levels and locate slip planes. The slip was diagnosed to be a shallow slip with a depth of 5.2m in the centre of the slip to ~4m at the toe of the slip. Between 1952 and 1953, the extremity of the landslide retrogressed upslope and to the southeast, resulting in additional damage to buildings and the railway. The width of the river had reduced from 38.1m to 24.4m and erosion of the slipped debris was in progress. The width of the slip was ~200m and the length ~215m; the weight of the slipped ground was ~300,000 tons. The slip retrogressed up slope in a series of small rotational slips exposing near vertical clay backscars. The landslide event has been established as a debris slide on a shear surface approximately 5m below ground level (see Figure 2.6). Remedial works undertaken included filling the major surface cracks and river bank protection; no drainage was undertaken.

The slip surface was assumed to lie parallel to the ground surface and during the winter the groundwater was generally at surface level and filled the cracks and fissures resulting from the slip. The location of the slip is shown in Figure 2.5.

Between 1953 and 1971, the landslide migrated westwards to the Tile Museum and further damage occurred to the railway bridge. Further slippage of Salthouse Road occurred which involved some further 8m movement towards the river and 2m of subsidence between 1966 and 1971 (Halcrow, 1990).

In 1984, further ground movement occurred to the west of the 1952 area of landslide. Salthouse Road was carried into the river and was replaced by a temporary roadway constructed along the line of the former railway. Movement also took place at this location in 1971 (Halcrow, 1990). Remedial measures included drainage and the protection of the river bank at the toe of the landslide. However, despite these remedial measures ground movement still continues in the area. The location of the 1984 slip is shown in Figure 2.5.

2.3.2.5 Recent Ground Movement

Recent ground slippage has been observed during the walkovers undertaken as part of this study up until August 2003. Ground movement has been observed on the Jackfield slopes west of Salthouses (possibly a reactivation of the 1952 slip) and to the north of the river in the area downslope of Lloyds Cottage on the Lloyds Coppice slope.

The recent movement on the Jackfield slope shows stepped and undulating ground with significant tension crack development, indicative of a retrogressive debris slide (Plates 4 to 9). The causes of landslides at the Jackfield site are discussed in Section 3.3.

Movement observed downslope of Lloyds Cottage suggests that retrogressive rotational failure, possibly of a previously failed block, has occurred following a period of heavy rainfall

(Plates 10 to 13). Borehole instrumentation, and their logs, shows a shear surface above river gravels at approximately 11m depth. However, the profile of the slip surface cannot be determined from the provided borehole data and it is uncertain whether the profile of the slip plane toes out at river level or toe failure has resulted in a retrogressive slip up slope. The current causes of ground movement at Lloyds Coppice is discussed in Section 3.4.

2.4 Frequency of Landslides

Landslides have been recorded since 1700's. Since 1925 landslides have occurred at the Jackfield site which have resulted in damage and disruption to property and infrastructure, on a frequency of approximately every 20 to 30 years. Subsurface ground movement, that is subtle ground movement not recorded or observed at ground level, may have resulted in the leakage and damage to underground services, although damage may be a result of other factors rather than ground movement alone.

Halcrow (1990) have calculated that small landslides occur on an average frequency of one event per annum, although there is considerable annual variation. It was observed from data collected that a number of small events at the Tuckies were associated with differential shearing at the margin of the landslide complex. Movement was observed to occur throughout the year, with the frequency of landslides increasing in the winter months, suggesting a relationship with high groundwaters and/or high river levels and flows.

Simple analysis between the relationship between landslides, rainfall and river levels has been undertaken in Section 2.5.

There have been no recorded large scale landslide events in the Lloyds Coppice area of study, however, the shearing of the Lloyds Pump House shaft suggest that ground movement has occurred in the recent past. Although significant movement is currently occurring from Wesley Road junction to the east of Lloyds Cottage along the Lloyds. Records from utility services show repairs have been made to damaged services in the western and eastern extremities of the road itself; the damage has been established to be the result of landslide displacement. Halcrow also show that events in the Lloyds Coppice occur at an average frequency of 1.5 events per year; more frequently than at Jackfield. Events occur throughout the year, but occur more frequently in January to April.

Remedial measures have been previously undertaken within all three sites and maintenance is a constant requirement to maintain road access. The construction of a gabion retaining wall in the area of the School House arrested 'over-riding' failures of debris in the 1960's (Halcrow, 1990), although ongoing displacement and distortion of the wall is apparent (Plate 14). Remedial works at Lloyds Head and Lloyds Cottage are described later within this report in Section 2.9.

2.5 Hydrogeology, Hydrology and The River Severn

The brief for this section was to establish a greater understanding of the hydrogeological and hydrology structure in the area based on the investigation results.

2.5.1 Hydrogeology

Hydrogeology is controlled by the geological structure, ground mass and the chemical characteristics of the groundmass. In the Ironbridge Gorge area faulting may significantly complicate the hydrogeology.

Babtie (2003) report the Carboniferous Coal Measures and the alluvial and glacial drift deposits as minor aquifers. Any groundwater flow is likely to be restricted to the sandstone units, which are subordinate to mudstone and siltstone units in the Upper Coal Measures, which predominate throughout the study area. However, fractured rock allows fissured flow through horizons of lower permeability. Of potentially greater significance is the flow of water along abandoned mine workings within both the north and south slopes of the Ironbridge Gorge.

Both Babtie (2003) and Halcrow (1990) report numerous springs, seepages and wet ground on both the Lloyds Coppice and Jackfield slopes. Springs are likely to occur at the interface of a higher permeability arenaceous horizon underlain by a lower permeability argillaceous material and where the dip of the beds falls to the valley side. Ponding is evident on the Lloyds Coppice slope which may have developed from water flowing through fissured rock or surface run off being blocked by landslide debris.

The hydrogeological character of the site can be divided into two areas: the north slope and the south slope of the River Severn.

Within the north slope the dip of the strata, both north and south of the Lloyds Coppice Fault is into the slope, approximately 7^o to the north-east. It is anticipated that a proportion of water would flow away from the side of the valley, although some will be drawn-down to the valley.

In the south slope the dip of the strata is generally 4^o to 7^o to just south of east. It would be expected that water would flow down dip to the River Severn, or beneath to the Lloyds Coppice Fault on the north side of the river. However, a 'block' (which straddles the River Severn) formed by the 'Tuckies' Fault dips 18^o to the south east and comprises the largely argillaceous strata of the Coalport Beds, where groundwater is anticipated to flow south to the Tuckies Fault.

The south slope is further complicated by the Doughty and Jackfield Faults, which, like all the faults in the site, may act as either a conduit or a barrier for groundwater, depending on the permeability of the material both in the fault and on either side of the fault. A brecciated fault zone is likely to allow water flow, but a thick gouge zone containing abundant clay minerals may act as a barrier to flow. There is no evidence within the ground investigation to suggest that a borehole has been cored through faulted material and, therefore, the nature of the fault zone is difficult to determine. Faulting is likely to have offset water-bearing sandstone horizons against an argillaceous horizon, which would also significantly affect groundwater flow. It is noticeable that the pond identified at Lloyds Coppice has formed directly upslope of the fault.

However, water wells sunk at the Tuckies are situated up dip of the Tuckies Fault. This may suggest that the fault may either be preventing groundwater flow away from the mined level or simply allowing extraction of mine water where water is prevented from flowing and pressure builds up.

Generally, the dip of the strata in the Jackfield area required mining to be undertaken to the south and west of mine shafts. Gravity drained groundwater towards the shafts which was then removed by pumping. Further discussion on the effects of groundwater with regard to mining is presented in Section 2.8.

The presence of groundwater near ground level has been observed by ground investigations in the Jackfield area of 1952 and 1984, both undertaken following landslides. The source of this water is likely to be primarily from infiltration of prolonged and heavy rainfall, with accelerated infiltration along fissures and tension cracks. However, the in situ weathered clay lying beneath the mine waste deposited throughout the period of mining at Jackfield, is likely to be acting as a barrier preventing further infiltration of rainwater. It has also been suggested that mine shafts overtop and that fractured ground, as a result of subsidence, provides avenues for water flow which could enter landslides systems; there is no evidence to suggest that this has occurred, however, this is discussed in more detail in Section 2.8.

Movement of water under hydraulic gradient, especially where sandstone units outcrop, would be expected to issue along valley sides. Groundwater is likely to be issuing into former landslide debris, along potential slip surfaces and into mine waste deposits, which are extensive on both sides of the gorge.

Permeability tests were carried out in the Lees Farm boreholes by the IGS (1973) on two sandstone units, namely the Thick Rock and the Stinking Rock. Permeabilities ranged from 10^{-7} to 1.4×10^{-6} m/sec for the Thick Rock and 2.2×10^{-7} m/sec for the Stinking Rock. Both of which can be considered relatively low permeabilities for sandstone. However, these results are presumed to be for unfractured rock over the test zone and may not reflect the bulk permeability of the fractured or jointed rock mass. Regionally, groundwater flow usually follows the dip of the bedding due to interbedded layers of arenaceous and argillaceous coal measures confining flow. In the case of Lloyds Coppice, the confined flow of water along the dip of the beds probably contributes to the instability along the eastern valley side of Coalport Road, where the Thick Rock outcrops.

Denness (1977) carried out permeability tests on both the arenaceous and argillaceous facies of the Coalport Beds. Packer tests determined the upper sandstone (the ‘Thick Rock’) was more permeable than the mudstones, but the permeability of the mudstone could not be measured as it was beyond the sensitivity of the equipment. No water was observed in the upper sandstone, but water was observed in the lower sandstone (the ‘Stinking Rock’). Testing found that the upper sandstone was more permeable than the lower sandstone. The Thick Rock (which is partially obscured by slipped material on the Lloyds Coppice valley side) outcrops on the western side of Coalport Brook valley, which has not incised to the level of Stinking Rock. This is significant as groundwater can drain into Coalport Brook from the Thick Rock, whereas water in the lower sandstone is contained within the slope, or where the horizon is exposed within the valley.

Furthermore, mining induced disturbed strata and bed separation will increase the bulk permeability of the rock mass; this is discussed further in Section 2.8.

Current groundwater levels are discussed in Section 2.6.

2.5.2 Hydrology

Quarterly rainfall data, in graphical form, from the Coalport and Coalbrookdale rain gauges for the periods 1974 – 2002 and 1992 – 2002 respectively are presented in Babtie's (2003) report. No data has been made available for the Ironbridge Gorge area prior to 1974.

Babtie (2003) report that maximum and minimum rainfalls recorded, during the period of data provided, are 169.4mm in the fourth quarter of 1974 and 25mm in the second quarter of 1976, for the Coalport rain gauge, and 129.9mm in the fourth quarter of 2000 and 26.8mm in the first quarter of 1993 for the Coalbrookdale rain gauge.

There are no records of rainfall from the Coalport rain gauge for 2000 and the third quarters of 2002. A minimum of 28mm was recorded for the first quarter of 1993. For most quarters rainfall patterns are similar, as would be expected between two nearby rain gauges. Based on this similarity, rainfall has been plotted against water levels of the River Severn, see Figure 2.7. River level data is recorded at the Buildwas Gauging Station.

2.5.3 River Severn: Flood Events

Figure 2.7 identifies that flood events or near flood events (relative to the Ironbridge Wharfage Flood Level) occurred following:

- Rainfall greater than ~90mm during or just preceding the quarter of a flood event
- Rainfall greater than ~75mm during the quarter of the flood following rainfall greater than 50mm per quarter for the two preceding quarters
- When rainfall for two successive quarters is greater than ~70mm per quarter

The most significant flood occurred during the fourth quarter of 2000 when river level reached ~43m AOD at the Buildwas Gauging Station. This event followed a period of prolonged rainfall through the 2nd and 3rd quarters (70mm plus per quarter) and peak rainfall in the 4th quarter of ~129.9mm (Coalbrookdale).

The high rainfall in the Ironbridge area during or preceding a flood is likely to exacerbate the problem of flooding rather than trigger a flood event. The triggering of a flood event is more likely to be dependent upon the rainfall within the catchment of the River Severn upstream of Ironbridge.

In an attempt to identify upstream behaviour compared to Ironbridge, analysis of peak floods at Welshbridge (Shrewsbury), have been compared to peak floods at Buildwas to determine any relationship between corresponding flooding events. This relationship can be observed in Figure 2.8. The comparison of floods at Buildwas and Welshbridge gauging stations suggests that floods experienced at Ironbridge are not considered flash floods and the floods are a natural progression of the flood wave downstream. Data available for Welshbridge peak floods is unavailable after 1999. Babtie (2003) have analysed flood events back to the 17th Century and have assessed that one flood event has occurred every decade up until 1990. They also report that since 1990 a major flood event at Ironbridge has occurred 'nearly every year'.

Flooding has been observed to occur during the first and fourth quarters of the year, when rainfall is high and the ground is likely to be saturated preventing further infiltration and enabling greater run off into stream systems.

Simple correlation between rainfall, river level and ground movement has been undertaken for the period between 1986 (the earliest rainfall records) and 1990 (end date for ground movement and river level data collection), see Figure 2.9. Small landslide events do not readily show a trend with either or both rainfall and river level. This is more than likely a result of the small data set (ie a 4 year period). Further analysis should be undertaken, investigating small landslide data after 1990, in order that any relationship between ground movement, river level and rainfall, may be identified. However, data collection should be on a day-by-day basis so that ground movement (or reports on disruption to services) on a particular date can be correlated to antecedent rainfall or river level. For this reason correlation of small landslide events against flood levels has not been undertaken due to the insufficient detail of the data sets.

TWC (2000b.i) reports large floods to have occurred in November 1770 and January 1795, in which ice floes were brought downstream as a result of rapid thaw, damaging then destroying a mill on the Severn bank at Calcutts. Water levels were reported half-way up the chimney stacks at Jackfield. Further flood events were reported in 1839 and 1852.

2.5.4 River Severn: Incision and Erosion

River bed level was surveyed in the area downstream off the Freebridge in 1935 and 1978 over a 500m distance. Maximum and minimum bed level lowering has been calculated to be 1.5m and 0.4m respectively. A component of this lowering of bed level may possibly be a result of subsidence from mining as well as the natural process of river erosion. Based on the levels provided, rates of erosion vary between 0.035 and 0.0093 m/year. The area downstream of the Freebridge comprises strata of the Middle Coal Measures.

Erosion of the river banks is a result of the hydraulic action of the water, abrasion (mechanical wear) and corrosion (chemical action). The course of the river is such that some areas along the banks are subject to greater rates of erosion (ie banks on the outside bend of the river than those on the inside of a bend), Plate 15. Landsliding also alters the course of a river. While landslide debris deposited in the river will be eroded by the action of the river, accelerated erosion is likely to occur on the opposite bank, leading to a more meandering course. Erosion through turbulent flow and abrasion (the action of rock particles carried in the water scraping along the banks and bed of the river) increases greatly during flood events. Capacity for bed load increases rapidly with stream velocity as the swifter the current the greater the turbulence and stronger the dragging force against the bed. Capacity to carry bed load increases a third to fourth the power of the velocity, so when stream velocity doubles, capacity for bed load is increased from 8 to 16 times. Corrosion is an unknown quantity within the River Severn, and is likely to be of secondary importance.

A fourth factor affecting bank erosion is the susceptibility of the bank material to erosion (ie the composition of the river banks). Poorly consolidated material, such as clay, sand and tile waste, is more readily erodable than rock. Both sides of the river within the study area show made ground, colluvium and weathered Coal Measures at bank level (Plate 15).

Copied historic maps within the Halcrow (1990) report (also copied into the Babtie (2003) report) show Lloyds Coppice, Jackfield and the course of the River Severn since 1881 and subsequent surveys in 1901, 1925 and 1969. Evidence by observation shows the width of the river to have been affected by landsliding. This is notable on the Lloyds Coppice side, opposite The Calcutts, where the river has been significantly reduced in width. Although not observed on the historic maps the river has also been subject to narrowing following the 1952-53 slip at Jackfield, where the width of the river was reduced from 38.1m to 24.4m following 13.7m of river bank movement (Henkel and Skempton, 1954).

The 1881 Jackfield map shows alluvial deposits within the river downstream of Salthouses. By 1901 these deposits have been elongated by river action and by 1925 there are no deposits evident. The change in shape and disappearance by 1925 suggest that the deposits were recent to 1881, possibly being an accumulation of tile/ mine waste tipped on the river foreshore.

Usually a river course follows a geological structure such as a fault. Evidence within BH 16 of the recent ground investigation (see Section 2.1.11) identifies a horizon of river gravels at 11.0m depth, approximately 2m above present river bed level. This suggests that the course of the river has advanced southwards, possibly from the line of Lloyds Coppice Fault. This is also the premise suggested by Shropshire County Council (SCC, 1995) who show an arc-like course around the Jackfield site towards Coalport (see Figure 2.10), which suggests that landsliding events at Lloyds Coppice have had a greater effect on the morphology relative to the Jackfield landslides.

2.6 Ground Investigation and Geotechnical Properties

2.6.1 Introduction

Sub-surface investigations commissioned by TWC were undertaken recently at all three sites of the study area. The ground investigations included cable percussion and rotary cored and open hole boreholes, detailed logging (of most boreholes), the installation of borehole instrumentation and laboratory testing.

Jackfield was divided into two areas, A and B. Area A encompasses much of Salthouse Road and the fields to the southwest; Area B centres around the Jackfield Tile Museum. Fieldwork was undertaken in Areas A and B during the Spring of 2002. The Factual Reports prepared by Ground Investigation and Piling Ltd for Areas A (Report No AJM/ajj/10215) and B (AJM/taj/10215) were finalised on the 29 April 2003.

The fieldwork for Lloyds Head was undertaken during the winter of 2002 and the Factual Report (AJM/taj/11648) was also finalised on the 29 April 2003.

The fieldwork at Lloyds Coppice was undertaken between January and March 2003. The Factual Report is yet to be completed, although draft borehole logs have been provided.

The prefixes for many of the boreholes are not consistent throughout each document, that is the factual report logs, drawings and borehole instrumentation data. Table 2.3 attempts to clarify the nomenclature used within this study for each borehole within each of the three sites.

TABLE 2.3 BOREHOLE NOMENCLATURE

Site	Prefix to Number	Method of Boring	Notes
Jackfield	RC x, R x	Rotary cored boreholes RC and R are interchangeable with the number of the borehole	Borehole logs, figures and groundwater data are prefixed RC Inclinometer plots are prefixed 'R' only
	BH x, CP x, 00x	Cable percussion boreholes	BH, CP and 00 numbers are interchangeable with these boreholes. Borehole logs and groundwater data are prefixed using BH Inclinometer plots are prefixed using 'CP and 00'
Lloyds Coppice	RO x	Rotary open holed boreholes	The number of the boreholes is interchangeable with all prefixes. Where the borehole is suffixed by 'R & CP' (see Figure 2.1) a rotary borehole has been sunk adjacent to the cable percussion borehole. An RO borehole has been sunk for instrumentation adjacent to a cored or cable percussion borehole following possible borehole collapse or for instrumentation purposes only. Inclinometer plots are prefixed 00.
	RC x	Rotary cored boreholes	
	BH x 'R'	Rotary bored boreholes either open holed or cored	
	BH x, 00	Cable percussion boreholes	
	BH x R & CP	Cable percussion continued with rotary boring	
Lloyds Head	RO x	Rotary open holed boreholes	The number of the RO and RC boreholes is interchangeable with all prefixes. BH prefixes overlap CP boreholes with no uniformity in numbering. The borehole logs in the Factual Report refer to CP numbers. Inclinometer plot for RO1 is prefixed RA.
	RC x	Rotary cored boreholes	
	BH x	Cable percussion boreholes	
	CP x	Cable percussion boreholes	

Note
x denotes borehole number
The term 'Figures' applies to those used within this report

2.6.2 Borehole Instrumentation

2.6.2.1 Introduction

The interpretation of borehole instrumentation, both inclinometer and piezometer, installed during the recent ground investigation, including the May 2003 round of readings, have been summarised in Tables 2.4a, b, c & d (note, boreholes without instrumentation have not been included in these Tables).

In addition Tables 2.4a, b, c & d, describe, in brief, the principal horizons (eg made ground, clay and coal seams), along with horizons of worked ground, non intact and poorly recovered core, which are important to understand any ground movement, groundwater preferential flow and the possible levels which may have been mined (and, possibly, not recorded). Mining and the effects of mining on slope instability are discussed in Section 2.8 of this report.

It is understood that for financial constraints that not all the boreholes were cored and logged by a qualified engineering geologist. Some of the boreholes in the Lloyds Coppice site were sunk using rotary coring only with the strata detail described by the drilling foreman. Some of the upper ground information detail will be missing from these boreholes, however a number of these rotary holed boreholes are adjacent to cable percussion boreholes that have been logged in detail in the upper ground zone. Tables 2.4a, b, c & d identify boreholes where driller's descriptions have been used to describe strata by showing '*'.

2.6.2.2 Inclinometer Readings

Base readings of boreholes installed with inclinometers were undertaken during the fieldwork. Inclinometer data has been received during the course of this study as and when monitoring has been undertaken. Spurious readings were observed following the May 2003 set of readings; further sets of readings were taken from June to August 2003 to try and resolve these problems. Not all the problems have been resolved and although many readings confirm trends of previous subsurface movement, some show exaggerated and stepped data. Time constraints have prevented analysis of these anomalies, but the most recent round of monitoring has been included in this analysis, in addition to the readings assessed during the early stages of this study.

It is likely that systematic errors have occurred during the taking of the readings, either through operator error or by the equipment used to take the readings. It is understood that the inclinometer torpedo has had to be changed more than once (due to the loss of the torpedo down particular boreholes). The makeup and peculiarities of each individual torpedo will build in errors to previous readings no matter how well a torpedo is calibrated. These errors can usually be rectified, dependent upon the type of error (ie bias-shift, rotational and depth errors) using a graphing program (eg GTilt) to correct the error visually or to generate a displacement value for calculating a correction. Some of the inclinometer plots also suggest possible incorrect placement of the inclinometer casing or that the borehole itself has not been correctly backfilled with grout (ie the grout has leaked out through non-intact horizons); these readings are unlikely to be rectified by manipulation of the data. It is recommended that a thorough diagnostic assessment of the inclinometer data should be undertaken to address, understand and possibly correct any errors.

The most recent inclinometer plots for each borehole are shown in Appendix B1. Tables 2.4a, b, c & d interpret inclinometer data received to date and for the purposes of this report have identified any displacement within the plots to represent ground movement although it is recognised that systematic errors during the readings or through the equipment recording the data may have caused these spurious readings.

The following describes the ground movement observed from inclinometer plots for Lloyds Head, Jackfield and Lloyds Coppice. The following should be used in conjunction with Tables 2.4 a to d, which identify the depth the inclinometer tubing has been installed to, Appendix B which shows the inclinometer plots for each of the boreholes instrumented with inclinometers and Figure 2.10 which shows borehole locations. The plots in Appendix B identify A+ as the downslope direction with B+ the lateral component of movement at 90^o to the A+ direction in a clockwise sense. A- and B- are the directions 180^o to their respective positive directions.

Lloyds Head

RO 1 (RA): Possible ground movement observed at 2m and 30m bgl. Displacement of up to 15mm downslope with significant lateral component (down bedding dip) to the east. However, movement may be a reading error as it shows displacement from the base of the inclinometer tubing.

Jackfield (Area A)

CP7: Slight appreciable trend of ground movement of ~3mm down slope from base of inclinometer tubing. Probable reading error May 2003 (the incremental plot also suggests reading error).

CP18: Significant ground movement of approximately 110mm can be observed at ~6m bgl within clay horizon. Movement in this zone of ‘softened clay with greasy polished surfaces’ shows a relative downslope movement of the underlying stiff clay. The trend of movement is uniform. The borehole is situated on the flanks of the 1952 slip zone.

R5: Readings suggest ground movement at ~ 5.0m bgl of ~10mm although any shear surface is not distinct. Movement in this zone of ‘gleyed laminae / shear surfaces within a clay’ shows a relative downslope movement of the overlying ground. The trend of movement is not uniform, though overall movement is accelerating downslope. The negative component within the incremental inclinometer plot may represent an over-riding block at the toe of a failed slipped zone.

Possible movement at ~20m bgl may represent subsidence above mined coal horizons, although the incremental plot suggests discrete movement at this depth.

R6: Ground movement of approximately 10mm can be observed at ~4m bgl at the interface between made ground and weathered in situ material. The rate of movement is relatively uniform since the appreciable commencement of movement at this depth in November 2002. The trend of movement is identified as shear and represents the made ground slipping down slope relative to the weathered mudstone. There is also a lateral component to the west, possibly representing surface morphology of the slope rather than following bedding dip to the east.

Readings between 30 and 45m bgl suggest movement with little downslope component but significant lateral component to the west. Readings at this depth commenced in Jun 2002 and have shown an increasing trend since. This may represent subsidence (ie a shortening of the tubing) due to possible worked ground at depth, or an error in the monitoring procedure (eg full depth of survey may have reduced to a blockage at the base or the wrong starting depth).

The incremental plots show no increasing lateral component to represent ground movement to the west and no downslope shear movement at 30 to 45m bgl.

R7: Ground movement of approximately 55mm can be observed at ~7.5m bgl at the interface between made ground and in situ material. The rate of movement is relatively uniform. The trend of movement is identified as shear and represents the made ground slipping down slope relative to the underlying in situ clay. There is also a lateral component to the west, possibly representing surface morphology of the slope rather than the bedding dip to the east.

R8: No significant trend in ground movement.

<u>Jackfield (Area B)</u>

CP 11: No apparent trend in ground movement. Jan 03 reading likely to be taken with inclinometer torpedo 180^{o} from true.

CP 14: Probable shear surface developing at ~6.0m bgl of ~20mm downslope movement where made ground is moving relative to the underlying in situ material.

CP 20: Small ground movement, less than 1.25mm, at 6.0m bgl, possibly showing the backwards tilt of a discrete block failure.

CP 21: No significant trend of ground movement, probable spurious reading in May 2003.

R4: No significant trend of ground movement over course of monitoring. Possible shortening of the inclinometer tube either by the effects of subsidence (worked horizons noted throughout the borehole logs) or by operator error.

Lloyds Coppice

RC 3: No significant trend of ground movement.

RO 4: No significant trend of ground movement.

RO 6: No significant trend of ground movement. Although possible movement observed at ~5m bgl. Movement may represent ground displacement at the made ground/ clay and coal measure interface. Further monitoring is required to identify trend of movement.

RO 7: Trend of ground movement observed in upper 6m, possibly identifying relative backwards tilt of slipped block in zone of poor recovery/ non-intact core.

RC 8: No significant trend of ground movement. The plots suggest errors have occurred during the course of the readings.

RC 9: No significant trend of ground movement. The plots suggest errors have occurred during the course of the readings.

RO 10: No significant trend of ground movement. The plots suggest errors have occurred during the course of the readings.

RO 11: Significant shear surface observed at ~3.5m bgl of ~35mm displacement. The movement represents the relative downslope displacement of a soft weathered clay overlying coal measures. Significant lateral component of ~15mm to the east, possibly along dip of bedding.

RC 12: Possible shear surface developing at ~5.0m bgl of ~5mm displacement. The movement represents the relative downslope displacement of a soft weathered clay overlying a stiffer clay. No significant lateral component.

RC 14: No significant trend of movement observed prior to readings ceasing. The reason for the ceasing of readings is not known.

RC 15: No significant trend of ground movement.

RC 16: Discrete shear surfaces at 6m and 11m bgl. Displacement is significant totalling 120mm. The upper shear surface lies within the weathered clay and, at the clay and river gravel interface, respectively. There is also a significant lateral component to the east of ~70mm. This borehole is discussed in more detail in Section 3.4.

RC 17: No significant trend of ground movement, although plots do show readings that suggest ground movement could be developing between 20m and 40m bgl.

BH 16c: Discrete shear surfaces at 4m and 13m bgl. Displacement is significant totalling 45mm. The upper shear surface lies within made ground and, at the stiff clay and coal measure interface, respectively. There is little lateral component to the west. This borehole is discussed in more detail in Section 3.4.

RC 18: Possible trend of ground movement at ~20m bgl at the clay/ coal measures interface. Displacement is ~5mm downslope with no appreciable lateral component.

RC 19: No significant trend of ground movement, although plots do show readings that suggest ground movement, downslope, could be developing at 32m and 39m bgl. Both depths show lateral component to the east.

RC 20: Possible ground movement showing uniform trend of movement, which may either be a result of possible subsidence or reading error.

2.6.2.3 Groundwater Data

The most recent groundwater data for piezometer installed boreholes are shown in Appendix B2 and groundwater levels for each borehole are described in Tables 2.4a, b, c and d. Groundwater strikes observed during the ground investigation and current groundwater levels are shown on the cross sections in Figures 2.13a and 2.13b.

Groundwater data for Jackfield identifies some seasonality in the level of the groundwater showing relatively dry and wet periods of the year. More significantly there is a marked difference in groundwater levels for those boreholes positioned in the Jackfield slip area. Boreholes BH 6 and BH 9 show a difference of over 2m in groundwater level between winter and summer periods, with groundwater levels reaching a peak of ~5m bgl in BH 6. Most of the piezometer boreholes are positioned along Salthouse Road.

In the area of Jackfield Tile Museum, Borehole RC 2 shows the groundwater level to vary between ~26.0m bgl during the dry season and rise ~0.5m to 25.5m bgl during the wetter part of the year. This borehole is situated above a mined level and may be affected by the local effects of preferential groundwater flow through the abandoned mine workings. RC 3 which is situated mid slope between Salthouse Road and the river shows a water level varying between 2.7m and 1.7m bgl, dependent upon the season.

The Salthouses area shows little variation in water level about (+/- 0.5m) for BH’s 17 & RC 10. BH 9 shows some seasonality with relatively high groundwater levels during the winter and spring months. RC9 shows almost uniform groundwater levels at shallow and deep level piezometers of approximately 5.5 m bgl.

With the exception of R5, all piezometers being monitored in the Lloyds Coppice site show little variation in groundwater level throughout the monitoring period (April to August 03).

Borehole R 16A (both deep and shallow) show groundwater level almost at ground surface. This borehole is situated within the Lloyds Cottage area of current ground movement.

Borehole R11c and along with BH 12a (deep), which has been installed relatively adjacent, show groundwater levels at ~17.0m bgl (BH 12a (shallow) only shows a trace of water). This is likely to reflect the dip of the bedding that would probably drain water into this slope.

Borehole R11c is situated above the area of Red Clay mining from Blists Hill, which may also have a secondary effect on the water in this area, if the mine is acting as a 'drain' for deep groundwater. This type of groundwater flow may also be occurring beneath the Old School area, where groundwater is relatively deeper (R18a – groundwater level: ~11.8m bgl) than the remainder of boreholes being monitored which show groundwater between 5.0 and 7.5m bgl (CP10, R15a, CP 15, CP19, CP 21 and R20a).

Groundwater monitoring at Lloyds Head show little variation in water level over the three months of monitoring between January and March 2003. Groundwater levels are relatively uniform at 6.3m bgl (+/- 0.1m) for RC 2 and for RO 2 water level is at 7.5m bgl (+/- 0.1m). RC 2 shows water level within the made ground horizons and RO2 within a clay layer beneath the made ground.

2.6.3 Geotechnical Properties

This section of the report identifies the observed soil parameters determined from the recent laboratory testing and compares these results with previous testing undertaken in the study area. Analysis concentrates on the laboratory shear tests which provides effective stress shear strength parameters c' and tan ϕ', parameters necessary to undertake slope stability analysis of a natural drained slope.

Geotechnical testing was carried out in accordance with BS 1377 1990 'Methods of tests for soils for Civil Engineering Purposes'. All testing was carried out in an UKAS Accredited laboratory, apart from organic content and hand vane tests. In addition to these two tests, tests included moisture content, Atterburg limits and particle size distributions.

Effective stress testing, consolidated undrained triaxials and ring shear tests, were undertaken by DTS Raeburn of Birmingham and Structural Soils Ltd of Bristol.

The results of the consolidated undrained triaxial and ring shear tests are shown in Table 2.5. Figure 2.11 shows the plot for shear stress against mean effective stress for the Jackfield and Lloyds Head laboratory tests (NB Lloyds Coppice data yet to be provided) to obtain the average shear strength parameters. With regard to Jackfield it has been established that the zone of the slip surface is approximately 5m deep, therefore, the tests have been divided into Upper and Lower Clays, that is clay above and below the shear zone.

The value for both the upper and lower clays is very similar, giving an approximately ϕ' value of 26.5^o, with a c' of zero for the consolidated undrained triaxial tests, suggesting that both materials are similar, as would be expected for weathered clays outside the area of shear. The ring shear tests give residual values ranging from 9^o to 19^o. It is likely that the range variation demonstrates the effect of increased normal stress to the testing of the samples.

The results for the consolidated undrained triaxials should be viewed with some caution as the correction factor applied to the final measurements is quite considerable; this was to enable rapid testing (ie 1 day).

TABLE 2.4A LLOYDS HEAD: GROUND INVESTIGATION RESULTS

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
RO 1 (RA) Inclinometer installed to 30m depth. EoB 37.3m	*GL to 6.6m Made Ground; 16.7 to 18.6m Weak broken coal; 31.0 to 31.4 rotten egg coal. Coal at 34.8, 37.2, 37.8, 44.5 & 47.2m	Depth 9, 14, 18 & 28m buckling observed. Overall possible backward tilt of ground. However, Aug 03 reading shows possible shear zones at 2 and 30m	Water strike at 17.0m bgl in weak broken coal	Water evident within possible worked coal horizon at 17.0m. Coal at 31m(?). Soft Clay around 9m, very weak mudstone at 14.7, worked coal (?) around 18m and weak mudstone at 28m may indicate the buckling appearance observed on the inclinometer plots. Aug 03 reading shows movement down bedding dip (if combining lateral and downslope displacement)
RO 2 Piezometer installed to 15.3m depth. EoB 66.0m	*GL to 5.7m Made Ground Coal at 19.2, 28.2, 42.3, 47.6, 52.6m. Worked ground (coal and timber fragments observed) between 21.6 and 22.5m	-	Seepage at 14, 18 and standing at 7.5m o/c of drilling. Monitoring up to Mar 03 identifies water level at ~7.5m bgl	Insufficient detail of borehole log to suggest seepage at 14 and 18m.
RC2 Piezometer installed to 17.0m depth. EoB 37.5m	GL to 10.6m Made Ground. Coal at 15.55, 18.1, 18.9, 24.6, 29.8, 32.45, 37.1m. Lost core at 23.7m beneath possible ironstone horizon	-	Ground damp at 9.0m; water standing at 8.0m following day, 7.4m end of shift. Monitoring up to Mar 03 identifies water level at ~6.3+/- 0.1 mbgl	Groundwater level within Made Ground. Standpipe piezometer installed at clay band within mudstone and underlying coal horizon – possible shear surface at 14.45m
RC3 EoB 26.8m	GL to 5.3m Made Ground. Coal at 17.75, 18.35, 26.05. No core recovery 19.1 to 20.1m, possible worked coal horizon	-	-	-

TABLE 2.4B JACKFIELD, AREA A: GROUND INVESTIGATION RESULTS

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
R5 72.7 Inclinometer installed to 24.0m EoB 58.8m	No made ground, only grass and topsoil in top 0.5m ~5m soft grey gleyed laminae/ shear surfaces within clay horizon 6.7 to 7.3m No core recovery within clay horizon 9.3 to 9.7m Core non intact; gravels retrieved 12.5 to 12.6m non intact core within siltstone 14.6, 32.0, (45.15?)m Made Ground 19.35, 20.35, 25.45, 26.82 Core non intact in coal horizon Coal also evident at 54.08 & 56.7	Slight buckling at 2m and 19m; significant buckling at 5m (Possible spurious readings on the 8 Jul & 28 Nov 02)	'Possible' water strike at 11.0 to 12.0m	Insufficient detail on borehole logs (drillers description) to determine buckling event at 2.0m. Firms to stiff clay with gleyed laminae/ shear surfaces overlying very stiff clay at 4.6m. Movement within 1952 area of slippage. Non intact core within coal horizon at 19.35m, possibly worked horizon.
R6 48.7 Inclinometer installed to 59.9m EoB 59.9m	GL to 4.8m Made Ground 4.8 to EoB Coal measures Coal at 11.25, 11.6, 14.45, 39.0, 47.75, 50.5, 53.3, 53.9, 56.1, 57.0m Worked Ground at 14.9, (21.4?), (27.1?)	Last two readings identify downslope movement in top 4m showing ~8mm displacement. Buckling evident at 15, 28, 31, 35 & 44m Significant lateral component to movement. May 2003 data shows increasing trend of recorded ground movement	Water strike at 5.8m	Trend of movement observed at level between made ground and weathered mudstone. Movement/ contraction in made ground horizon at 15m; possible worked ground at ~27m; clay partings, brown discolouration at 31.4; Red Clay horizons at 33.9m within mudstone horizon – possible subsidence. Core fractured and non intact at 44.4m. *Note Borehole log states inclinometer installed to 59.9m, but plot only shows readings down to ~50.0m*
CP 6 48.7 Piezometer installed to 7.3m E0B 7.6m	GL to 4.8m Made Ground 4.8m to EoB Sandstone and Mudstone	-	Water strike at 5.1. Monitoring shows seasonality with gwl at ~4.5m during the summer and ~2.6m bgl during the winter	Groundwater remains within made ground all year

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
R7 41.7 Inclinometer installed to 37.4m EoB 37.4	GL to 7.0m Made Ground 10.8m core non intact recovered as clay within mudstone horizon 15.8 to 16.2m strata broken, wet and very weak Coal at 16.95, 17.3, 19.48m Core non intact/ poor recovery at 17.75, 20.6, 21.02, 23.6, 33.85, 34.45, 37.3m Worked ground at 35.4m – purplish clay	At ~7.5m depth trend of ground movement observed shows ~50mm displacement at depth and ground level, movement generally downslope with slight lateral component. Kinks in plot at 22 and 32m.	Water strike at 2.75, 20.6 & 28.0m; standing at 2.0m o/c of drilling	Ground movement likely to be the made ground 'slipping' on the underlying stiff clay. Slight kinks in plot correspond to depths showing fractured core and weaker bands in strong sandstones overlying weak mudstones. Kinks at depth correspond to very weak mudstone and non intact core at 23.6 and 33.55m
CP 7 41.9 Inclinometer installed to 9.0m EoB 9.4m	GL to 7.6m Made Ground 7.8m to EoB Coal Measures	At 7.5m depth trend of ground movement observed, shows ~3mm displacement at ground level; movement generally downslope with lateral component. 19 May 03 reading possibly spurious.	Groundwater strike at 4.5m within made ground	Ground movement likely to be the made ground clay 'slipping' upon the in situ mudstone. Note a transition between the made ground and mudstone of stiff clay. Further readings required to confirm trend of movement.
R8 75.1 Inclinometer installed at 43.0m EoB 58.3m	GL to 3.8m Possible clay fill 3.8m to EoB Coal measures Coal at 5.8, 23.15, 28.3, 29.4m Possible Worked Ground at 19.8, 23.4 Core non intact/ poor recovery at 12.6, 15.9, 17.1, 17.4, 21.7, 23.4, 29.4, 37.1, 38.2, 38.6, 49.4, 58.0m	Bucklings at 2m, 16m, 19, 22, 29, 40m. May 2003 data mimics Jan 03 results which is a marked contract to the 4 previous results	In flow of water at 5.9m,	Core non intact at ~16m within siltstone horizon; possible worked ground at ~19m; core non intact around 22m; core non intact of highly weathered mudstone above coal horizon; friable clay bound fragments at 40.1m Jan & May 2003 requires further monitoring to confirm trend
R9 48.1 Piezometer installed to 45.9m and 30m EoB 61.0	GL to 16.0m Made Ground 16.0 to 28.5m Generally firm clay 28.5m to EoB Coal Measures coal at 55.5, 58.7 Core non intact/ poor recovery: 22 to 26.5m, 44.0, 45.7, 48.8 Worked ground: 28.9, 31.6, 31.65, 48.1, 50.9	-	Groundwater strike at 8.0m, second strike at 20.0m, third strike at 29.0m, fourth strike at 43 to 49.9m; standing at 7.0m final day of drilling	Shallow: readings vary between 5.0mbgl (winter) and 5.75mbgl (summer). Deep: generally uniform around 5.2m bgl. 20m gravelly sand above poor recovery horizons; worked ground at ~29m; between 44 and ~49m poor recovery and worked horizons

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
CP 9 48.1 Piezometer installed at 12.5m EoB 17.2m	GL to 15.45 Made Ground. 15.45 to EoB Stiff clay	-	Groundwater strike at 5.2m rose to 2.4m after 20 mins; standing at 2.7m	Fluctuations in groundwater level throughout summer between 4.8 and 2.9m bgl. GWL's steady during the winter of ~2.65m bgl, all within made ground
R10 51.4 Piezometer installed at 12.0m EoB 44.9m	GL to 3.0 Made Ground 3.0 to 14.5 generally stiff clay and gravel 13 to EoB Coal measures Coal at 25.52, 25.88, 31.01, 31.58 Core fractured/ non intact: 35.26, 44.07, 45.57 Worked ground: 29.36, 30.86, 32.36, 33.76,	-	Groundwater seepages at 2.6 & 4.0m; groundwater strike at 11.5 (artesian 1.5m agl)	Gravel horizon at 13.0m below clay capping bed. Monitoring shows general trend of groundwater at 3.0m bgl during the summer and ~2.5mbgl during the winter.
CP 17 52.3 Piezometer installed to 10.7m EoB 13.0m	GL to 1.0m Made Ground 1.0 to 11.8m predominantly clay with gravel horizons 11.8 to EoB Clay/ Mudstone	-	Groundwater strike at 9.2, rose to 2.6m in 20 mins; standing at 2.3m	Disregarding initial readings, groundwater levels steady around 3.4m bgl during summer and rising to ~2.5m bgl throughout the winter
CP 18 Inclinometer installed to 12.0m EoB 12.18m	GL to 0.5m Made Ground 0.5 to 11.0m Clay 11.0m to EoB Mudstone	At ~6.0m downslope trend of movement of some 60mm, with lateral component. Accelerated movement May 2003 to ~110mm.	No groundwater encountered during drilling	At 5.75m horizons of softened grey clay overlaying very stiff clay. Greasy polished surfaces noted throughout horizon. On flanks of 1952 slip.

TABLE 2.4C JACKFIELD TILE MUSEUM (AREA B): GROUND INVESTIGATION RESULTS

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
CP 11 50.6 Inclinometer installed to 7.6m EoB 7.8m	GL to 0.8m Made Ground 0.8 to 4.6m Firm to stiff clay 4.6 to EoB Coal measures	No apparent trend in movement, however, last reading shows small downslope displacement in top 0.5m. 24 Jan 03 reading likely to be spurious	Water strikes at 2.4m and 3.6m, both within clay horizon.	Further readings required to determine trend of any movement.
CP 14 48.7 Inclinometer installed to 10.0m EoB 10.1m	GL to 6.0m Made Ground 6.0 to EoB Coal measures	Shear surface at 6.0m, downslope movement of 5mm at surface. Accelerated movement May 2003 to some 20mm	Water strike at 3.8m, 2nd water strike at 7.1m.	Ground movement likely to be the made ground 'slipping' upon the in situ mudstone. 2nd water strike rose to above made ground level (ie slipped material)
CP 20 51.0 Inclinometer installed to 6.5m EoB 6.9	GL to 2.5m Made Ground 2.5 to 5.5m Soft becoming stiff with depth Clay 5.5m to EoB Coal measures	Very small ground displacement <1.25mm at 6m depth showing 'upslope' movement. May 2003 movement shows ~2.5mm downslope displacement at 6.5m depth.	Water strike at 2.55m	Movement is small (<1.25mm) and could be a failed block rotating backwards? May 2003 requires further monitoring to confirm trend
CP 21 48.2 Inclinometer installed to 8.6m EoB 8.6m	GL to 3.6m Made Ground 3.6 to 7.9 Clay with sand & gravel underlying at 4.8m 7.9 to EoB Coal measures	Very small ground displacement <1.25mm at 2.5m prior to last reading, which shows backwards tilting from base of borehole. May 2003 shows 'upslope' movement	Groundwater strike at 5.1m within sand & gravel rising to above clay layer	Movement is small and could be the displacement of ground along a ceramic layer at 2.4m and the 'superficial' ground above the coal measures at 8m. May 2003 requires further monitoring to confirm trend
RC 2 67.6 Piezometer installed to 43.0m EoB 72.0	GL to 2.3m topsoil and clay; 2.3m to EoB Coal measures Coal at 7.0, 31.4, 33.9, 59.3m Worked ground, core non intact/ fractured at 6.1, 7.0, 8.2, 10.95, 20.3, 31.4, 33.9, 34.5, 40.6 – 42.5 (Goaf?), 45.75 – 47.0 (Goaf?), 48.3, 55.7m	-	Groundwater strike at 3.5m. water standing at 6.7m, 13m & 28.2m during drilling. Monitoring shows steady water level at ~25.5m depth	Water standing at 6.7m due to permeable horizon in coal fragment horizon; 13m within ironstained siltstone suggesting history of water flow. Water draining through sandstone horizon at ~28m depth. Artesian water pressures showing in piezometer.

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
RC 3 45.6 Piezometer installed to 11.4m EoB 40m	GL to 3.5m Made Ground; 3.5 to 6.0m Soft clay 6.0 to EoB Coal measures Coal at 14.2, 14.45, 15.3, 16.3m Worked ground/core non intact at 12.0, 14.2, 14.45, 15.8, 17.1, 17.2, 17.6, 20.8m, 33.0 – 34.0m (void), 34.0-34.8m (mg)	-	Groundwater strike at 11.0m rose to 2.5m in 5 mins; 2nd strike at 33.0m. Monitoring shows seasonality with water level at ~2.3m (summer) and 1.8m (winter) depth	
RC 4 51.7 Inclinometer installed to 32.2m EoB 32.2m	GL to 1.5m Made Ground; 1.5 to 6.0m Soft to stiff clay 6.0 to 7.1 No core recovery 7.1 to EoB Coal measures Coal at 19.6, 20.8, 21.52, 21.75m Worked ground/ core non intact: 8.0, 13.8, 14.35, (17.1), 20.35, 20.9, 23.5, 26.0m	Buckling at 14m, 16- 18m, 23m, 29m. last reading shows possible backwards tilting of block and downslope movement in upper 2m of ~2mm ground displacement. Some spurious readings over course of monitoring	Seepage 3.0, 7.0, 17.1; water standing at 3.5m during drilling.	Water seepage below soft grey clay layer underlain by stiff clay, the void at 7.0m is acting as a conduit for water; possible workings at 17.1m allowing water flow. Buckling at: 14m, core non intact; 16-18m, possible worked ground; 23m, non intact core recovered as fragments at 23.5m; 29m, striated & polished 45 deg discontinuity

TABLE 2.4D LLOYDS COPPICE: GROUND INVESTIGATION RESULTS

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
RO 1 (RO 1A drilled adjacent) 133.07 Inclinometer installed to 25m in RO 1A – EoB 25m 100m	*GL to 11.4m Made Ground 11.4 to EoB Coal measures Coal at 74.3, 80.4m	No inclinometer plots received	Groundwater strike at 41.0m.	Water strike at approximately siltsone horizon
RC 3 147.94 Inclinometer installed to 35m 108.5m	GL to 4.2m Made Ground 4.2m to EoB Coal measures Coal at 32.9, 36.1, 56, 63.9, 64.2, 65.2, 95.6m Non intact core/ fractured: 13.5 to 16.8m, 21.1, 26.6, 32.9, 44.35 to 44.9, 47.8 to 48.4, 53.3, 64.2, 655.2, 67.9, 68.1, 72.5, 73.2, 77.5, 86.9, 95.6, 97.35, 99.5, 104.1m 106.3 to 107.7 Conglomerate and sandstone	No significant trend of ground movement	No groundwater observed due to mist flush	No recorded horizons of worked ground, although evidence of non intact core within coal and red clay horizons and significant weathering at depth
RO 4 140.88 Inclinometer installed to 32.0m 51.0m	GL to 9.2m Clay (* from 49.6m) 9.2m to EoB Coal measures Coal at: 48.9m	Slight kink at 22m depth, showing possible backwards tilt, displacement ~1mm. Jul 03 reading shows possible development of shear zone at 6m.	Slight seepages noted – no depths given	Further readings required to confirm any trend of ground movement
RO 5 112.36 Piezometer installed to 36m 121.0m	*GL to 0.3m fill 0.3m to EoB Coal measures Coal at 52.1, 81.2, 108.4, 109.9m	-	Possible seepage at 40.0m	Awaiting water levels. Seepage within mudstone/sandstone
RO 6 81.57 Inclinometer installed to 34.0m 55.0m	GL to 1.10m Made Ground 1.10 to 4.0 Clay 4.0 to EoB Coal measures Coal at 21.35, 29.38, 40.35, 42.6, 44.35, 51.1, 53.95m Fractured/ non intact: 4.0, 6.9, 10.36, 13.0, 20.5, 21.65 to 23.35m, 38.35, 39.0, 47.0,	Ground movement observed at 32m depth, shows downslope 'tilting' of ground above (ie not sheared) of 3mm displacement at surface level Jun & Jul 03 plots show trend of backwards tilt at 32m depth and buckling in upper 5m.	Seepage at 7.6m and 41.6m	Movement observed near very weak completely weathered mudstone. Both seepages at base of sandstone horizons

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
RO 7 106.48 Inclinometer installed to 50m 83.0m	GL to 4.5m Peaty to firm to stiff clay (*from 50.5m) 4.5 to EoB Coal measures Coal at 11.5, 42.58, 43.28, 65.2, 70-72.0, 72.4-78, 79-80.0m – rotten egg odour Poor recovery/ non intact coal: 5.0, 6.7, 11.5, 14.2, 16.5, 18.25, 24.4, 25.15, 29.6, 30.2, 35.75 to 36.25m (nodules), 37.0, 38.9, 42.5m Worked ground: 42.58 to 43.28m	Movement recorded at 5m, 25m, 30m and 49m.	Groundwater noted at 38m	Groundwater near sandstone/ gravel horizons. At 5m poor recovery in mudstone; 25m core recovered as nodules in siltstone; 30m, very weak siltstone and non intact; 49m, approximate interface between sandstone and red marl* Further readings required to confirm any trend of ground movement
RC 8 104.67 Inclinometer installed to 50m 88.0m	GL to 6.0m firm to stiff clay (* from 42.6m) 6.0 to EoB coal measures Coal at 9.75, 13.0, 26.9, 32.43, 33.15, 38.88, 39.74m Core non intact/ fractured: 16.0, 28.3, 32.43, 39.83,	No significant ground movement up to Jun 2003, which shows 'stepping' in the plot at 4.0, 12.0, 16.0, and 23.0m. The Jul 03 plot does not show the Jun 03 steps, but does show possible upslope movement at 14.0m and ~42.0m. Aug 03 reading shows downslope movement in contrast to previous readings	Slight seepage at 71.66 to 88.0m	Further readings required to confirm any trend of ground movement
RC 9 97.50 Inclinometer installed to 30m 66.0m	GL to 3.75m peaty to stiff clay (* from 31.4m) 3.75 to EoB Coal measures No coal recorded except thin coal seams 11.0 to 16.3m within sandstone horizon Core non intact/ fractured: 8.8, 11.7 to 13.7 to 16.05m, 24.35, ~30.5m disturbed strata,	Ground movement observed at ~3.75m showing displacement of ~2mm at surface level. Jun & Jul 03 readings show no similarity	Water strike at 40m depth.	Only one reading to date. Possible movement of clay over in situ rock at 3.75m depth. Water strike within mudstone horizon. The Jun & Jul 2003 requires further monitoring to confirm trend
BH 10 66.14 Piezometer installed to 14.5m 14.7	GL to 6.0m Made Ground 6.0 to 14.0m clay 14.0m to EoB Coal measures	-	No groundwater encountered during drilling	Awaiting water levels

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
RO 10 (Open holed) 66.14 Inclinometer installed to 50m 60m	*GL to 9.3m Made Ground 9.3 to 12.6m Clay 12.6 to EoB Coal measures Coal at 25, 27.2, 29, 29.4, 42.7, 53.5, 57.5, 58.2m	Discrepancies in last two readings 10 & 21 Jul 03) cannot confirm backwards tilting of block or potential shear zone at 12m	Groundwater strike within 'pit waste', 2nd strike at 24.5m and 3rd strike at 27.0m.	2nd strike observed at 'soft sticky black mudstone' above coal seam-possible worked ground? 3rd strike at coal horizon-possible worked ground? Further readings required to confirm any trend of ground movement
RO 11 (Open holed) 77.42 Inclinometer installed to 50m 100m	*GL to 3.5m Soft weathered clay 3.5m to EoB Coal measures Coal at 33.6 (rotten egg odour), 34.4, 59.8, 69.6, 72.5, 75, 81.0m Worked ground/ fractured rock: 16.3, (46.5m gits/gravel – goaf?), 81.0, 85.4 (timber fragments)	Possible shear surface at 3.5m, showing some 20mm downslope surface displacement (shear surface displacement some 15mm). Remainder of surface movement resulting from possible 'wander'. Aug 03 reading shows a trend of ground movement at this depth, which has reduced in downslope displacement	Groundwater strike at 15.6m	Only one inclinometer reading to date, but 'shear surface' observed. Possible shear surface at clay / coal measure interface – 3.5m. Groundwater above marl horizon within siltstone bed. Further readings required to confirm any trend of ground movement
RO 11C Positioned 1m from RO 11 Piezometer installed to 17.5m	See RO 11	-	-	Awaiting water levels.
RC 12 72.54 Inclinometer installed to 42m 63.0m	GL to 3.0m Made Ground (* from 41.0m) 3.0 to 5.9m Soft to stiff clay 5.9m to EoB Coal Measures Coal at 33.85, 34.07, 35.45, 36.05, 36.15, 58.2, 62.0 Worked ground/ factured/ core non intact: 4.45, 9.0, 9.95, 13.0, 16.2, 20.0, 31.9, 33.85, 35.45, 39.0m	Trend of movement at 5m bgl and a slight kink (~2mm) at 5m and 14m, confirmed by Aug 03 reading	Water strike at 9.6m	Possible slip surface at 5m, at soft / stiff clay interface; 14m, very weak mudstone/ sandstone interface.
RC 12A Positioned 3m from RC 12 Two piezometers installed at 27m & 9.0m 27.0m	See RC 12 Note Coal at 5.6m	-	-	Awaiting water levels.

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
RC 14 66.46 Inclinometer installed to 38m 60.0m	GL to 2.5m Fill (* From 41.1m) 2.5 to 4.0m Clay 4.0 to EoB Coal measures Coal at 6.0, 20.9, 24.9, 26.9, 32.6, 33.3, 33.35, 52.5m Worked ground/ factured/ core non intact: 6.0, 6.15, 9.0, 12.0 to 15.0m (poor/ no core recovery), 20.9, 24.9, 26.9, 32.6, 33.7, 38.5, 41.1m	Slight kink at ~28.0m and at 2.0m depth, both showing ~2mm displacements Jun 03 reading shows confirmation of previous readings, the Jul 03 data is spurious	No groundwater encountered	Unable to read inclinometer borehole – reason not known. At 2m bgl, fill moving downslope upon clay; very weak mudstone/ sandstone interface
BH 15 46.92 Piezometer installed to ~8.0m 10.09	GL to 1.45 Made Ground 1.45 to 9.4m Firm to stiff clay 9.4m to EoB Coal measures	-	Water strike at 0.3m, 2nd strike at 6.6m	Awaiting water levels. Gravel becoming dominant in clay at 6.45m
RO 15 (Open holed) 46.92 Inclinometer installed to 33m 60.0m	*GL to 4.0m Fill 4.0 to 7.5m Clay 7.5 to EoB Coal measures Coal at 9.5, 29, 36.5, 42.5 Void at 17.8m	No significant movement, although buckling observed at 6, 17, 19, 24 and 30m.	Groundwater strike at 9.5m	Further readings required to confirm any trend of ground movement Groundwater in gravel horizon
RO 15A (Open holed) Assumed adjacent to RO 15 Piezometer installed to 18m 18.0m	See RO 15	-	No groundwater details recorded	Awaiting water levels
BH 16 (016c) 48.24 Inclinometer installed to 14.2m 14.24	GL to 5.3m Made Ground 5.3 to 13.8m Firm becoming stiff clay 13.8 to EoB Coal measures	Two shear surfaces at 4m and 13m depth, showing total surface displacement ~30mm downslope, no significant lateral component The Jun & Jul 03 results confirm previous movement	No groundwater encountered	Upper zone of slippage within made ground (from 3.5m gravel and cobble size slag). From 11.25m polished shear surfaces(?) immediately above in situ sandstone – ground slipping on coal measures – sandstone providing high pore water pressures.
RC 16 44.13 (Open holed from GL to 14.0m, cored from 14.0 to 34.0m, and open holed from 34.0m to 45m) Inclinometer installed to 40m 45.0m	GL to 4.5m Made Ground 4.5 to 11.0m Clay 11.0 to 12.0m River Gravel 12.0 to EoB Coal measures Coal at 12.5, 18.0, 20.05, 21.0, 26.55, 31.75,m Core fractured/ non intact: 16.5m (strata disturbed), 17.4, 18.0, 20.65, 26.7, 27.5, 27.7 to 28.2 no core recovery), 28.2, 28.5 to 29.8m (no core recovery), 31.75,	Two shear surfaces observed, showing significant incremental downslope movement over three readings, at 6m and 11m depth. Ground displacement is observed, at ground level, to be ~70mm. The 11m depth shear surface shows ~40mm ground displacement and the 6m shear surface some 30mm.	Groundwater shows damp ground at 6m depth and 'very wet' at 11.0m	Ground movement is observed at the interface between the yellow brown and grey clay; and, the clay/ river gravel interface. High pore water pressures from the river gravel may also be acting upon the overlying clay as water is

Borehole **Level mAOD** **Instrumentation** **End of Borehole**	**Principal Horizons**	**Ground** **Movement Recorded**	**Groundwater**	**Interpretation**
	Worked ground: 20.05, 20.48,	The Jun & Jul 03 results show accelerated movement > 80mm at surface level		observed at the top of the gravel horizon.
RO 16A (Open holed to 13.0m) 44.23 Piezometers installed to 12m & 7m 13.0m	See RC 16	-	No groundwater details recorded	Awaiting water levels
BH 17 55.35 Piezometer installed to 12m depth 19.4	GL to 12.3 Made Ground 12.3 to EoB Stiff clay	-	Groundwater strike at 11.5m	Awaiting water levels. Water strike within made ground
RC 17 (Open holed GL to 12.0m, cored from 12.0m to 45.0m and open holed from 45.0 to 57.0m) 55.28 Inclinometer installed to 41.5m 57.0m	GL to 12.85m Made Ground (* From 45.0m) 12.85 ton 25.5m Clay 25.5 to EoB Coal measures Coal at 36.2, 37.1, 41.45, 42.25, 50m Poor recovery/ non intact core: 12.0, 25.6, 30.5, 30.9, 33.0, 34.4 to 35.4m, 36.2, 37.1, 40.2 (possible workings), 40.5 (loss of flush), 41.25, 43.2 to 44.8,	No significant ground movement observed.. The Jun & Jul 03 results show buckling at ~15.0, 20.0, 28.0, and 34.0m; the Jul reading shows exaggerated Jun movement	Groundwater strike at 16.0m	Groundwater at 'soft grey clay (probable shear surface)' horizon within gravelly clay. Further readings required to confirm any trend of ground movement
RC 18 50.21 (Open holed from GL to 6.0m, 12.0 to 14.0, 45.0 to 60.0; cored from 6.0 to 9.0, 14.0 to 45.0m) Inclinometer installed to 42.0m 60.0m	GL to 6.0m Fill 6.0 to 20.25m Clay (possible sandstone boulders 6.0 to 7.15m) 20.25 to EoB coal measures Coal at 23.75, 24.1, 25.25, 53.0 to 56.0m Poor recovery/ fractured core: 7.15, 9.0 to 12.0, 23.73, 24.1, 25.25, 28.1, 28.9, 29.1, 29.4, 39.7,	Early data provided by TWC gave two plots for 0018, showing 1) no significant ground movement and 2) backwards tilting of the upper 7.5m and possible shear surface at ~20.0m. Both plots show depth to 50m where borehole log shows installation to be 42.0m The May & Jul 03 plots reflect 2) above; with the Jul plot showing steps at 20, 25, and 40.0m.	Groundwater strike at 25.3m	Further readings required to confirm any trend of ground movement
RC 18A Open holed to 27.0m, located adjacent to RC 18. Piezometer installed to 27m.	See RC 18	-	Ground damp at 12.0m and wet at 25.0m	Awaiting water levels. RC 18 shows no core recovery above clay at 12.0m. At 25.3m non intact coal in parts.

Borehole Level mAOD Instrumentation End of Borehole	Principal Horizons	Ground Movement Recorded	Groundwater	Interpretation
BH 19 39.50 Piezometer installed 7.0m 8.5m	GL too 3.10 Made Ground 3.1 to 7.6 Clay with gravel at depth 7.6 to EoB Coal measures	-	Groundwater strike at 6.6m	Awaiting water levels. Water strike within gravelly clay
RC 19 39.54 (Open holed from GL to 8.0m, 39.5m to 60.0m, cored from 8.0m to 39.5m Inclinometer installed to 40m 60.0m	GL to 3.5m Made Ground 3.5 to 8.0m Clay with 20cm gravel band at 6.0m 8.0 m to EoB Coal measures Coal at 20.96, 21.14. 25.3, 25.7, 48.0m Poor recovery/ core non intact: 8.0, 8.75, 9.0, 12.0 to 12.50m, 12.75, 15.0 to 19.5 (mostly non intact), 20.5 to 21.5m, 20.96, 21.14, 25.3, 26.5 to 31.8m (mostly non intact), 33	Slight step at 32m and 39.0m, <10mm downslope surface displacement, greater component of lateral displacement observed.	Strata damp at 6.0m (gravel bed), very wet at 11.0m. (sandstone)	Strong sandstone/ very weak mudstone interface at 39.0m. Further readings required to confirm any trend of ground movement
RC 20 39.76 (Open holed from GL to 5.0m, 20.0 to 60.0m, cored from 5.0 to 20.0m) Inclinometer installed to 27.5m 60.0m	GL to 5.0m Clay 5.0 to 5.9 No core recovery 5.9m to EoB Coal measures Coal at 25.5 (soft drilling), 58.5m (wet) Poor recovery/ core non intact: 5.0, 5.9, ~15.0m	Buckling at 5m, 8m, 13m with apparent overall backwards tilt of ground. The Jul 03 data shows an exaggerated trend of the previous movement	Water recorded at 14.5m (in siltstone)	Clay above no core recovery horizon at 5.0m, ~8.0m soft wet clay bound gravel sized mudstone; 13m, at 12.655m 45 deg discontinuity with siltstone nodules in siltstone horizon. Further readings required to confirm any trend of ground movement
RC 20A Open hole to 17.5m, located adjacent to RC 20 Piezometer installed to 17.5m	See RC 20	-		Awaiting water levels
BH 21 LOCATION NOT KNOWN Not Received Piezometer installed to 15m 15.15	GL to 9.95m Made Ground 9.95 to 12.15 Stiff clay 12.15 to 13.35 Sand 13.35 to 14.9 Gravel 14.9 to EoB Coal measures	-	Groundwater strike at 13.5m	Awaiting water levels. Water strike within gravel

* Driller’s description

TABLE 2.5 SUMMARY OF GEOTECHNICAL PROPERTIES FROM RECENT LABORATORY TESTING

Site	Borehole, Depth & Material Tested	Testing Method*	c' kPa	ϕ' °
Jackfield Area A	BH 5, 8.2m, Stiff very silty CLAY	CUT	10	25.6
	BH 9, 15.7m, Stiff very silty CLAY	CUT	14	29.2
	BH 10, 7.5m, Stiff silty sandy CLAY	CUT	13	30.4
	BH 15, 6.0m, Stiff very silty CLAY	CUT	9	31.3
	BH 18, 4.10m, Stiff very silty CLAY	CUT	5	32.8
	BH 6, 4.5m, Made ground: silty CLAY	RS	0	21.5
	BH 6, 5.1m, Stiff very silty CLAY	RS	0	20.0
	BH 7, 7.95m, Very silty CLAY	RS	0	8.5
	BH 9, 5.2m, Firm/stiff sandy silty CLAY	RS	0	17.5
	BH 9, 13.6m, stiff silty sandy CLAY	RS	0	21.0
	BH 10, 6.5m, Very silty CLAY	RS	0	11
	BH 15, 4.0m, Slightly sandy silty CLAY	RS	0	17.0
	BH 15, 8.4m, Stiff/ firm very silty CLAY	RS	0	14.5
	BH 16, 7.4m, Very silty CLAY	RS	0	12.5
	BH 16, 9.65m, Silty sandy CLAY	RS	0	15.0
	BH 17, 8.0m, Slightly sandy silty CLAY	RS	0	14.0
	BH 18, 5.3m, Very silty CLAY	RS	0	10.0
Jackfield Area B	BH 2, 2.1m, Stiff very silty CLAY	CUT	4	30.1
	BH 3, 4.1m, Soft silty sandy CLAY	CUT	8	34.7
	BH 13, 4.0m, Stiff slightly sandy silty CLAY	CUT	9	31.5
	BH 19, 5.3m, Stiff/ firm slightly sandy silty CLAY	CUT	7	25.2
	BH 2, 1.5m, Very sandy silty CLAY	RS	0	20.0
	BH 2, 2.8m, Very silty CLAY	RS	0	13
	BH 3, 3.0m, Slightly sandy very silty CLAY	RS	0	26.0
	BH 12, 2.6m, Very sandy silty CLAY	RS	0	27.5
	BH 14, 5.5m, Silty CLAY	RS	0	21.0
Lloyds Head	BH 2, 8.06, Slightly clayey sandy GRAVEL	CUT	8	29.5
	BH 3, 5.36m, CLAY	CUT	18	24.0
	BH 4, 4.95m, Slightly gravelly CLAY	CUT	7	31.5
	BH 1, 5.0m, silty very gravelly SAND	QSB	6	38.5
	BH 1, 7.0m, silty very sandy GRAVEL	QSB	15	39.5
	BH 1, 12.0, CLAY	PRSB	0(8)	27(12)
	BH2, 4.0m, silty very gravelly SAND	QSB	8	39
	BH 2, 7.0m, gravelly CLAY	PRSB	44(22)	16.5(13)
	BH 3, 4.0m, silty very gravelly SAND	QSB	38	26.5
	BH 4, 3.0m, sandy gravelly CLAY	PRSB	0(0)	38(34)
	BH 1, 11.2m, very clayey GRAVEL	SRS	0	14.5
	BH 4, 6.0m, slightly gravelly CLAY	SRS	0	19

* CUT – Consolidated undrained triaxial test
RS – Ring shear: test for residual strength
QSB – Quick shear box
PRSB – Peak and residual shear box, residual strengths in brackets

SRS – Small ring shear: test for residual strength

2.7 Ground Investigations and Published Geology

The Lloyds Head, Jackfield and Lloyds Coppice slopes show a varying thickness of made ground deposits comprising colliery/ mine and tile waste. The superficial geology, including made ground, is important in understanding ground movement within the Ironbridge Gorge as recorded ground slippage appears to have been shallow within the upper weathered material and overlying made ground.

The majority of the made ground on the mid and lower slopes of the Jackfield and Lloyds Coppice appears to be colliery and/or mine waste, with tile waste predominantly deposited in the Lloyds Head area. It was anticipated that the superficial geology comprising mostly made ground deposits could be divided into colliery/ mine and general industrial/ foundry waste (eg tile). However, the made ground deposits described in the borehole logs contain such similar material within each borehole (eg clinker, ash, coal, tile, ceramics, slag, etc) that this has not been possible.

Figure 2.12 identifies the superficial geology and the made ground composition across the study area. The information has been collated from borehole logs from the recent ground investigation in the study area and inferred between these boreholes where possible.

Within Jackfield Area A there is up to 16.0m thickness of made ground comprising ash, coal, clinker, tile and ceramics in the area of RC 9 (see Figure 2.10). Although the borehole description identifies this as colliery spoil, the inclusion of tile and ceramics deposits suggest that this was also foundry spoil possibly from nearby tile manufacturers. The boreholes up slope within Area A show little or no made ground, with the possible exception of RC 8, which records 'possible fill'. The likely extent of mine waste deposited on this slope is in the area of the Jolly and Wallers' Pits. Elsewhere the made ground ranges in thickness from 0.5m to 7.6m and is randomly spread.

Figure 2.13a shows Sections BB, EE and GG of the Jackfield site; these sections are considered to be representative of the Sections AA to GG on the southern side of the gorge and have also been used in the slope stability analysis (see Section 3.7). Figure 2.13b shows Sections 3 and 4 which are across-gorge sections of Lloyds Coppice and Lloyds Head (Section

3) and Lloyds Coppice and the Jackfield site. The line of these sections can be located in Figure 2.10.

These sections show the geological horizons determined from the recent ground investigation undertaken in 2002 and 2003. In addition, these sections also show the conjectured stratigraphical horizons interpreted by the published data, namely the geological memoir (BGS, 1995).

The cross sections do not show the extent of the 1990 geomorphological mapping undertaken by Halcrow. These cross sections only show the implied superficial geology based on borehole interpretation and the anticipated slope processes. It is considered inappropriate to apply Halcrow's geomorphological unit boundaries to the cross section based on the possible ground movement that may have occurred between the date of the mapping and the present topographical survey.

With regard to the borehole logs for the Lloyds Coppice and Jackfield sites analysis of the logs identifies horizons within the upper weathered clay of the coal measures comprising possible shear surfaces at depths down to 11.5 m. In addition it has also been identified that this upper weathered clay zone is slipping on in situ rock. These recordings within the borehole logs and the data gathered from borehole instrumentation tend to concur with Halcrow's (1990) geomorphological mapping that the slopes are subject to relatively shallow retrogressive rotational ground failures.

The geological memoir identifies marker beds that separate the Lower, Middle and Upper Coal Measures and their relevant formations. For example the New Mine Coal lies at the top of the Lower Coal measures and is overlain by the Pennystone Marine Band of the Middle Coal Measures. The Upper Coal Measures lay uncomformably on the Middle Coal Measures with varying horizons of the Middle Coal Measures being recorded to underlay the Hadley Formation (the lower formation of the Upper Coal Measures) throughout the region.

It has not been possible to identify these marker horizons with any degree of confidence from the borehole logs. Therefore, it has been necessary to identify known mined horizons, such as the Red Clay and the Brick and Tile Clay mined within the Hadley Formation and conject the most suitable horizon to delineate the formations and each Coal Measure.

The varying nature of coal measures makes the task of determining the stratigraphy even more difficult without identifying a known horizon. In some cases, the borehole logs do identify, for example, a 'rotten egg' smell within a coal horizon which can with some degree of certainty represent the Sulphur Coal horizon. Where this is evident in a borehole the horizon has been transposed up or down dip to the relevant section. These 'marker' horizons of known certainty are rare within the borehole logs, although, the recognition of the Hadley Formation, for reasons given above, has enabled the identification of the Middle Coal Measures in the Lloyds Head area (see Figure 2.13b, Section 3)

Section BB lies within the 'faulted block' between the Doughty and Jackfield Faults and mainly comprises geology of the Upper Coal Measures. It can be observed that mining has been undertaken in this section for the Red Clay. Significantly there is little evidence of slope instability from borehole instrumentation given that mining has been undertaken. Although made ground can be observed at the surface of the slope, instability may be negated by mining subsidence shallowing the angle of the slope. Furthermore, the Jackfield Tile Museum which is located downslope of the area mined at depth, and its associated walls maybe acting as a retaining structure.

Sections EE and GG lie between the Doughty and Madeley Faults and both sections have the 'Tuckies'cross fault, running approximately east-west near the base of the slope. Both sections mainly comprise geology of the Upper Coal Measures although strata of the Middle Coal Measures have been conjectured at depth.

Section EE has been chosen as a representative section showing the area of the Jackfield slips of 1952 and 1984. Mining has been observed to have been undertaken for Brick and Tile Clay at depth. Faulting has resulted in a thicker sequence of the Upper Coal Measures being conjectured in this section compared to Section BB. Ground movement within the upper horizons of this section is limited to the top 5m of ground (the Jackfield 1952 slip zone) with little evidence for movement at depth to the base of borehole instrumentation. Surface mapping of the Jackfield slip identifies the area of the slip to terminate towards the west against the line of the Doughty Fault. The significance of the fault cannot be determined without suitable subsurface data identifying the nature of the fault, that is, if the fault is water bearing and providing a conduit for water infiltration down dip of the beds into the slip area. Given that the slip zone comprises mainly weathered clay it is likely that any influence of the fault has been reduced by the deterioration of the upper material by weathering.

Section GG lies to the east of Section EE within the same ‘faulted block’ but outside the Jackfield slip area. There is little evidence for significant ground movement in the area of this section, based on borehole instrumentation and monitoring surveys.

Generally, the dip of the geological beds is shallow to the east-south-east for all three sections with the exception of Sections EE and GG which to the north of the Tuckies Fault has a change in dip of the bedding to approximately south at an angle of 18^{o}.

The relevance of this fault could explain the ground movement experienced east of the Doughty Fault (the Jackfield slip) compared to no ground movement being observed on the Jackfield Tile Museum side of the fault. However, this does not explain the lack of movement along Section GG, although the combined effect of dipping strata and the varied nature of argillaceous (non-water bearing) and arenaceous (water bearing) horizons within the coal measures, which are not significantly apparent from the borehole logs, could result in the different zones of ground movement.

Furthermore, the dip of the strata north of the Tuckies Fault is likely to provide hindrance to structural down slope movement of the Jackfield slope and the attitude of the bedding is such that water is likely to drain from the lower slopes of Lloyds Coppice towards the Tuckies Fault. Without cored data on the material of the fault it is difficult to assess the influence of the Tuckies Fault regarding its water bearing qualities and ground movement within Sections EE and GG. Similarly to the Doughty Fault, weathering is likely to have changed the fabric of the strata and deteriorated the effects of the fault in the shallower zones of the slope.

Sections 3 and 4 show sections where current slippage is occurring and historic failure, respectively. The Lloyds Coppice slope identify exposures of the Middle and Upper Coal Measures at surface level which have been controlled by faulting and valley development.

Section 3 identifies the Middle Coal Measures to outcrop south of the Lloyds Coppice fault, with the Upper Coal Measures exposed to the north. It is likely that the river has preferentially eroded the less competent beds of the Middle Coal Measures and followed the throw of the fault, to the south, as the valley has developed. Although the dip of the strata would inhibit slope movement towards the river, the upper material comprising the slopes between the river and the fault comprises mine spoil and alluvial material of low shear strength.

The location of the fault in Section 3 is nearer to the river than its position in Section 4 and, furthermore, the location of Section 4 comprises the faulted block between the Lloyds Coppice and Tuckies Fault, which has strata dipping at an angle conducive to slope movement (ie downslope towards the river). Section 2.5.4 of this report suggests that the alignment of the river historically followed the direction of the Lloyds Coppice Fault and as the valley developed there was preferential movement of the Lloyds Coppice lower slopes in this area ‘pushing’ the river towards the south on its current alignment. Ground movement was probably greater in this area of the valley due to the beds being ‘slide facilitators’.

The Lloyds Coppice Fault could possibly be influencing ground movement in the lower slopes of Lloyds Coppice by providing a backscarp for slope movement and allowing water to flow through the fault into more permeable horizons within the slipped mass. However, the effects of the fault may be significantly reduced by weathering and the subsequent breakdown of the material fabric towards the shallower zones of the slope.

2.8 Monitoring Pins

2.8.1 Introduction

Surveying has been undertaken of the sites located along Lloyds Road, Salthouse Road and in the area of Lloyds Head, in parts, since 1994 by the Council and preceding authorities, with further sites set up in January 2003 and March 2003. Surveying has involved measuring lateral and vertical displacement by EDM methods. The results of the ground monitoring of the pins are shown in Table 2.6.

The monitoring pins have been grouped (see Table 2.6) into manageable units determined from observation of the monitoring data and are those identified in Section 2.1. These areas also delineate zones of currently active and historically active ground movement. (These units have also been used to divide the lower slopes into areas suitable for undertaking the risk assessment (see Section 3.2)). Figure 2.14 identifies recorded movement since 1994 and the results of the 2003 monitoring.

The movement across the study area has been calculated to be very slow based on Cruden & Varnes (1996) rationalisation of the velocity of landslides, which classifies the probable destructive influence as ‘some permanent structures undamaged’. Cruden & Varnes have rationalised previous scales of landslide velocity in order to achieve their own classification. Whilst the classification of movement is termed “very slow” this must be seen in the context of landslide movements worldwide. However, in the context of disruption to property and infrastructure within the Ironbridge Gorge as a result of landslides these movements are very significant, more so given that movement is likely to be concentrated within the winter months.

TABLE 2.6 SUMMARY TABLE OF GROUND MONITORING PINS

Area	Units	Lateral Displacement	Vertical Displacement (-ve indicates downwards movement)	Rate of Movement Since 1994 & Classification*
Jackfield	Jackfield Tile Museum	Up to 200mm to the NE	Up to -15mm	-
	Salthouse Road – Jackfield slip area	Up to 4.95m to the NNW since 1994 Generally, recent readings show up to 300mm to the NNE	Up to –847mm Up to –32mm	550mm/yr Very Slow
	Salthouses	Up to 18mm to the NNE	Up to –14mm	-
	Tuckies	<10mm to the NNE	Up to –11mm	-
Lloyds Coppice	Lloyds Cottage	Up to 2200mm to the SW since 1994 Recent spurious readings - show upslope movement	-20mm	244mm/yr Very slow
	Old School Area	Up to 1240mm to the west (~ normal to the road alignment) since 1994 Otherwise generally negligible recent movement	Up to –50mm	138mm/yr Very Slow
	The Lloyds House Area	Generally, negligible recent movement; possible spurious reading P023		
Lloyds Head	West of Railway Crossing Cottage	Up to 1900mm to the NNW since 1994	Up to –1016mm	211mm/yr Very Slow
	Lloyds Head	Recent readings show up to 200mm to the NE	Up to –23mm	-

* after Cruden & Varnes (1996)

2.8.2 Survey Results

Recent significant movement is concentrated on Salthouse Road in the area of the Jackfield slip. Downslope movement is directed towards the closest point to the river. The area of greatest movement is where the road has been realigned (Plate 7), which also shows the greater vertical displacement.

The Salthouses unit also shows movement of similar vertical displacement to the Salthouse Road unit outside the area of realigned road.

The Tuckies shows negligible lateral displacement, but around 10mm of vertical downwards movement.

The Jackfield Tile Museum shows riverwards displacement and up to 15mm of vertical downwards displacement.

Two areas along The Lloyds show significant trends of ground movement.

1. The area around Lloyds Cottage since 1994. Recent monitoring shows spurious readings upslope and downwards vertical displacement; it is unlikely that these readings represent a rotated block.

2. At the area of road near the Old School House, where The Lloyds runs down to the banks of the river, horizontal movement of up to 1.2m has been observed almost normal to the alignment of the road and vertical downwards displacements of 0.5m have been recorded since 1994. Vertical displacement is greater at the eastern limit of the recently constructed gabion wall (P020) and is negligible at P019.

Lloyds Head shows show significant lateral and vertical displacements recorded since 1994 in the area between the Railway Crossing Cottage and Black Swan Public House. Movement elsewhere in the Lloyds Head area is riverwards and shows similar displacements to the Jackfield areas (outside of the Salthouse Road re-alignment area).

The monitoring pins have shown that all units within the study area are experiencing some active ground movement (with the exception of the Lloyds House unit). Four units show significant ground movement since 1994: Lloyds Cottage and the Old School House (both on the Lloyds Coppice site), the Jackfield Slip sub-unit and the central area of the Lloyds Head site.

2.9 Mining

2.9.1 Mining within the Study Area

Mining has been undertaken in the study area for coal, ironstone and clay. The plans provided show extensive extraction of minerals within the Jackfield study area from the Lower and Upper Coal Measures. At Lloyds Coppice the only recorded mining is that of Red Clay from the Hadley Formation. Coal was mined from the Middle Coal Measures at Lloyds Head. Although mining records show particular minerals to have been extracted and recorded at depth, it is likely that any mineral encountered would have been mined if possible.

TWC (2000b.i) identifies coal mining to have taken place in Broseley Parish in the early 15th Century. The first recorded mining was undertaken in 1545 at Salthouses and in 1575 coal mining was being undertaken at the Tuckies. Coal mining was the dominant industry in the area by the 17th Century. By the end of the 18th Century the coal pits were becoming exhausted and only serviced local industry rather than for export from the area. By the start of the 20th Century only three pits were being mined. Coal mining ceased in the area in the mid 20th Century. Coal was principally mined from the productive coal measures of the Lower and Middle Coal Measures.

Ironstone replaced coal as the main product of the area in the early 19th Century. The ore began to run out in the 1870's. Iron ore mining was undertaken at the Calcutts and Ladywood to the west of the study area.

Tile making was undertaken in the mid-1500's using surface clay. Mining for clay was first established in the Broseley area by 1776 and by the 19th Century clay mining was undertaken in former 18th Century coal pits. Coal and clay were often mined together as both fuel and raw material. Red Clay and Tile Clay were principally mined from the Hadley Formation, and the fire clay from the Lower Coal Measures. One bed of clay suitable for brick and tile making has been stated to be 17ft thick (TWC, 2000b.i). Clay is reported to have been mined to a depth of 91.4m.

Figure 2.14 identifies the extent of recorded mining in the study area.

Pits identified for mining coal, clay and ironstone are identified in TWC's report (TWC, 2000b.i). Mine pits recorded with depths and/or mineral mined within the study area are shown in Table 2.8. Bearing in mind the number of shafts recorded in the area the extent of mining of all minerals may be expected to be greater than that shown in Figure 2.15 with unrecorded workings occurring throughout the area.

TABLE 2.8 SUMMARY OF RECORDED MINING

Pit Name	Mineral Mined*	Depth Mined*	Comment
Wallace Pit (Shaft Nos 42 to 44)	Red Clays and Tile Clays	75.9m	Shaft No 42 also shows a mined depth of 69.0m, mined from the 1830's to 1940. An underground lake was found half way to the Milburgh Pit, which was pumped out at this pit each day
Doughty's Pit (Shaft No 10)	Red Clay	23.8m.	Red Clay 2.13m thick, almost total extraction bounded to north by old workings and to SE by 40m downthrow fault, worked up to 1902
Milburgh Pit (Shaft Nos 33, 35 & 83)	Brick and Tile Clay	22.0m	connected to Wallace Pit by tunnel.
Wallers Pit (adjacent pits known as Jolly and Bonny Pits) (Shaft Nos 39 to 41)	Sulphur Coal and Red Clay	Coal at 51.2m	Flint Waggonway ran underground to Woodhouse Farm from Waller's Pit. BGS identify red Clay to have been worked ~9m above coal.
Alders Meadow Colliery (Shaft Nos 36 to 38)	Tile clay & brick clay	64.8m	Tile thickness 2.3m thick beneath 1.8m thick of brick clay, pillar extraction; shaft filling undertaken in 1984
Tuckies Pit (Shaft Nos 47 to 48)	Sulphur Clay, Red Clay and two seams of Fire Clay	64.0m	Both shafts also show 64.0m depth; capped by the Maws' factory and Severn Valley railway. The mines at Tuckies had a pit shaft and water shaft
Blists Hill	Red, Brick and Tile clay	Variable	SL ~99.0m. Main Sulphur Coal aat –8; Big Flint Coal at –41; New Mine Coal at –67

* Mineral and depth mined taken from TWC (2000b.ii)Jackfield Stability Study

TWC's (2000b.ii) mining study identifies the following:

- typical extraction of the clay as 2.0m and of Sulphur Coal 0.6m
- mining utilised the pillar and stall method
- collapse is unlikely to be total as workings were shallow
- extraction for both minerals would be ~50%
- workings were known to be very wet and flooded quickly requiring daily dewatering
- extensive unrecorded mining extraction is supported by the number of unrecorded mine shafts on mining plans
- the concentrations of shafts to the western side of the area reflects shallow coal and clay.

Statutory requirements to prepare and deposit records of mine workings were introduced in 1850 and 1872 respectively. Therefore, it is inevitable that mining records for the whole site are very incomplete, especially any recordings at the Lloyds Coppice site.

2.9.2 Methods of Mining

Three methods of mining have been reported within the Ironbridge area: bell-pit; pillar and stall; and the longwall method.

The earliest method of mining, albeit there is no evidence that this method of mining was undertaken in the study area, involved bell-pits, which were only suitable for seams near the surface. As these surface seams became exhausted mining was undertaken at greater depths.

The earliest underground mining within the study area was carried out from levels or adits driven into the seams from the valley side. Roadways, such as the Flint Coal Waggonway, were driven several hundreds of metres to allow extraction to the level mouth. In order to maintain a drainage gradient roadways were driven in northerly and southerly directions to allow for the easterly dip of the strata.

Shafts were recorded as early as the 16th Century, although it is not clear whether these were for mining purposes or ventilation, TWC (2000b.i) reports that shafts were built normally in pairs for ventilation.

Mining, up to the 1720's was predominantly using the pillar and stall method, where unworked pillars were left to support the overburden (TWC, 2000b.i). This type of mining often involves the 'robbing' of pillars during the retreat of mining operations. With this type of mining there is little surface subsidence at the time of mining, but it eventually occurs if the pillars settle into the mine floor or are 'robbed' or beam failure occurs in the roof strata between the pillars, to form collapsible chimneys which may eventually form crown holes at the surface. This very much depends on the overlying strata competence, depths and thickness of seam extraction, and the geometry of the mined seam.

During the 1720's mining methods changed to the longwall system, although there is no specific date at which this occurred. The Shropshire Coalfields are credited with being the first to introduce the longwall system of mining, which enabled long coal faces to be extracted. The roof was encouraged to collapse behind the face to avoid overstress in the face, with only the roadways being supported. The caved area of the mine where a seam was worked (the *"goaf"*) was often backfilled (by*"gob"*). This method of mining caused rapid disruption to the overlying strata and ground subsidence.

2.9.3 Ground Stability in Mined Areas

The ground surface within the study area may still be responding to the effects of mining. The pillar and stall method of mining is unlikely to have initially affected the overlying strata, whereas the longwall method would have caused rapid disturbance and bed separation to the overlying strata. However, given the extent of unrecorded mining in the area and that pillar and stall mining was the method of extraction before official records began, it is likely that subsidence may not be complete in the area. Other factors which are important on the effects of ground behaviour are the nature and condition of the overlying strata (both rock and superficial material). In the Jackfield area, ground behaviour is further complicated by the (recorded) mining at different levels for coal and the clays and the possible different types of (unrecorded) mining at various depths.

All records of mining in the Jackfield site show workings after 1720, which would suggest that the longwall method of mining was the primary method, however, it has been reported that 18th Century miners had met seams worked by the pillar and stall method (TWC, 2000b.i). Therefore, this section of the report summarises the general effects of both deep mining methods on ground behaviour and then discusses in detail the effects of mining in the study area.

Pillar and stall workings usually result in three main mechanisms of deterioration and collapse of workings (CIRIA, 1984):

1. Floor heave: this involves the creeping and swelling due to the absorption of free water, particularly where a seatearth is present. Heave continues until the lift is sufficient to counterbalance the thrusts which develop from the weight of the overlying strata passed down through the pillars. The normal effect of heave is to give lateral support to the pillars and tend to reduce the deterioration at their perimeter. The settlement by 'punching through the floor' ultimately results in the lowering of the ground surface, strains and tilting occurring around the periphery of the settlement basin.

2. Crushing of pillars: although few reports of pillar collapse have been recorded, it is generally considered that deterioration and failure of pillars can occur from the combined or separate effects of spalling and weathering. The pillars are required to sustain the redistributed weight of overburden and are subject to compression. Stress concentrations develop at the pillar margins causing spalling failure, increasing the stress and further deterioration of the pillar. If one pillar fails as local ground loading becomes critical, the redistribution of the loading is likely to result in further pillar failures. Pillar stability depends on the type of rock and pillar dimensions, centre distance of pillars, depth of workings, seam thickness, strength of the rock and local conditions. The presence of groundwater is likely to accelerate pillar deterioration.

3. Roof collapse: the deformation and collapse of roof material is the primary closure mechanism applicable to shallow mine workings. Principal reasons for collapse are discontinuities in the overlying strata. The roof may continue to fail until bulking of the collapsed roof material fills the void left by the worked seam or a stratum is reached which has sufficient tensile strength to span the opening. Crown hole formation is associated with roof collapse less than 70m depth, depending on excavation type.

The above is typical of a level ground surface, however, sloping surfaces give rise to rapid changes in depth of cover. Generally, where the depth of cover ranges from 10-30m, there is significant likelihood of the mudstones, and to some extent sandstone and siltstone horizons, above being heavily weathered. The main influence of a sloping ground overlying pillar and stall workings appears to be that of reduced depth near the outcrop increasing the likelihood of crown holes and depressions, which may change the pattern of surface drainage with the disturbed strata acting as conduits for groundwater. Undoubtedly the slope above the mine workings gives rise to a weakening effect, resulting in slumping and an increase in slope gradient.

Longwall mining does not usually result in catastrophic ground movement. The subsidence resulting at ground surface level corresponds, generally, to the seam thickness multiplied by a subsidence factor which is related to the ratio of width to depth extraction. The lateral extent of surface subsidence above the worked ground, the angle of draw, depends on the type of overburden and seam dip. Following mineral extraction, the worked areas are subject to loading from the overlying strata until the void is largely closed. In strong rocks strain can concentrate at faults resulting in a subsidence step being observed at ground level. Partial or solid stowing may reduce surface subsidence, but the subsidence wave is not affected by stowing.

The extraction of a seam by the longwall method of mining under sloping ground gives the effect of undermining the toe of the slope, which results in slope shear failures and slumping. The magnitude and frequency of shearing is dependent on the competence of the overlying material and groundwater. Further mining into the slope is likely to result in less shearing and an overall lowering of the beds. Overlying disturbed and fractured strata may intercept unstable slope shear planes, although this does tend to affect shallower seated shear planes rather than the deeper seated. If a pillar is left at the outcrop surface slumping is often avoided, however, significant surface crack development immediately over the extraction side of the pillar occurs owing to the concentration of tensile strain, which decreases as the depth of cover increases. The surface over the advancing face experiences an increase in gradient.

The recent ground investigation identified some water strikes at horizons logged as fractured and non intact core. Although mine workings cannot be substantiated based on these described horizons, some poorly recovered core horizons do correspond to worked depths. It is likely that some of these fractures are remnant-abandoned workings, which may provide routes for groundwater flow including the possibility of flow into the overlying landslides. Following the cessation of mine operations in the area, and the necessity to pump groundwater out of the mines, groundwater levels undoubtedly have increased in the mine network.

Halcrow (1990) refer to a mining report prepared for Western Region of the Railway Executive in 1952, stating that the Wallace Pit was full of water and that the Wallers Pit, being lower was also overtopping, although the latter was not observed. It was suggested that the tile clay workings, which extended to the southwest up to an elevation of 50m OD were drained towards Wallers Pit and water could then enter the landslide via the shaft, the nearby fault or subsidence induced fissures. Although this has not been substantiated, it is considered theoretically possible for Wallers Pit to overtop, providing that all the tile clay workings are flooded up to the level of the highest workings. Incidentally, no high groundwater pressures were found within the strata underlying the 1952-53 landslide area.

The fractured and disturbed strata above mine level may have a positive influence on shallow ground instability allowing positive drainage of shallow groundwater to deeper levels. However, mine water is likely to cause weathering of pillars and mineral faces at depth and generally cause deterioration of subsurface strata. A potential consequences may be the build up of water pressures at fault interfaces and variations in geological strata.

Halcrow (1990) summarised the recorded mining information in relation to each landslide event; a copy of the table of these landslide events is presented in Appendix C. Halcrow (1990) identify that Ash Tree Pit, Jolly Pit, Bonny Pit and Woodhouse Pit were sunk through the landslide system. Halcrow have also determined the extent of workings from the Broseley Hall Estate Plan (c1728/ 1760's), although the plan shows the Flint Coal workings to have apparently terminated against the Doughty Fault, suggesting considerable inaccuracy of the records/ plan. The only other plan showing coal mining is that of the Sulphur Coal workings from Wallers Pit. It has been reported that this was the last coal workings in the vicinity of the landslide and mine operations ceased in 1884. Table 2.8 summarises the recorded extractions for coal and clay from specific pits.

It can be observed that the Tuckies and Wallers Pits have had over 7m of mineral extraction from depths around 60m. Although the Tuckies Pit shows some 2m of Sulphur Coal extraction this is outside the area of ground movement observed in the Jackfield slip areas.

The pits identified to have been sunk below the landslide system have extracted clay mineral with only Wallers Pit extracting coal. The thickness of coal extracted at Wallers Pit is unlikely to have influenced current slope stability.

TABLE 2.8 SUMMARY OF RECORDED MINERAL EXTRACTIONS (after Halcrow, 1990)

Pit	Red Clay/ Thickness	Brick & Tile Clay/ Thickness	Fire Clay/ Thickness	Sulphur Coal/ Thickness	Flint Coal/ Thickness	Best Coal/ Thickness	Total Thickness Extracted
Wallace	?						?
Tuckies	3.35m		2.44m	2.13m			7.92m
Doughty's	2.13m						2.13m
Wallers	2.44 – 3.05m	3.96m		0.46m			6.86 – 7.47m
Jolly & Bonny					c1.0m (?)		1.0m?
Millburgh		3.96m					3.96m
Alders Meadow		1.8 & 2.3					4.1m
Cornbatch						c1.0m (?)	1.0m?
Blists Hill	4.88m +1.52m						4.88m +1.52

Based on field observations in British coalfields the maximum value of surface subsidence can be calculated by factoring 0.9 x seam thickness (Whittaker and Reddish, 1989), where extraction conditions permit development and that stowing has not taken place, suggest that up to 6.7m of ground subsidence could possibly have occurred around the Wallers Pit. The extent of the subsidence profile, based on a 35^o angle of draw, would give a further 44.8m lateral extent to the area affected by mining subsidence. This would have the effect of increasing the gradient of the slope in the Tuckies and Wallers Pits' areas. Possible mining at shallower levels, faulting and the fact that mining was undertaken beneath sloping ground can compound the affects of subsidence.

Piggot et al. in CIRIA (1984) has postulated that maximum height of collapse in pillar and stall workings is often taken as five to ten times the seam thickness and up to 20x has been observed over roadway intersections in South Wales; however, it is considered that relationships which give maximum heights of collapse should be viewed with caution.

Jones et al. (1991) researched the relationship between landsliding and the process of undermining sloping ground surfaces in the South Wales Coalfields. Analysis included physical and finite element numerical modelling (FE) of particular slopes at East Pentwyn and New Tredegar and the effects of coal extraction at depth. In brief, it was found that:

- Prior to mining all stresses were compressive and approximately parallel to the slope

- Following extraction of a seam the model predicts major concentrations of vertical stress about the pillar locations, effectively 'punching' the pillars into the floor rocks
- Between the pillars vertical stresses become tensile [within the sandstone strata at East Pentwyn], simulating potential bed separation as the strata subsides into the mining void
- Significantly, a feature of the fracture pattern of the FE analysis showed that it was relatively insensitive to changes in roof and floor rock parameters, suggesting that fracture zones are primarily dependent on the mining layout and are relatively insensitive to the strength and stiffness of the rocks concerned.

In summary, the modelling demonstrated that pillars remaining in shallow workings result in disturbance to strata above and below the seam. Jones et al. goes on further to postulate that changes in the stress field above a pillar along with the floor strata displacement towards the outcrop (by the punching effect of the pillar) are characteristics which are compatible with the development of a deep-seated failure surface. The effects of shallow mining on a slope (based on FE analysis) are shown in Figure 2.16. Further modelling analysed the influence of steeply inclined fault planes, which found that the behaviour of the rock was dominated by movements of blocks bounded by the fault plane and that faults concentrated subsidence and strain. Jones et al. do acknowledge that there were limitations to the method of analysis.

The sites modelled above are not the exact equivalent of the Jackfield slope and, therefore, the conditions and characteristics cannot be readily transposed and the model totally compared. Mining recorded in the Jackfield area is at depth and below the level of the River Severn, the compression zones observed, as found in Jones et al FE modelling, in the strata below the mined seam would have no release space for deep seated failure to occur and to toe out.

However, mine workings around the Alders Meadows Colliery area (worked depth 64.8m deep until 1940 for Tile Clay – seam 2.3m thick) is reflected in the surface morphology (Morphological Unit III, Halcrows (1990)) which is described as a series of multiple rotational failures and shows active movement to have occurred more recently than in other areas. The back scarp of the Jackfield landslide system terminates just north of Woodhouse Farm. Mining has taken place beneath and towards the south of Woodhouse Farm, where there is little evidence to suggest that mining subsidence has influenced surface morphology. This may be a result of the depth of overburden and that the overburden increases as the workings follow the dip of the seam. Furthermore, mining records show worked seams of the Middle Coal Measures (eg Flint Coal), which are deeper in the geological succession than the mined clays.

With regard to Lloyds Coppice, there is only one recorded mined level, worked from the Blists Hill area. The characteristics of this mined level and slope can be compared, to some degree, with the model developed by Jones et al. The Blists Hill seam has been worked at relatively shallow depth (4 to 34m bgl) and the level is sufficient distance away from the slope surface to simulate the effect of a pillar near to the slope face. As described in Section 2.3, Halcrow (1990) mapped more pronounced terrain and a graben-like feature directly above this level of working (Unit IV), suggesting relatively recent movement compared to the morphology elsewhere at Lloyds Coppice. Although, the slope movement cannot be directly related to the underground workings, this graben-like feature is only located in the area above this mined level.

The modelling confirmed that changes in stress fields as a result of mining result in fractured and disturbed strata, both above the seam worked and below.

2.10 Remedial Measures at Lloyds Head & Lloyds Cottage

TWC's (2000a) geotechnical desk study at Lloyds Head assessed the stability of the ground of the Lloyds Head highway. The road is reported to be underlain by discarded tile waste which has 'resulted in the formation of a highly mobile unconsolidated "false bank" '. The frequency of repairs to the road and the construction of the Jackfield Freebridge resulted in proposals for several road refurbishment schemes. The preferred works involved the installation of 5.5m long soil nails at 1m centres and at an angle of 45 degrees overlain by backfill; the design of an overlying geotextile was excluded from the works. The remedial works were undertaken in September 1995 and further refurbishment was undertaken in June 2000, this time incorporating the geotextile proposed in 1995.

Further movement at Lloyds Head led to the need for the TWC study in 2000. This recommended the use of an anchored contiguous bored mini pile wall along the length of road affected by ground movement and stabilisation of the river bank.

SCC's design report, dated April 1995, identifies ground movement at the Wesley Road Junction, in front of and to the east of Lloyds Cottage. As part of the study a ground investigation and a crack map was undertaken in the area of Lloyds Cottage. Field inspection and borehole instrumentation identified movement to the retaining wall east of Lloyds Cottage and extensive development of large cracks in the area of the Canoe Club both along the road and into the neighbouring woodland. Substantial deposits of made ground were encountered between the road and the river. Significant movement was identified at 18m depth at the made ground/ in situ strata interface, within two boreholes installed with inclinometers.

The report recommended a composite solution based on the principle of forming a reinforced block under the road by installing soil nails at lengths and angles similar to those at Lloyds Head. The works were undertaken in the 1990's.

It is likely that the movement observed during the recent walkover at Lloyds Cottage is a continuation of the movement observed in 1995. It is also possible, however, that wholesale movement of the 'stabilised reinforced block' may be occurring.

2.11 Climate Change

The Hadley Centre (2002) describes four alternative future climate scenarios for the UK. The alternative scenarios are based on varying rates of global emissions, predicted by the International Panel on Climate Change (IPCC).

Over the last 100 years the average temperature has risen by 1.0^{o}C in central England. The 1990's was the warmest decade since records began in the 1660's. Winters in the UK have been getting wetter, with a larger proportion of the rainfall occurring during the heaviest downpours, while summers have been getting slightly drier.

The future change in climate over the next 80 years will be influenced by the volume of greenhouse gases emitted.

The Hadley Centre predicts that summer temperatures may by rise up to 3.5 ^{o}C by the 2080's, depending on the scenario. Annual average precipitation across the UK may decrease by 0 to 15%, although there are likely to be large regional and seasonal differences. However, the seasonal distribution of precipitation is likely to result in winters becoming wetter. Extreme winter precipitation will become more frequent. By the 2080's, winter precipitation events that have been experienced once every two years on average, may become up to 20% heavier and very wet winters like 1994/95 may occur on average almost once a decade.

With regard to Ironbridge this is likely to have the effect of increasing and concentrating the precipitation into the catchment area of the River Severn and cause an increased number of flood events in the Ironbridge area. In addition groundwater levels in winter may rise to landslide trigger levels on a more frequent basis.

2.12 Do Nothing Scenario

2.12.1 Introduction

This scenario identifies the likelihood of events should no active intervention be undertaken during the short, medium and long term. The do nothing scenario usually means that no remedial works and maintenance are undertaken by any party, such as slope stabilisation and river bank protection or the sealing of cracks in any roads. However, as part of Health & Safety requirements Local Authorities and third party agency's will have to undertake minimal maintenance in order to maintain public safety.

It has been considered that there is a range of likely outcomes from the do nothing scenario: minor-type events, for example, continued crack development in the roads and slopes, to catastrophic events of potential damming of the River Severn from slope instability, as occurred in 1773 at The Birches, Buildwas.

Generally, across the site slope instability is likely to continue and the rate of ground movement will be determined by riverbank erosion and rainfall infiltration.

Future movement is likely to accelerate as groundwater levels become higher during the wetter winters predicted by the Hadley Centre (2000). Flooding events have been recorded nearly every year over the last decade and there is no reason why this should not continue given the climatic changes to some degree currently experienced.

This section of the report will describe the consequences of this scenario generally across the site, but first it will describe the areas of primary concern.

2.12.2 Lloyds Coppice

The most significant area of concern in the short term is the Lloyds Cottage area, which is currently active and ground movement appears to be moving at significant rates. The road is presently reduced to one lane of traffic and tension cracks within the road and lower slopes are opening. The retaining wall beneath the road has detached itself from the pavement and the aperture of which continues to increase (Plate 11).

Further failure of the ground will almost certainly result in the loss of road in this area. Traffic on this road will have to be diverted through the residential area of Madeley and, more than likely, Lloyds Cottage will be lost on safety grounds. Utility services, gas and water, are likely to fail before road severance.

Failure of the Lloyds Cottage slopes has the potential to toe out into the River Severn, although the total damming of the river is unlikely (the profile of the slip plane is yet to be resolved and requires further investigations to determine the total magnitude of failure). Debris from any failure, however, is likely to advance the line of the present river bank. This will have repercussions on the southerly bank as the river realigns itself around the newly formed debris toe and accelerates erosion at Lloyds Head. As the toe of the landslide is eroded by the river this will further undermine the Lloyds Cottage and Lloyds Coppice slopes.

It is possible that this type of scenario may occur across the entire length of the Lloyds Coppice study area.

2.12.3 Jackfield

The slopes at Jackfield, in the Salthouse Road area, are likely to continue moving downslope. Although movement is slow, with time increased rainfall and groundwater levels may accelerate ground movement and is likely to result in damage to structures and further damage to the road. Continued maintenance of the over ground services and the fittings to where they go underground is likely.

The concern at this site is if the Salthouse Road is impassable or severed emergency vehicles will not be able to access the Tuckies area. Furthermore, the residents and the public will not be able to access property and businesses.

Further ground movement will also push the river northwards into the Lloyds House area of Lloyds Coppice and possibly accelerate toe erosion on this slope. However, it is possible that the rate of erosion by river action may be similar to rate of movement, that is no advancement of the river bank. However, this scenario involves the constant removal of support of the Jackfield slope and therefore equilibrium is never achieved.

2.12.4 Lloyds Head

Further erosion of the riverbank in the area of Lloyds Head will ultimately result in continued loss of ground along the top of the riverbank as the slope tries to achieve equilibrium. Buildings have recently been demolished, on the grounds of public safety, and damaged as the riverbank has retreated. This will, more than likely, accelerate due to the effects of the landslide at Lloyds Cottage toeing out into the river, causing greater erosion on the south bank.

The combined effects of subsidence and river erosion are likely to result in Lloyds Head becoming impassable and property being damaged and, possibly, considered unfit for safe habitation.

3 SLOPE INSTABILITY

3.1 Introduction

This section describes the instability currently evident within the study area and discusses this in the context of the natural development of the slopes and the consequences of human interaction, primarily through mining. Areas of slope instability that have the potential to threaten property and infrastructure and cause injury or harm to the public are identified.

A qualitative risk assessment of the three sites within the study area has been undertaken as part of this report in Section 4.2.

Figure 3.1 shows data from the relevant figures used to identify areas of ground movement, geomorphological mapping, and areas of mining and has layered them to show the influences that these factors have towards slope stability.

The following has been observed:

1. Current active movement at Lloyds Head, Lloyds Cottage, School House, and Jackfield (Salthouse Road) and the failed sheet pile wall in the Lloyds House area are situated on the outside bends of the River Severn.

2. Areas of significant movement along Salthouse Road have been undermined. This may be true of the School House area also.

3. Slopes showing movement contain deposits of mine spoil/ made ground.

3.2 The Causes of Slope Instability

Slope instability at Ironbridge Gorge is a result of the development of the valley since its initial formation during the end of the last glacial period. It can be seen that the action of the River Severn is cutting through the relatively incompetent geological strata and has promoted and still promotes ground instability. Observations within the study area show that erosion of the river banks is greater on the outside of the bends and, in places, where material has been placed in the river to provide white-water conditions for canoeists.

Coal Measures which outcrop on the slopes on both sides of the valley, comprise weak argillaceous materials, which weather to clays of low shear strength. Weathering is increased at surface exposure, where ground has been disturbed by landsliding activity and at depth where mining has induced fracturing of the ground above.

Within the Coalport Beds of the Upper Coal Measures, exposed on the Lloyds Coppice slope, the Thick Rock and Stinking Rock provide two water bearing sandstone horizons, which are considered to have promoted instability by providing a passage for water to soften the argillaceous rocks at their base and possibly creating high pore water pressures within critical areas of the slope (IGS, 1973 and Denness, 1977).

On the Jackfield side of the valley the geological structure is favourable to ground movement because the dip of the strata is out of the slope.

Groundwater has, more than likely, been a trigger for most ground movement since glacial times. High groundwater levels were observed during both the 1952 and 1984 slips at Jackfield. In most cases, the ground investigation shows some water strikes around the interface of made ground with underlying strata suggesting that possible perched water tables have developed in the more permeable and uncompacted deposits. This would have the effect of increasing the loading of the underlying strata during periods of high rainfall infiltration and reducing the effective strength of the uncompacted man-made materials.

The effects of long periods without rain followed by intense or prolonged rainfall may possibly be the triggering factor for the recent observed ground movement at Jackfield and Lloyds Cottage; although significant toe erosion of the river banks has also occurred at Lloyds Cottage. A reduction in groundwater levels reduces porewater pressures in a slope. It may also reduce the driving force on a slip plane. A rise in water table increases pore water pressures within the soil mass and reduce the effective stress. This gives a consequent reduction in resistance to shear.

Thus changes in the groundwater regime may result in periods of inactivity followed by possibly significant active ground movement. For relatively shallow slips high water pressures from individual rainfall events can rapidly reach slip surfaces, causing creep with possible periods of accelerated movement during higher rates of infiltration.

The human influence on the natural slopes in the study area is significant: spoil has been deposited on the slopes and river banks, and mining has created voids at depth resulting in bed separation and a change in the stress field of the overburden. The industry and properties located on the lower slopes throughout the study area may have contributed to instability through water pipe and drain leakage. This leakage may be due to ground movement or simple age related deterioration in condition.

The landsliding evident on the valley sides corresponds to areas where Coalport Beds are exposed and is restricted to areas where the geological structures and/or mine workings make the slopes additionally susceptible to movement.

Within the study area it is probable that the incidence of instability has shifted from one side of the valley to the other. Following failure on one side of the valley, that slope becomes relatively stable. Meanwhile the failure debris 'toes' out of the failure area into the river. This results in lateral erosion to the opposite slope as the river is 'nudged' towards it around the debris. The same process repeats itself over time on the opposite side of the valley.

It is considered that landsliding is a result of a combination of factors including river incision and the natural development of a valley system. Vertical erosion of the river bed reduces support to the toe of the slopes and along with the effects of lateral erosion, which removes landslide debris from the action of the river, landsliding results.

In addition bank collapse can occur through periods of flooding when water imposes additional weight on the bank further increasing the susceptibility to fail. Furthermore, high water pressures can result from a rapid lowering of the water level where the slope material cannot readily drain at the rate at which the water falls. Excessive pore water pressures not only reduce the shear strength of the material, but can allow piping of the fine particles which are washed away by seepage leaving only the coarser materials and voids, resulting in surface erosion.

With regard to 1952-53 Jackfield slip and the interaction between mining and the subsequent effects of subsidence and fractured overburden it is difficult to attribute that this is one of the major contributory factors to slope instability as the areas of mining also coincide with sections of the riverbank that have a high rate of erosion (ie the area is situated on the outside bend of the river).

3.3 The Causes of Current Slope Instability: Jackfield

The landsliding evident on the valley sides corresponds to areas where the relatively incompetent Coal Measure Formations are exposed and is restricted to areas where the geological structures and/or mine workings make the slopes additionally susceptible to movement. Any influence mining has had on current slope instability cannot be substantiated, although mining in this area appears in some part to have defined the margins of ground instability. However, the effects of mining and the likely resulting bed separation and subsidence of the overlaying horizons cannot be disregarded, especially as not all mine workings have been recorded. Furthermore, the active lower slopes of the Salthouse Road area of Jackfield coincide with the mining for coal and clay at shallower levels than elsewhere along the slopes. The effect of at least two minerals being mined at shallow depth may have resulted in the overlying bedrock being more susceptible to slope failure.

Within the study area it is probable that the incidence of instability has shifted from one side of the valley to the other as the debris of the failure area 'toes' out into the river. This results in lateral erosion to the opposite slope as the river is 'nudged' towards this slope. This may account for the variation in stability on each side of the Gorge, where sections of the slope appear stable where there is more toe support (eg Jackfield Area B, Salthouses and The Tuckies on the south bank) and the converse is true where instability is identified on the opposite banks (eg School House area and to the west of Lloyd's House). This is also true for the Lloyd's Head and Lloyd's Cottage areas.

In addition, the Tuckies and Doughty Faults have been identified to delineate areas of instability from slopes more stable. Jackfield Area B (Jackfield Tile Museum) has been identified to be more stable than its adjacent slope of Jackfield Area A (Salthouse Road).

Halcrow (1990) report the area of Jackfield to be relatively inactive, with the exception of the Salthouse area where instability has been reported over 200 years. The continued failure of the area around the 1952 –53 slip was observed during the walkover undertaken as part of this study. Borehole instrumentation in this area, installed as part of the recent ground investigation, shows a shear surface at ~5m depth, the depth at which Henkel and Skempton (1954) identified the failure zone. This section of the slope, around Wallers Pit, shows substantial accumulations of spoil from mining works. These deposits have increased the loading on the lower part of the slope. Halcrow have identified that the spoil extends upslope to the extent of the 1952-53 slipped ground. In addition, the extent of the 1952–53 slip corresponds to the area of worked ground from Wallers Pit. These workings are bound by the Doughty Fault to the west and the 'Tuckies' Fault to the south (note Wallers Pit Shaft must have been sunk through the fault). Jones et al. (1991) have modelled the effects of mining at depth and found that changes in the stress fields result in bed separation and fracturing of the overburden. Furthermore, mining subsidence may have resulted in a steepening of the slope, although this may have been negated by the dumping of mine spoil. Mining would also have affected the natural hydrogeology of the area, providing preferential pathways for water flow and enabling possible build-up of pressures at mined faces and faults. The problem of groundwater is likely to have been made worse as the pumping of mine water ceased with the abandonment of the mines. Survey results from pins located along Salthouse Road identify greater ground displacement in the 1952-53 slip area than the remainder of Jackfield.

Geomorphological mapping has identified the remnants of a series of rotated blocks, where failure acted retrogressively for all the sub-sites in the Jackfield area. These relatively deep-seated blocks are presently in a state of equilibrium. The upper part of the blocks have been subject to weathering; the ground is largely weathered clay and deposits of mine waste have been dumped above.

It is unlikely that the area of the 1952 slip (Salthouse Road sub-unit) has any relation to the in situ underlying geology and failure occurred in the weathered zone in the form of a debris slide as the toe was eroded by river action and weakened by groundwater infiltration. There are no reports to suggest that failure occurred at this particular site prior to 1952. The action of this possible first time failure in 1952 was to realign the platey clay particles within the shear zone and reduce the strength of the material to its residual value. It can be surmised that the current ground movement observed is a reactivation of the 1952 slip, where disturbance forces are presently greater than resisting forces.

The effects of this type of failure would appear to be:

- slow moving ground, eg creep
- relatively large area of active movement, retrogressing upslope and laterally
- susceptible to seasonal changes in rainfall/ periods of heavy rainfall, giving increase in velocity

Boreholes identify made ground deposits along most of the length of the lower slopes at Jackfield. The effect of the made ground, given that it was unlikely to be compacted and that it is likely to have a higher permeability than the underlying weathered clay, may give rise to perched water tables and increased loading.

Observations from monitoring pins and inclinometer data identify the areas of current instability to also coincided with the outside bend of the river and areas of mining. The most active area would appear to be that of the Salthouse Road area and the western flank of the Salthouses area, both of which are areas that have had some form of mining (predominantly for clay) undertaken beneath. There is relatively little movement in the remainder of the area; Tuckies and Jackfield Tile Museum.

In addition, the relative lack of tree and shrub cover at Jackfield compared to Lloyds Coppice, would enable greater infiltration and less normal stress acting on the ground.

The effects of the above have contributed to landslide activity at Jackfield. The current instability is a result of further development of the pre-existing landslides formed during valley development and the geological structure. The rate of ground displacement is controlled by the:

- Rate of incision of the river
- The groundwater regime and amount of infiltration following rainfall
- The presence of mine spoil on the slopes
- The ‘unsubstantiated’ effects of mining subsidence

3.4 The Causes of Current Slope Instability: Lloyds Coppice

The site has been divided up into three management units (see Figure 2.2). The Lloyds Cottage and School House areas show current ground activity.

Halcrow (1990) identified that the western part of the toe of the Lloyds Coppice slope [Lloyds Cottage sub-unit] is most active and concluded that the main causes of slope instability appear to be increased loading of the landslide by mining spoil and lateral erosion of the toe of the landslide by the river. Damage to the junction of Wesley Road and The Lloyds was considered to be the failure of a spoil heap, which was failing itself due to the underlying movement of landslide deposits. Remedial works of concrete blocks and a sheet pile wall indicate that the loss of support at the toe of the landslide has been a problem for some time.

The river has narrowed from tipping and possibly the landsliding of the southern river bank, this has resulted in erosion of the northern river bank. Halcrow acknowledge that no mining plans or records or subsidence beneath Lloyds Coppice were found and that any effects of mining on stability cannot be assessed. However, they do show the mining works from the Blists Hill mine on their Drawing No KC/ SCA/ R1/ 6. Halcrow's geomorphological plan shows the only graben-like feature across the site to be located above this mined level. Although the existence of this feature cannot be attributed to the presence and possible failure of the underground workings, Halcrows do not mention the feature might be due to possible mine-induced structural failure of the ground above. The lack of mining records cannot substantiate that mining has fractured strata and disturbed bedding.

During and subsequent to the walkover undertaken as part of this study ground movement was observed in the area around Lloyds Cottage in addition to continued movement at the junction of Wesley Road and The Lloyds (Plates 17 & 18). Ground movement has opened up tension cracks within the road and necessitated the closure of one lane of traffic. HPR wrote to TWC concerning the movement observed. A copy of this letter dated 2nd June 2003 (ref. 2008/3/S2003-019/DGC), is shown in Appendix D.

Two boreholes have been sunk in this area, CP16 and R16, and both have been installed with inclinometers. CP16 shows made ground down to a depth of 5.3m below ground level (bgl) underlain by firm becoming firm to stiff slightly sandy slightly gravelly CLAY to a depth of 13.8m bgl. The clay is underlain by bedrock. Probable shear surfaces were logged at 5.8m, 6.9m and 11.25m bgl. Inclinometer readings show a shear surface at ~12m depth and a further shear surface at ~3.5m depth, surface level displacement is some 35mm downslope. Although no groundwater was encountered within this borehole during drilling, water was found in borehole R16 and was standing at 6.0m bgl; R16 is located on the easterly flank of the slip area. Within R16 made ground was observed to a depth of 4.5m. This was underlain by clay with a layer of river gravels between 11.0 and 12.0m bgl. Inclinometer readings show distinct shear surfaces at ~11m and ~5.5m depth. Ground displacement is significant showing more than 80mm at surface level.

Results of inclinometer readings show that movement has occurred recently. It may be that the present movement is a reactivation of a historic failure, possibly a previously failed rotated block. The rear of the block may lie upslope of the cottage, and could be formed on the Lloyds Coppice Fault.

A combination of lateral erosion of the toe of the slip by the River Severn and the high rainfall experienced prior to the ground movement was, more than likely, the trigger for the ground movement in this area. It is likely that ground movement will continue with high levels of rainfall. Increased infiltration to the slip will occur through fissures and cracks recently developed.

The landslide has probably been triggered by toe erosion of the riverbank, removing support to the block and high rainfall infiltration into the ground following a prolonged period of precipitation.

If this failure is due to the presence of a previously failed block, it is likely that the remainder of the lower slope of the Lloyds may comprise similar ground conditions and therefore, the potential for failure exists at other locations.

The Old School House section of Lloyds Coppice shows ground movement where the road turns and twists towards the toe of the slope. It is evident that a number of coal board recorded shafts are located in this area both upslope and downslope of the road. These shafts are situated down dip of the Middle and Upper Coal Measures, which may have been used to work the Main Sulphur seam. Ground movement cannot be attributed to any underground workings without further knowledge of the mines in this area.

The Lloyds House area of Lloyds Coppice comprises a faulted block which dips 18^{o} to the south-east. The structure of the bedding would be conducive to ground instability in the area as river erosion removes support of the toe of the slope. Observation shows a southerly migration of the river in this area suggesting significant landslide activity in the past. This is evident where the river has been pushed towards the Jackfield slip area and accelerated toe erosion of the river bank.

As at the Jackfield area, continued valley development and river incision erode the toe of the river bank. This may result in a rotational failure on the lower slope, with subsequent translational sliding of debris and mine waste from higher levels. The mine waste loads the natural slope. During periods of high rainfall and infiltration the effective stresses are reduced and the resistance to sliding is decreased.

3.5 The Causes of Current Slope Instability: Lloyds Head

Monitoring identifies significant ground movement towards the river and inclinometer BH RA (see Appendix B) shows one reading of significant movement at depth (30m bgl and >10mm downslope displacement). In addition the inclinometer plot also shows buckling at various depths. It is considered that the ground movement is at the depth of the coal seams of the Middle Coal Measures where the inclinometer plot shows a possible component of the movement to be controlled by the dip of the bedding.

Primary causes of slope instability are lateral erosion of the riverbanks by fluvial action and subsidence as a result of high groundwater levels washing fines out of the uncompacted tile waste and the mass movement of this waste material downslope.

The tile waste has little if any cohesive properties and was unlikely to have been compacted during placement. There are unsubstantiated reports of mining in the area, mainly for coals from the underlying Middle Coal Measures. It is possible that, dependent on the method of mining in this area, that subsidence may also comprise an element of mining induced subsidence.

The displacement evident on BH RA plot of the inclinometer data requires further monitoring to identify the general trend of any ground movement.

3.6 The Ground Model

3.6.1 Introduction

The ground models developed for the Jackfield, Lloyds Coppice and Lloyds Head sites are an interpretation of the data received during the course of this study. The ground models developed as part of this study are useful for the purposes of indicating the type of movement and possible triggering factors. These ground models require further refinement in order that they can be used as a tool against which to design remedial solutions, as requested by TWC's brief. It is considered that no one ground model can be representative of the sites.

It is acknowledged that the size of the recent ground investigation was significant and much data has been obtained that has enabled a regional representation of ground movement in the area. However, in order that these ground models can be used for design purposes it is necessary to undertake more detailed analysis to include the following:

- Further subsurface investigations to identify the extent of ground movement near river level
- A topographic survey to accurately determine levels, depths and extent of any ground movement
- Ground mapping of the area to identify recent or current ground movement and the extent of any historic landslippage
- Fluvial monitoring and rates of erosion of the valley sides
- Continued monitoring of ground movement and groundwater to confirm the ground model

The ground model is unlikely to significantly vary within each site, therefore, any remedial measures are likely to be similar within each of the three sites within the study area. The areas of known ground movement have been identified and the only concern to the areas showing no significant trend of ground movement is the expansion of these known areas of landslip and the erosion of the lower slopes by river action.

3.6.2 Model Considerations

To establish the ground model, all factors which may have a bearing on the failures in the study area have been considered. To understand the landsliding it is necessary to identify the initial structure and the trigger process or processes. The factors are summarised below:

- the geology of the slopes is generally Coal Measures comprising interbedded competent and incompetent beds;
- the beds on the Jackfield and Lloyds House slopes, due to their dip, may be acting as slide-facilitators, whereas the remainder of the Lloyds Coppice beds may be slide-inhibitors;
- faulting has affected the continuity of the stratigraphy across the site and may be acting as slide surfaces or a lateral release surfaces for any slide, which is possible for the 1952 slip and the current ground movement at Lloyds Cottage;
- Furthermore, it is not clear whether the faults are conduits or act as barriers to groundwater flow;
- mining, for clay and to a lesser extent coal, at varying depths has probably resulted in subsidence disturbed strata and bedding separation – possibly increasing the gradient of the slopes;
- mining spoil has loaded the slopes;
- groundwater will be affected by the faulting at depth and will be further complicated by abandoned mining levels; shallow groundwater resulting from rain infiltration may enable perched water tables at the mine waste/ in situ clay interface;
- The high rate of fluvial erosion due to the gorge being relatively young in geological terms and is still in the process of valley development;
- climate change in the form of increased frequency of flood events and wetter winters may be affecting the area now;
- human influences (eg deforestation, mining, water leakage from drains and pipes); and,
- Vegetation cover is significantly different between all sites.

The amount of interaction between the above results in ground movement. The aim of any slope stability analysis is to model ground movement and to use it for prediction with some certainty of confidence. However, the varying nature and structure of the geology of the study area means that individual models must be determined for the different parts of the study area. However given the vast amount of information provided, it has been decided in consultation with TWC, to only target sections for slope stability analysis where movement has been recorded. Should any future movement occur at other sites, currently showing little or no movement, it should be possible to transpose and possibly fit the ground models with minimal manipulation.

3.6.3 The Ground Model: Jackfield

The ground model for the Jackfield site is shown in Figure 3.2.

The model for ground failure has been determined as:

1. river incision and high groundwater levels (through the combination of rainfall infiltration and high river levels) resulting in rotational failure of the toe of the river bank. The area of the 1952 slip is situated on the outside of a bend where failure from the opposite bank (on Lloyds Coppice) has ‘pushed’ stream flow to the Jackfield side.

2. this removes support to the material above, comprising of weathered clay, colluvium and in places mine and tile waste (which is uncompacted, with little cohesive property). This weakened material results in the sliding of the debris material at a depth corresponding to the depth of rotational failure of the toe of the slope.

3. movement along the slip plane is likely to be in phases, that is, not all of the shear surface is below a factor of safety of less than 1.0. It is likely that a certain section of the slipped mass has a FoS < 1.0, while the other sections are above limiting equilibrium. The effect of this type of failure is to give the hummocky terrain associated with debris slides.

4. the movement of the debris slide is slow and probably continuous, with periods of acceleration of movement following high water infiltration and/ or loss of support in the lower slope.

5. the debris slide is likely to retrogress upslope and laterally,

Other factors which are important to ground instability are:

- It is unlikely that there is potential for deeper seated failures given the angle of the slope and the structural control of the geology;
- Disturbed strata and bed separation as a result of mining subsidence is unlikely to result in deep seated failure but may have influenced current landslide activity, and had an affect on the geomorphology which has been observed by Halcrow (1990);
- Reactivation of the multiple rotated blocks developed during valley development are likely to be reactivated as a result of further significant incision of the river;
- Groundwater from mined levels through fissured flow etc.

3.6.4 The Ground Model: Lloyds Coppice

The ground model for Lloyds Coppice ground behaviour is shown in Figure 3.3.

The model for ground failure has been determined as:

1. Movement is presently located within the faulted block between the Jackfield and Doughty Faults and south of the Lloyds Fault.
2. Retrogressive failure of the slope appears to commence with ground movement at the toe of the slope. Similarly to Jackfield, it is believed that as river incision occurs, oversteepened banks fail as a rotated block. A contributory triggering factor would be high ground water levels.
3. Ground movement above the rotated toe block is also likely to be rotational, which could possibly daylight 'up slip surface' against the Lloyds Fault or comprise a series of rotational failures as the distance between fault and river increases downstream.
4. The graben feature observed by Halcrow (1990) may have resulted either from structural control of the failed rotated blocks or by the mining at depth for Red Clay bed separation and subsidence.

3.6.5 The Ground Model: Lloyds Head

The model for ground failure has been determined as:

- Slope failure of the riverbank as a result of the erosion of an uncompacted and low cohesive material by stream action
- Washout of fines through groundwater resulting in subsidence across the site.
- Possible slippage of the overlying ground above coal horizons.

3.7 Slope Stability Analysis

3.7.1 Introduction

The stability of slopes is normally dependent on their geometry, geological make-up, geotechnical properties and hydrogeology. Depending on the extent and accuracy of available information, slope stability analyses comprise a combination of quantitative assessment of the available accurate data and qualitative sensitivity analysis to assess the risk of uncertainty where data is less reliable.

Developing the ground model and the sections for slope stability analysis has required the interpolation between the BGS geological map, mining records and borehole data, as well as other studies. Interpolation of this type is open to inaccuracies from the geological map to mining data to borehole logging and identification of worked horizons. The slope stability analysis has been undertaken on best information provided by TWC and experienced interpretation of the data available. The modelling of the slopes has been undertaken using SLOPE/W Version 5.

For the purposes of stability analysis within this study the available information can be assessed as follows:

1. the geometry of the slopes along the Jackfield site has been defined in the 2002/03 ground investigation and the cross-sections AA to FF, provided by TWC. Analysis of cross-sections AA, BB, EE and GG for Jackfield and two cross sections for Lloyds Coppice has been carried out for the purposes of this study. The cross sections analysed are those with

sufficient borehole information and where inclinometers show sub-surface ground movement and shear surfaces. Historic failures have been recorded and are known to have occurred when ground water levels are high, almost at surface level, therefore it is possible to model slope failure at particular water levels.

2. the geology and soil strength parameters for slope stability checks have been interpreted from the results of the ground investigation carried out in 2002-03. Published data has also been used. Due to the variable nature of made ground deposited over much of the ground surface of the sites, a wide variety of soil strength parameters necessarily exists across the site. Appropriate lower bound soil parameters have therefore been used. Residual strength parameters have been used for materials overlying mined areas as it has been assumed that (for this part of the study) subsidence/ fracturing of the overburden has occurred.

3. because of considerable natural variation in permeability of different geological elements within the upper weathered clay and deeper coal measures, the groundwater conditions remain a considerable uncertainty on the site. From groundwater monitoring and information from the ground investigations it is known that conditions may vary from artesian or sub-artesian to fully dry.

Therefore a sensitivity analysis has been undertaken modelling groundwater as a specified depth below ground level. This has been undertaken for Section EE only as ground failure in 1952 recorded groundwater at surface level. This enables analysis to determine ground failure at known groundwater levels. The sensitivity analysis has been carried out using the following:

- by modelling groundwater at a permanent groundwater level of approximately 5m depth throughout; a reasonable realistic check is obtained of the current slope stability, whether the analysed slope is represented by predominantly arenaceous deposits or cohesive materials. The values of 2 to 5m were selected as being representative of groundwater monitoring data in boreholes and the water levels are representative of each section.

- reducing groundwater depth in 1m steps to surface level, simulating high rainfall and saturated ground as experienced in the 1952 slide.

In addition to specifying the piezometric level, groundwater modelling has also been undertaken using pore pressure coefficients (ru). An ru value of 0.2 provides a realistic check of the current slope stability and represents a condition with approximately 40% saturation, which is considered appropriate for the slopes at Ironbridge. In order to provide analysis for higher groundwater levels an ru value of 0.4 has also been modelled.

The analysed sections are shown in Appendix E. All sections were analysed using a large sample software search for the critical circular slip surface and using a range of fully specified slip surfaces chosen as likely slip surfaces from the geology and inclinometer data.

In most cases analysis has concentrated on the lowest Factor of Safety determined and these are the sections shown in Appendix E. Of necessity, the geology has been simplified from that given in the borehole logs and shown on the geological map, whereby major units only have been modelled and particular beds of interest (eg clay and underground workings, etc) have been included.

Although, the analyses are based on these simplified cross-sections they are certainly adequate to enable a realistic preliminary assessment of the relative importance of the factors affecting slope stability in the study area.

3.7.2 Geotechnical Parameters Used for Slope Stability Analysis

Henkel and Skempton (1954) identified the failure zone of the 1952 failure at Jackfield to consist of a soft clay layer 5cm thick. The water content of this zone was higher and the shear strength lower than that of the clay above and below the failure plane. The sensitivity of the clay was a little less than unity and the remoulded samples had a slightly greater strength than the undisturbed specimens. The clay was classified as an inactive clay of low plasticity (from Casagrande's plasticity chart). The factor of safety was calculated to be 1.12 using the undrained strength of clay in the softened failure zone. Using the effective stress parameters gained from testing undisturbed samples and using c'= 0 and a $\phi'=21^{o}$, the factor of safety was found to be 1.07. Henkel considered that the effect of over-consolidation on the shear strength of clays (in terms of c') may largely disappear on a geological timescale in clay slopes and that a value for c' may result in a misrepresentative factor of safety for a slope. The over-consolidation of the clay produced a highly dilatant structure in which much of the strength measured in the undrained compression testing was due to large negative pore water pressures set up during the shearing process. On a geological time-scale the negative porewater pressures are able to dissipate and the pore pressure acting on the failure plane will be determined solely by the groundwater conditions. Seasonal fluctuations of the water table will affect shear stress and effective pressures and produce softening of the in situ clays. In addition, the effect of progressive fissuring results in a reduction in c' and the strength of the clay.

Skempton (1964) re-examined and discussed the Jackfield site as part of the 4th Rankine Lecture in 1964. Skempton observed that the slide was confined wholly within the zone of weathered, fissured clay. The slip surface ran parallel to the slope (~10^o) at an average depth of 5.5m. Groundwater tended to be an average of 0.6m below ground level, however, during the winter of 1952-53 groundwater was at surface level. Skempton observed from laboratory testing that when the slide took place the strength of the clay was almost equal to its residual value ($<\phi_r' = 19^o$). Subsequent calculations on the actual slip surface correspond to an average angle of shearing resistance of 17^o.

SCC (1995) undertook slope stability analysis of the slopes in the area of Lloyds Coppice using the following parameters of ϕ': made ground (comprising ash and slag) 30^o, clay peak 28^o and clay residual 9^o. The latter value was based on laboratory testing and was found to be unrealistically low. Calculations using peak values showed the slope to be stable, which SCC found to be incongruous.

The soil and rock types identified for use in the modelling for this study are shown in Table 3.1. Given the similar geological horizons throughout the study area and the similar external factors which have affected the slope processes through time, the same parameters have been used for all slopes. Values for the soil and rock parameters have been derived from laboratory testing and compared with published data. Where discrepancies exist between both sets of data, the data set with the lower value has been chosen.

Parameters for detailed analysis of proposed slope stabilisation works will need to be confirmed from site specific strength testing obtained during the design process.

TABLE 3.1. SUMMARY TABLE SHOWING SOIL AND ROCK PARAMETERS USED FOR PRELIMINARY ANALYSIS OF THE STUDY AREA SLOPES

Soil/ Rock Type	γ	ϕ'_{peak}	c'_{peak}	ϕ'_{resid}	c'_{resid}	Explanation
Made ground/ Sheared Clay	15 to 17	25	10	19	0	Skempton (1964) gave values for c’ & ϕ’ of $10.5kN/m^2$ and 25^o respectively for the o/c clay outside the slip plane area; residual values of 0 and 19^o, but considered the phi angle to be rather less than 19^o, further analysis identified an average value of 17^o (the recent GI results average 0 kN/m^2 and 26^o respectively, although the shear zone was not recorded as being recently tested). Note no peak values for all clay-material horizons although, cohesion values have been required in some sections to provide realistic results. In order to allow for a simplified analysis, the slopes have been separated into beds based on the mining within the area, and allowances have been made for the likely fractured ground above in the form of residual parameters. This is obviously the worst-case scenario and assumptions have been made that the area of analysis has been subject to mining although mining may not necessarily have been recorded.
Weathered Lower Clay	18	27	Up to 10	25 or 26	0	
Disturbed Clay Horizons	18	-	-	26	0	
Disturbed strata of the Coal Measures	18	-	-	35	0	

*Note: Peak values given for completeness; slope stability has modelled residual values only. Disturbed strata are considered as residual values only.

Analysis has shown that using similar soil parameters for each section, some slopes give an unrealistic factor of safety (ie much less than 1) and therefore failure should have occurred. It has been necessary to add a cohesive element to the strata, in which some horizons may be in a highly weathered state or an uncompacted made ground; this has achieved realistic factors of safety for the given slopes.

3.7.3 Slope Stability Analysis

Results from the slope stability analysis are shown in Table 3.2 below.

TABLE 3.2 SUMMARY TABLE OF STABILITY ANALYSIS

Site	Section	Method Of Analysis	Groundwater Level at 2 & 5mbgl / at 0.2 & 0.4R_u	Factor of Safety Deep
Jackfield	AA	Fully Specified	5	1.330
		Fully Specified	0.2	2.076
		Fully Specified	0.4	1.512
		Rotational	0.2	1.253
	BB	Fully Specified	5	1.008*
		Fully Specified	0.2	1.037*
		Fully Specified	0.4	0.788*
		Rotational	0.2	1.059*
	EE	Fully Specified	2	1.073
		Fully Specified	0.2	1.174
		Fully Specified	0.4	0.859
		Rotational	0.2	0.745
	GG	Fully Specified	2	1.061
		Fully Specified	0.2	1.616
		Fully Specified	0.4	1.197
		Rotational	0.2	1.180
Lloyds Coppice	Lloyds Cottage	Fully Specified	2	0.959**
		Fully Specified	0.2	1.001
		Fully Specified	0.2	1.266**
		Fully Specified	0.4	0.933**
		Fully Specified	0.4	0.726
		Rotational	0.2	1.030**
		Rotational	0.4	1.070**
	Eastern Section	Fully Specified	2	1.126
		Fully Specified	0.2	1.271
		Fully Specified	0.4	1.011
		Rotational	0.2	1.411

* Cohesive element has been applied to give 'realistic' factor of safety
** Factor of safety achieved through manipulating slip surface through shear depth shown on inclinometer plot, or as close as possible for rotational failures

Groundwater sensitivity analyses results are shown in Table 3.3 for both fully specified and rotational analysis of failure.

TABLE 3.3 SENSITIVITY ANALYSES WITH REGARD TO GROUNDWATER

Section	Groundwater Level mbgl	Factor of Safety Fully Specified	Factor of Safety Rotational
EE	1	0.786	0.745
	2	0.928	0.870
	3	1.128	1.616
	4	1.207	1.714
	5	1.311	1.805

3.7.4 Slope Stability Results

Failure of slopes occur as the factor of safety reaches 1.0 and it is unlikely that the failure of a ground mass affecting the whole slope will be less than equilibrium. Failures of slopes with a FoS less than 1 usually involve rapid failure. Rapid ground movement is unlikely to occur for the type of ground movement observed at Jackfield and Lloyds Cottage. However, the rate of movement at Lloyds Cottage may be restricted by the remedial works undertaken in around 1995, and, therefore, the potential for rapid (and catastrophic) failure may exist.

The Jackfield sections (EE and GG) that identify movement at ~5m depth have behaved as would be expected during the modelling of a weathered clay overlain by mine spoil of residual shear strength values. Fully specified failure modelling has resulted in the lowest factors of safety not always being experienced at the toe of the slope. In some cases, failure is noted as discrete ‘blocks’ within a large translational slab-like slide and in the case of the circular slip method of control a rotational failure at the mid-slope level of the analysed section (GG).

All failures are considered shallow, that is within the weathered clay and mine spoil horizon. Given the shear strength parameters determined for geological horizons at depth, and with the exception of Section A, the modelling identified no significant deep-seated failures. The lowest factor of safety for a deep-seated failure in Section A was 1.253 for the circular slip method of failure.

Modelling of the Lloyds Coppice site has involved analysing a section through the Lloyds Cottage area and a more general section downstream of the Cottage area. The Lloyds Cottage section has been modelled to identify the lowest factor of safety for both the section as a whole and through the shear zone identified from the inclinometer monitoring.

In the case of the fully specified method of analysis for Lloyds Cottage, there is a considerable difference between the factor of safety for the modelling of groundwater for r_u values of 0.2 and 0.4. The factor of safety, for sections with the slip plane set at or near to the inclinometer shear zone, is greater by up to 29%.

Deep-seated slip surfaces have been modelled to occur within the eastern section of Lloyds Coppice, analysed by both the fully specified and circular slip methods of failure. However, in order to model potential deeper-seated ground movement it has been necessary to give residual values of shear strength for the material above the area of the Blists Hill mine level. Also, it should be noted that significant groundwater levels were modelled to induce movement (ru = 0.4), however, the factor of safety still remained above equilibrium.

The sensitivity analysis of the slopes to groundwater, specifically Section EE at Jackfield (Table 3.3), behaved as would be expected to an increasing piezometric level; that is a lowering of the factor of safety with increasing groundwater table. Equilibrium of the slopes was achieved between a groundwater level between 2m and 3m bgl for both fully specified and circular slip analysis.

Slope stability analysis is important for identifying potential ground movement (eg probable rotational-type failure) and predicting ground movement (ie a fully specified ground model) across sections of the study area. As has been discussed in Section 3.6.1 the varying nature and condition of the geology of the slopes within the study area means that it is difficult to determine true slope stability with any degree of confidence, other than where ground movement is currently occurring by established methods of monitoring.

3.8 Environmental Considerations

Any future works must take into account the environmentally sensitive nature of the study area and must utilise techniques which are sympathetic with the local environment. Full discussion and liaison with all interested parties including World Heritage Site representatives and other statutory consultees must be held during the detailed design of any future improvement works.

In all future circumstances it is likely that compromises will be required between engineering and environmental considerations in order to develop appropriate cost effective solutions that are in keeping with the environmentally sensitive locality.

3.9 Summary Conclusions of Ground Stability

In an attempt to review the main findings of the desk study and the slope instability sections all relevant data found during the course of this study has been summarised for each site.

3.9.1 Lloyds Head

- The made ground is uncohesive in nature and was possibly uncompacted during placement.
- The made ground is subject to subsidence (as groundwater washes out finer material) and is more susceptible to river erosion.
- The site is prone to flooding during high river levels which have become more frequent.
- Monitoring along Lloyds Head identifies that the ground surface has moved nearly 2m to the North-North-West (ie riverwards) and subsided over 1m since 1994.
- Inclinometer BH RA (RO1) suggest possible shear at the base of the borehole with downslope movement comprising a component of bedding dip (having said this further readings are required to confirm any movement).
- Any ground slippage is likely to involve the made ground slipping over the in situ weathered clay of the Middle Coal Measures or possibly, at depth, along slide facilitating beds adjacent to mine workings.
- The continued erosion of the banks caused by river action is likely to accelerate during high river levels and thus promoting riverbank failure.
- The extent of mining for coal within the Middle Coal Measures may have been significant given the relatively shallow exposure at this site. Dependent upon the method of mining (eg pillar and stall, longwall etc; of which no records have been made available for this study) mining subsidence may still be affecting the site.

The principle cause of ground instability is considered to be the erosion of the slopes by river action and the washout of fines in the uncompacted made ground resulting in slope recession and subsidence. The consequences of mining in the area may also be affecting the site.

3.9.2 Jackfield (Area A)

- This slope has been subject to rapid degradation by meltwaters during the last glacial period and the high groundwater levels associated with post glacial conditions.
- Currently river erosion is undercutting the valley sides and removing support at the toe of the slopes along the subunit Salthouse Road.
- Valley development has and will continue to initiate a cycle of landsliding activity as slope processes strive to reach equilibrium (ie a state of stability)
- Accelerated degradation of the slopes is aided by the relatively incompetent geology comprising interbedded clays, mudstones, sandstones and coals, and the geological dip of the beds.
- The dip of the strata is shallow (~4^{o}) towards the east which could facilitate ground movement towards the river
- The geological structure in the form of faulting may be providing conduits for groundwater and backsarps for slope movement, for example The Doughty and Tuckies Faults.
- The ground movement observed from the geomorphological mapping identified land units of multiple rotational back tilted blocks of various stages of degradation and translational (or debris) failures with secondary rotational failures.
- The presently active translational failure in the Salthouse Road sub-unit is a reactivation of the 1952 slip. Ground movement of this area is currently occurring, evidenced during a recent walkover.
- Road drainage appears to discharge directly onto the lower slope.
- The failure in 1952 was triggered by heavy rainfall and subsequent high groundwater levels, this is likely to have been the trigger for the most recent ground movement, although no data is available for actual rainfall in this period.
- The failed area of the lower slope (riverwards of Salthouse Road) contains substantial made ground deposits where the slip plane lies at the interface with the underlying clay

and further upslope the slip plane can be observed at ~5m depth within the weathered clay.

- The areas of instability coincide with areas that have been mined at shallower depths than Area B for Red Tile Clay and Sulphur Coal. The combined effect of more than one seam being mined may have involved greater bed separation of the overlying strata and subsidence, which has reduced the integrity and strength of the material resulting in the localised instability along the Salthouse Road subunit.
- The area of the 1952 slip is located on the outside bend of the river where more turbulent water erodes the toe and removes support of the ground upslope.
- Borehole instrumentation has identified that the Salthouse Road sub-unit is currently active and areas outside this sub-unit are relatively stable.
- Groundwater levels are 5m bgl on the lower slope of the Salthouse Road sub-unit and 2m to 3m bgl outside this unit. This suggests that given the slopes are currently active, slope stability is very sensitive to increases in the groundwater level.
- The sensitivity of groundwater was analysed using slope stability software and found that areas of the slope are prone to failure with a rising water table.
- Furthermore, perched water tables may occur above the in situ clay material within the relatively more permeable made ground which will further reduce the strength of the material.
- Slope stability analysis has been undertaken for typical slope profile across the Jackfield site. Analysis has required the residual soil parameters values to be used to promote ground failure at representative groundwater levels. Residual values allow for possible bed separation as a result of mining.
- Slope stability analysis identified that discrete sections of the slope had a factor of safety of less than 1 and that the whole slope was unlikely to fail en masse.
- Analysis identified that the majority of failures were relatively shallow and deep rotational failures could not be realistically modelled.
- The area of the 1952 slip was analysed to have a factor of safety near to 1 when groundwater was 2m bgl.
- Survey monitoring has identified up to 5m NNW movement since 1994 and almost 850mm of settlement in the slipped area. The average rate of movement is ~0.5m/ year.

- Outside of this area there is negligible lateral and vertical movement.

The principle cause of ground instability is considered the erosion of the slopes by river action and the high groundwater levels following periods of heavy or prolonged rainfall. The consequences of mining in the area may also be affecting the site.

The movement of the debris slide in the area of the Salthouse Road sub-unit is slow with accelerated periods of movement following high water infiltration. Figure 5 shows the ground failure model for the site.

3.9.3 Jackfield (Area B)

This area contains the Jackfield Tile Museum sub-unit of the Jackfield site.

- Slope stability analysis identified that this slope had a factor of safety greater than 1 for all realistic soil and groundwater parameters computed.
- This sub-unit has been extensively undermined for Red Tile Clay and has substantial made ground cover comprising mining and tile waste.
- Survey monitoring, during 2003, has identified lateral ground movement to the NE (towards the river) of up to 0.2m and settlement of up to 15mm.
- Part of this sub-unit failed in 1984 around the lower slope.
- Part of this slope is also located on the outside bend of the river which may have contributed to the 1984 failure, otherwise this subunit has more toe support than the adjacent slopes (ie Area A).
- Inclinometer monitoring (CP 14) identifies made ground to be slipping on in situ material, which may be subject to sub-artesian water pressures. Ground displacement is ~20mm downslope, all other boreholes show negligible displacements.
- Groundwater data suggests a uniform water table of ~2.5m bgl.
- It is possible that the Jackfield Tile Museum walls may be acting as a retaining structure to the toe of the slope.
- Mining subsidence may have resulted in a shallowing of the slope.

Although there appears to be little evidence of significant ground movement in the area, ground movement has occurred in the past and further data collection may confirm ground movement which may presently be developing.

3.9.4 Lloyds Coppice

- This slope has been subject to rapid degradation by meltwaters during the last glacial period and the high groundwater levels associated with post glacial conditions.
- Currently river erosion is undercutting the valley sides and removing support at the toe of the slopes.
- Valley development has and will continue to initiate a cycle of landsliding activity as slope processes strive to reach equilibrium (ie a state of stability).
- The relatively incompetent geology comprising interbedded clays, mudstones, sandstones and coals and the dip of the strata enables accelerated degradation of the slopes which is aided by the geological dip of the beds beneath Lloyds Coppice Fault.
- The dip of the strata is shallow (~4^{o}) towards the east which could facilitate ground movement towards the river. Above Lloyds Coppice Fault the bedding dips into the slope.
- The geological structure in the form of faulting may be providing conduits for groundwater and backsarps for slope movement.
- The Lloyds Coppice Fault may also be providing a surface or acting as a backsacrp facilitating ground slippage.
- The ground movement observed from the geomorphological mapping identified land units of multiple rotational back tilted blocks of various stages of degradation.
- Movement appears to have commenced following the period of heavy rainfall during the winter of 2002/03 which more than likely raised groundwater levels.
- The failed area contains substantial made ground deposits although the slip plane lies above a river gravel horizon.
- There are no records to suggest that mining has taken place beneath Lloyds Cottage, however, borehole logs suggest that ground has been worked ~20m bgl at a depth of a coal seam.
- The effects of mining may possibly involve bed separation of the overlying strata and subsidence, which is reducing the integrity and strength of the overlying material.
- The only recorded mining is for Red Clay from the Blists Hill pit. Geomorphological mapping identifies a graben feature, which coincides with an area of relatively shallow mining.
- This area is located on the outside bend of the river where more turbulent water erodes the toe and removes support of the slope above; recent toe erosion has been observed.

  - Borehole instrumentation has identified that the Lloyds Cottage sub-unit is currently active, with ground movement also observed in boreholes upslope of the New Houses sub-unit (near The Pond); areas outside these sub-units show no significant trend in ground movement.
  - Two distinct shear surfaces can be observed from the plots: shallow and relatively deep (~4m and 13m bgl dependent on borehole location).
  - Groundwater levels at Lloyds Cottage show groundwater level near surface level (one reading only received to date). It is considered that the near surface level of water is a major factor in slope movement.
  - Furthermore, perched water tables may occur above the in situ clay material within the relatively more permeable made ground which will further reduce the strength of the material.
  - Slope stability analysis has been undertaken for typical slope profiles across the Lloyds Coppice site. Analysis has required the residual soil parameters values to be used to promote ground failure at representative groundwater levels. Residual values allow for possible bed separation as a result of mining.
  - Slope stability analysis identified that the Lloyds Cottage slope has a factor of safety near or below 1 with conservative groundwater levels.
  - Analysis identified that the majority of failures were relatively shallow and deep rotational failures that could be modelled would fail against the dip of the bedding.
  - The other section analysed, towards the east of the site, calculated factors of safety above 1 even with relatively high porewater pressures.

- Survey monitoring has identified significant lateral and vertical movement along The Lloyds in the Lloyds Cottage and Old School sub-units. Up to 2.2m and 1.2m has occurred since 1994, respectively. Average rates of movement for the respective sites are 244mm/yr and 138mm/yr. Outside of this area there is negligible lateral and vertical movement.

The principle cause of ground instability is considered to be the erosion of the slopes by river action and the high groundwater levels following periods of heavy or prolonged rainfall. The consequences of mining in the area may also be affecting the site.

Furthermore, the Lloyds Coppice Fault maybe acting as a backscarp or a sliding surface facilitating ground movement.

4 IRONBRIDGE GORGE SLOPE STRATEGY PLAN

4.1 Introduction

It has been established in Section 2.12 – Do Nothing that further ground failure and the subsequent failure of sections of slope and road along Lloyds Coppice and Salthouse Road would threaten public safety, potentially damage property and services and cause disruption to the infrastructure and businesses of the area. Furthermore, it is not unprecedented for a landslide to partially dam the River Severn, which would cause raised water levels upstream and possible flooding. Additionally slope instability will accelerate following rapid drawdown after a flood.

Given the World Heritage Site status of the study area it is necessary to maintain the legacies of the industrial past and the safety of the public and infrastructure. The foregoing discussion has identified that not only is infrastructure, property, public access and access to the World Heritage Site at risk but that some of the assets that form the World Heritage Site are also at risk.

The do nothing scenario identifies that this scenario is unacceptable and that active intervention is required. Therefore, it is necessary to consider the options suitable to maintain the current infrastructure. These are:

- Road Diversion and realignment

For The Lloyds this is unacceptable as the alternative route would have to be diverted through the residential area of Madeley (see Figure 4.1); Salthouse Road is a cul-de-sac and therefore road diversion is not an option. Road realignment as a stand-alone option is unlikely to preserve and maintain the historic characteristics of the study area. In Lloyds Head, road realignment is likely to involve the demolition of property.

- Remedial Works

The stabilisation of the slopes and the protection of the toe of the banks from river erosion is an acceptable option that would maintain the present access within the study area. Any works would have to be designed and constructed to maintain the character of the area and to be compatible with the World Heritage Site status and the environmental sensitivity of the area.

Remedial works can be implemented as part of a management strategy. However, it is necessary to identify and prioritise actions within any management plan and a tool for doing this can be achieved by a risk assessment. A qualitative risk assessment has therefore been undertaken and details are presented in the next section.

4.2 The Risk Assessment

4.2.1 Introduction and Methodology

Previous studies have not included a risk assessment of the three sites within the study area. However, this study includes a 'desk study-type' risk assessment as a tool to identify and prioritise areas at risk to landslide, and a lesser extent rockfalls, based on historical data and the data observed from monitoring, inclinometer and piezometer instrumentation within the study area. It will be necessary to undertake a full walkover site assessment of the hazards in the future by an experienced engineering geologist in order to complete this risk assessment.

This section of the report identifies the risk to the Lloyds Coppice, Lloyds Head and Jackfield sites establishing the hazards that exist and the vulnerability of the public and property to those hazards.

The following definitions have been used:

Hazard – a condition with the potential for harm and causing an undesirable consequence (e.g. a landslide)

Risk – a measure of the severity of the consequence and probability of occurrence of a particular hazard to public health and safety and property (e.g. a member of the public being injured by a landslide or a consequence of the landslide)

Acceptable Risk – A risk for which, for the purposes of life or work, is acceptable with no further management; society does not generally consider expenditure in further reducing such risks justifiable.

Landslides – involves transportation and/or scour of superficial materials on the slopes, largely by debris slide and rotational failure downslope.

Rock falls – involve the instability associated with individual boulders and rock blocks exposed from the crest of the slope above Lloyds Coppice. Failure initiates block movement downslope. The blocks roll, slide and/or bounce until they come to rest on the slope.

Data provided by Halcrow (1990) and Babtie (2003) identifies a number of landslides that have occurred since the 1700's. The data that has been recorded are the landslides that have damaged property or infrastructure. No information is recorded on the size of the material that has slipped. Records are unlikely to include landslides where there was no human consequence. Rockfalls have occurred in the past, based on boulders observed on the slopes of Lloyds Coppice during the site walkover, however, relatively few boulders were observed and hence this is considered a low frequency event.

Because of the lack of historic data detail (ie magnitude and extent of landslide) and a detailed geomorphological map identifying ground behaviour units, it has not been possible to complete a rigorous quantitative risk assessment for the study area. Therefore, a qualitative assessment was considered appropriate based on data available and the proximity of the property, infrastructure and the public to the hazard based on plans of the area.

The study area has previously been divided into a series of slope sub-units (see Figure 2.2). These sub-units have been used for the risk assessment to maintain some consistency of areas at threat from ground movement. It should be noted that a detailed walkover survey of each area has not been carried out as part of this assessment.

4.2.2 The Nature of the Hazards

Evidence for large-scale historical instability can be observed intermittently along the valley slopes, and this together with historical records provides qualitative information from which judgements on the scale of historic failures may be made.

Generally there are likely to be precursory indicators to large-scale failure events (e.g. large-scale failures are usually preceded by the development of tension cracks). The terrain and extent of the slopes make regular monitoring and inspection necessary and this is currently being addressed by TWC.

The development of a slope risk assessment involves identifying the principal types of hazard. The slope instability problems evident along the slopes in the study area which may be a hazard are:

- Small landslides: debris slides involving the upper ~5m of the material
- Deep seated slides: multiple rotational failures which may develop retrogressively upslope
- Reactivation of shallow and deep seated rotational failures
- Rockfall from the exposed escarpment along the crest of Lloyds Coppice

The nature of the hazard is primarily from landslides. The ground failures present potential risks to the Salthouse and Lloyds Coppice Roads, and properties located at the toe of the slopes and people in the area, as follows:

- damage and potential loss of properties along Lloyds Coppice Road and Salthouse Road
- disruption to infrastructure by the potential severance of a road
- injury to persons using the roads in/out of Jackfield and the roads north and south of the Severn;
- potential damage to vehicles using the roads;
- landslide damage to The Lloyds and Salthouse Road possibly resulting in a traffic accident;
- landslide debris could block the roads restricting access to properties and Ironbridge access routes from the east and south, resulting in the loss of work while the debris is removed and disposed, invoking additional financial costs;
- potential risk to the public walking on the roads and the slopes during a major failure;

- potential loss of a road as a result of a major ground failure causing costly delays, diversions to traffic and construction costs;
- loss of vehicle and/or traffic incident (with person/s in the vehicle) using the road where a major/minor slope failure occurs;
- potential damming of the river from major landslide and the potential for water levels (and flooding) to increase upstream;
- rapid discharge of the dammed area with potential flooding downstream;
- increased rates of erosion of the banks and river bed downstream on release of dam water from a landslide extending into the river.

4.2.3 Incidence of Hazard and Its Relation to Rainfall

The level of risk is assessed by consideration of the magnitude of the hazard and frequency of occurrence within the study area. A small isolated failure may occur at any time, without any warning. The probability of a member of the public being injured by such an event is considered low based on the following:

- the frequency of failures is relatively low (approx. one per year); and/ or,
- the rate of the failure is very slow or not noticeable on a day-to-day basis.

However, the density of people using the access roads and living in the areas of study is relatively high. Therefore, it is likely that persons would be affected by a landslide, but given that historic failures have typically been slow it is considered unlikely that persons would be seriously injured or would be injured by primary landslide activity.

With regard to rockfall at Lloyds Coppice, the probability of a person being struck by a rock is approximately proportional to the size of the fall; and there is a greater probability of minor injury than serious injury. The time of the day and the time of year that a fall occurs will also affect this probability. The density of people using Lloyds Coppice is considered low and the slope gradient and vegetation growth are likely to result in the rock being arrested well before the road or property downslope. The occurrence of small isolated rockfalls, likely to fall following heavy rainfall/ freeze-thaw action is considered an acceptable risk and has not been considered any further.

The historical data are shown in Appendix E, illustrates the incidence of landslides and their locations. An analysis of this data records the following from 1925 to 1990:

- Total number of landslides recorded: 72
- Percentage of landslides to have affected Lloyds Coppice: 48%
- Percentage of landslides to have affected Jackfield: 38%
- Percentage of ground movement to have affected Lloyds Head: 14%
- Total injury incidents in separate incidences: 0
- Total fatalities in separate incidences: 0

The data above would seem to indicate that nearly half the landslides have occurred at Lloyds Coppice. But, most of the records observed have involved utility services damage. The only reported non-service damaged landslips occurred in 1925, 1931, 1936, 1952-53 and 1984 (Halcrow, 1990, after Brown, 1975); these failures apart from the 1936 slip (at Madeley Wood) all occurred at Jackfield. Simple statistical analysis suggests the following magnitude of risk in incidents per year:

- Personal Injury 0
- Fatal injuries 0
- Damage to property and infrastructure 0.86

4.2.4 Risk Rating System

The consequences of failure cannot be predicted with any certainty, but can be expressed in a qualitative fashion to give a relative risk rating based on the hazard and vulnerability of the public and property. The basis for this approach to scoring each section is:

- High hazards + high vulnerability to the public and property = high risk
- Low hazards + low vulnerability to the public and property = low risk

and combinations between these extreme cases. Intermediate categories can be assigned, and on this basis a high*, high, medium and low rating system has been developed for the study area. A summary of the risk rating designations and which areas fall into which risk category is given in Table 4.1 below.

TABLE 4.1 RELATIVE RISK RATING

Risk Rating	Description of Risk	Consequence of Risk	Remediation Requirement	Risk Category for each Sub-Unit
Low	**Low risk:** to the public and property from their location adjacent to areas of historic landsliding. .	Low risk sections require periodic visual inspections in order to check for deterioration of the slopes.	No immediate requirement of remediation other than monitoring.	Nil
Medium	**Medium risk:** as per risk rating Low; and including areas of historic landsliding and areas adjacent to areas of current landslide activity.	Slope hazards can be defined but further deterioration is required prior to the probable onset of instability. Remediation is considered necessary in the future; these sections require periodic visual inspections in order to monitor further deterioration of the slope. Total failure of the sheet pile wall may result in ground movement unless replaced.	Remediation required within c.5 years to reduce risk	Jackfield Tile Museum, Lloyds House Salthouses, Tuckies
High	**High Risk:** as per risk rating Medium; and including the areas of current landsliding that may affect people, property and infrastructure	These areas present slope hazards that can occur in the near future and are of a risk to the public but are not considered as high a priority in terms of remedial action compared with the High* Risk sections. Provision for remedial engineering works should be included for in future budget planning. Regular monitoring and inspections should be undertaken in the intervening period until remediation is implemented.	Remediation required within c.2 years to reduce risk.	Salthouse Road (part), Old School
High*	**High* Risk:** Conditions generally as risk rating High, but located at areas where people, property and infrastructure are currently affected by landsliding	These areas comprise the greatest risk to the public in the immediate future and are considered to be priority areas for remedial action. The state of instability is such that immediate provision is required for remedial engineering works.	Urgent attention required to reduce risk either by remedial works or using an early warning monitoring system.	Lloyds Cottage, Salthouse Road (Jackfield Slip Area)

Notes:
1 Time periods quoted are illustrative reflecting a combination of a realistic manageable budget and the perceived urgency, and should be subject to revision in light of unforeseeable future events, such as accelerated movement in the Jackfield slip area.

2 Note without a quantitative risk assessment the frequency of failures cannot be realistically resolved

The treatment of risk in this manner highlights the areas where mitigation measures are priority, and those areas where provision is required for future treatment within a strategy framework.

Notwithstanding the fact that some areas have a lower priority for remedial action, vigilance is required since isolated slope failures can occur along the valley side. On going observations and monitoring should identify changes in slope conditions and the potential for isolated failures within the time spans indicated within the above timetable.

The risk assessment forms the primary element of the Slope Management Strategy. This risk assessment is not a static document, and the priority of areas displaying the highest risk will change in response to dynamic processes (such as subsidence from mining) acting on the slopes. All areas should have ongoing monitoring and as appropriate the risk rating should be revised in accordance with changing circumstances.

4.3 The Slope Management Strategy

The risk assessment above has identified priority areas for future monitoring, further studies and remediation.

Having defined that an unacceptable risk is present in specific sections, various options are available to mitigate these risks. All options for addressing slope hazards can be placed into one of the following three categories:

Protection – containing the effects of landslides, or isolating the public from such effects by:

- removing the public from the toe of the slopes.
- warning signs to alert the public to the hazards (In this context it is appropriate to refer to 1998 Case Law[1] where injury resulted to a member of the public caused by a cliff fall. In the judgement the Local Authority was found in breach of its common law duty when providing public access to a beach subject to erosion and cliff falls without appropriate warning signs).

[1] Annon (1998) High Court of Justice Queens Bench Division 1993 K No.1000, 1994 k No.238

Prevention - reducing the occurrence of any landslide by engineering works. Selection of the engineering intervention will dependent on the specific nature of the hazard. Intervention techniques specific to the study area are described in Section 4.7.

Monitoring –monitoring to ensure that remediation is employed before the onset of significant instability. This involves an acceptance of an element of risk. Monitoring may be undertaken by:

- visual inspection and measurement on a routine basis. Specific features may be monitored by visual means or where access allows by measurements of open tension cracks etc.
- Remote instrumentation. Automatic monitoring systems are available that can measure displacements and can be remotely interrogated to ascertain movement in critical parts of the study area. Such systems can include alarms to alert to the onset of instability (early warning systems).

4.3.1 Development of the Strategy

A number of fundamental principles must be addressed to provide a framework for the development of a management strategy. These are:

- To continue the regular programme of slope monitoring and record the data.
- Ensure that the data received has been analysed for errors (eg inclinometer data)
- Increase the frequency of monitoring during the rainy season.
- Record all future landslide events in detail for use in future quantitative risk assessments or research, whether or not these have an impact on property or roads. Details such as landslide size, location, time, weather, run-out distance, material, etc should all be recorded.
- Frequent inspections and structural surveys of buildings and retaining walls in the areas of relative risk of landslide movement for signs of ground movement (eg cracked walls, difficulty closing doors, tilting floors, etc), such as The Jackfield Tile Museum and other buildings which may affect WHS status.

- Develop contingency plans to implement safe stabilisation measures should the slope monitoring reveal evidence of a deterioration of the slopes that could lead to instability.

- Develop contingency plans for the immediate emergency response to rare, but potentially very serious, stability problems,

- To ensure that all elements of the management strategy enhance or maintain the environment

The finalisation of the scope and content of the future detailed Slope Management Strategy will require input from all relevant departments of the TWC, representatives of the World Heritage Site organisation and interested Third Parties (eg EA). Key issues such as the political considerations related to public use of the slopes, availability of resources, environmental and aesthetic aspects etc will form an important part of the strategy.

Actions required by the management strategy will vary along the slopes within the study area, reflecting the range and urgency of the potential problems. Table 4.3 summarises the overall hazard and risk in each section and gives general recommendations for managing the risks identified. Further detailed recommendations for each part of the study area are given below in Sections 4.4 to 4.6. It should be emphasised that a detailed survey of all slopes should be undertaken in order to assess the exact requirements for both preventative and protective measures.

4.3.2 Implementation of the Strategy

The implementation of the Slope Management Strategy requires the instigation of a programme of prioritised actions including prevention of landslides in the most critical areas; protection of the public, further investigations and future monitoring. Key elements for the implementation of the Management Strategy include:

- The development of recording procedures during inspections of the slopes;

- The development of a programme of maintenance works that are defined as necessary in the short and medium term;

- Revising and updating the geomorphological map for the study area and developing ground behaviour definitions;
- A topographic survey and detailed engineering assessment of the study area slopes;
- Development of detailed engineering options and solutions in the first instance, for each of the High and High*priority sections arising from the study;
- Develop a programme of works and cost profile for strategy implementation at the High/ High* sites;
- Inspect all retaining structures and undertake remediation as necessary (such as the sheet pile wall at river bank level in the Lloyds House area and the Jackfield Tile Museum);
- A full review of the inclinometer data;
- A 5-yearly review of the management strategy, taking into account changing priorities and improved understanding of the slope processes.

Furthermore, it is recommended that the local population and interested parties are engaged in the slope management strategy through public consultation. The public consultation process will increase the awareness of the Council Members, World Heritage Site management, the local population and key stakeholders by way of presentations, meetings and discussions. In addition, advice to the public, especially tourists visiting the museums and areas of historic importance, on the potential hazards of landslides or that potentially hazardous areas have adequate warning to the public of any dangers. The form, content and location of the notices on the slopes and at each of the main access points to the valley slopes should be identified.

4.4 Jackfield Strategy

The following strategy has been identified for the Jackfield site, in no particular order of priority:

- Continued monitoring of inclinometers, piezometers and monitoring pins on a regular basis to identify trends of movement;
- More regular existing piezometer readings in the active zones of the study area;

- Liaison with utility services to identify date and exact location of damage to services;
- The installation of a weather station to monitor rainfall;
- The installation of real-time monitoring instrumentation to identify and measure the rate of movement and groundwater levels in the Jackfield slip. This can then be compared with weather data (ie effective rainfall);
- Updating the geomorphological map of the study area to confirm the ground behaviour of the Jackfield slopes;
- Ground investigation and the installation of borehole instrumentation up slope of the recent ground investigation in order that potential retrogressive failures and lateral ground movement can be identified and to identify the properties of the faults within the site area;
- Frequent inspections and structural survey of buildings and retaining walls in areas of relative risk of landslide movement for signs of ground movement (eg cracked walls, difficulty closing doors, tilting floors, etc), such as The Jackfield Tile Museum;
- Co-ordination with the Environment Agency to identify hydraulic processes of the River Severn with particular emphasis to the study area and its susceptibility to river erosion and potential remedial works;
- Co-ordination with land owners over riparian ownership of the riverbanks;
- Co-ordination with the service authorities who have services within and above Salthouse Road and other roads, to ensure any maintenance carried out does not have any adverse effects on slope instability;
- Develop a contingency and action plan for areas where major failure or blockage of roads may occur, ie to ensure access for emergency vehicles and utility companies, short-term rehousing, meeting health & safety requirements, etc.; and,
- Develop an emergency remedial works strategy should failure occur and sever the Salthouse Road and its services.

4.5 Lloyds Coppice Strategy

With regard to the **Lloyds Coppice** site, the potential for road failure and loss of access between Coalport and Ironbridge requires urgent remedial works at Lloyds Cottage. During the finalisation of this report, TWC commissioned further studies in the Lloyds Cottage area including additional ground investigations, topographic survey and the design of a remedial scheme. However, for the purpose of this report, the urgent actions recommended, and now completed, have been listed below for completeness. The ground movement observed and current rate of displacement is considered critical. There is a serious threat that the road might be severed in this location in the near future particularly with the onset of winter following a particularly dry summer. Therefore, the site specific requirements are:

- **URGENT** updating of the geomorphological map of the study area to confirm the ground behaviour of the Lloyds Coppice slopes;
- **URGENT** further ground investigation and the installation of borehole instrumentation up slope of the recent ground investigation in the area of Lloyds Cottage to allow shear surfaces and lateral extent of ground movement to be determined, and to understand the faulting in the area;
- **URGENT** undertaking of a topographic survey of the Lloyds Cottage area;
- **URGENT** undertaking of detailed design of the remedial works to the Lloyds Cottage area of failure, including river bank protection and slope stabilisation measures, which could include mechanical stabilisation (eg piles) and drainage;
- Continued monitoring of inclinometers, piezometers and monitoring pins on a regular basis to identify trends of movement;
- Regular monitoring of the failed sheet pile wall at the Lloyds House riverbank with remediation/ replacement of the sheet pile wall as required by the monitoring results;
- more regular piezometer readings in any actively moving landslide zones of the study area (to be determined following geomorphological mapping);
- Liaison with utility services to identify date and exact location of damage to services;

- Co-ordination with land owners over riparian ownership of the riverbanks;

- Use the weather station proposed at Jackfield to monitor rainfall, together with more regular piezometer readings in the actively moving landslide zones of the study area (ie Lloyds Cottage and the School House area);

- Develop a contingency and action plan for areas where major failure or blockage of roads may occur, to ensure access for emergency vehicles and utility companies, short-term rehousing, meeting health & safety requirements, road diversions, etc.;

- Co-ordination with the service companies who have services within The Lloyds, to ensure any maintenance carried out does not have any adverse effects on slope instability; and,

- Develop an emergency remedial works strategy should failure occur and sever The Lloyds.

4.6 Lloyds Head Strategy

The Lloyds Head site is subject to riverbank erosion and subsidence. Although it is considered that no infrastructure or property are at immediate threat from either of the above hazards, it is necessary to consider remedial works within the next two years before any assets are placed at significant risk and vehicular access is lost between Coalford and Jackfield.

The following points identified as part of the strategy should therefore be considered within the short term (ie 2 years):

- Continued monitoring and the implementation of a regular programme of crack mapping and spot levels to monitor ground movement and subsidence;

- Co-ordination with land owners over riparian ownership of the riverbanks;

- Further investigations to identify extent of any slip upslope by using inclinometers and mapping;

- Subsurface investigation into extent of tile waste deposits (ie by trial pits);

- Investigations into most suitable method of river bank protection;

- Development of design strategy for the prevention of further subsidence (ie grouting);
- Develop an action plan: emergency vehicle access, utility services, etc; develop a remedial works strategy; and,
- Develop contingency plans for a failure event: ie emergency works.

4.7 Options for Remedial Works

No single solution is likely to prevent the downslope movement of ground across the study area, any remedial works to prevent further slope movement is likely to require mechanical stabilisation and slope drainage.

Furthermore, river erosion of the toe of slopes has been identified to be a principle component in triggering slope failure; therefore, it is necessary to undertake riverbank protection measures as part of any slope stabilisation remedial measures.

There are no single engineering solutions to the slope instability and various methods and in some cases a combination of slope stabilisation methods are required in places such as the Lloyds Coppice and Jackfield sites. Potential engineering options are shown in Tables 4.2a & 4.2b, for slope stabilisation and toe protection.

There are few feasible options for protecting the river bank slope at Lloyds Head and preventing further subsidence. The height of the river bank and the limited land width above prevents the use of reprofiling and soft engineering option techniques of protection. A solid structure is required to prevent further washout of fines from between the tile waste and to provide suitable protection against river action. All options will require suitable foundations and may include methods such as gabion baskets, a mass concrete wall with an energy-dissipating fascia, or a combination of geotextiles and rock armour.

Further discussion with the Environment Agency will be required to agree any toe protection works within 8m of the waters edge.

TABLE 4.2a SUMMARY TABLE OF OPTIONS FOR PROACTIVE INTERVENTION FOR SLOPE STABILISATION FOR JACKFIELD AND LLOYDS COPPICE

	ENGINEERING CONSIDERATIONS		FEASIBILITY	ENVIRONMENTAL CONSIDERATIONS				
OPTIONS CONSIDERED	**STABILITY**	**BUILDABILITY**	**WITH RESPECT TO EXISTING ACCESS**	**SCALE OF WORKS**	**IMPACT ON FLORA AND FAUNA**	**AESTHETIC VALUE**	**COST**	**SUMMARY**
DO NOTHING **Short Term**	DETERIORATES	N/A	N/A	N/A	NIL	N/A	UNACCEPTABLE[1]	UNACCEPTABLE
SHALLOW DRAINAGE **<5m depth**	POOR	EASY	FEASIBLE	MINOR	MINOR	GOOD	LOW	ACCEPTABLE NOTE 2
DEEP DRAINAGE **>5m depth**	MODERATE	MEDIUM	FEASIBLE	MINOR	MINOR	GOOD	MEDIUM	ACCEPTABLE NOTE 2
SHEAR KEYS	GOOD	V HARD	FEASIBLE	MODERATE	MODERATE	MODERATE	MODERATE	NOTE 3
REINFORCED EARTH	MODERATE	MEDIUM	FEASIBLE	MODERATE	MODERATE	MODERATE	MODERATE	ACCEPTABLE NOTES 2,3
BORED PILES	GOOD	MEDIUM	FEASIBLE	MODERATE	MINOR	GOOD	MODERATE	ACCEPTABLE
SLOPE REPROFILING	MODERATE	HARD	UNFEASIBLE at Lloyds Coppice FEASIBLE at Jackfield	MODERATE	MAJOR	MODERATE	MODERATE	NOTE 3

NOTES:
1 Potential severance of The Lloyds in the Lloyds Cottage area, and with regard to Jackfield possible prevention of access along Salthouse Road to the Tuckies
2 Not a feasible single option, should be used in conjunction with other techniques.
3 Requires preliminary design to determine whether feasible or not and compatibility with river bank protection measures

TABLE 4.2b SUMMARY OF RIVERBANK TOE PROTECTION OPTIONS CONSIDERED FOR PROACTIVE INTERVENTION FOR JACKFIELD AND LLOYDS COPPICE

OPTIONS CONSIDERED	ENGINEERING			BUILDABILITY/ FEASIBILITY	ENVIRONMENTAL			COST	SUMMARY
	TOE PROTECTION	STRUCTURE STABILITY	HYDRAULIC PERFORMANCE		SCALE OF WORKS	IMPACT ON FLORA AND FAUNA	AESTHETIC VALUE		
DO NOTHING Short Term	DETERIORATES	N/A	DETERIORATES	N/A	N/A	NIL	N/A	NIL	UNACCEPTABLE
TOE PROTECTION STRUCTURES									
ROCK ARMOUR	GOOD	GOOD	V GOOD	HARD	MODERATE	MODERATE	MODERATE	MODERATE	ACCEPTABLE
MASS CONCRETE	GOOD	GOOD	POOR	MEDIUM	MODERATE	MAJOR	POOR	MODERATE	UNACCEPTABLE
REINFORCED EARTH	GOOD	GOOD	POOR	MEDIUM	MODERATE	MODERATE	MODERATE	LOW	UNACCEPTABLE
SOFT OPTIONS Eg wood, wattles, willow, faggots, etc	MODERATE	POOR	MODERATE	EASY	MODERATE	MINOR	GOOD	LOW	UNACCEPTABLE
GEOTEXTILES Eg woven polyester, coir, geogrid	GOOD	POOR	GOOD	EASY	MODERATE	MODERATE	MODERATE	LOW	UNACCEPTABLE
GABIONS	GOOD	GOOD	GOOD	MEDIUM	MODERATE	MODERATE	GOOD	MODERATE	ACCEPTABLE

NOTES

The above is not an exhaustive list of possible options. Discussions will be required with EA and land owners to identify the most suitable option

4.8 Summary of Remedial Recommendations

Table 4.3 summarises recommendations for remedial measures on a section-by-section basis (see Figure 2.2 for section locations). More details of the options for engineering intervention are given in Tables 4.2a & 4.2b in Section 4.3 above. The recommendations have been derived from the monitoring data and risk assessment and take into account the potential for instability and risk to the public using the slopes and property. It should be noted that, the recommendations represent the minimum level of intervention considered necessary to reduce the risks to an acceptable level, given the extent of landslide potential within the study area. The relative quantitative risk assessment undertaken as part of this study is based on data taken from previous studies and monitoring results to date and so, the recommendations reflect the conditions apparent at the time of the desk study. Revision may be necessary in the future arising from changes in the slopes and from results of future observation and monitoring.

The common recommendation for areas of High and High* risk to install slope instability prevention measures largely reflects the risk from landslides that are to a greater or lesser extent common to the entire slope lines. It may be considered that protective and monitoring measures (i.e. warning signs and early warning systems) on some slopes may prove sufficient as part of the slope management strategy. This may be undertaken over a strategic timescale, which is compatible with the management strategy, for instance 5 years. These measures would be sufficient to remove the immediate threat to properties along the base of the slopes. However, the Salthouse and Lloyds Coppice Roads would still be susceptible to potential landslide damage and would require preventative measures up slope to provide a risk considered acceptable to house-holders and road users. It is important to emphasise that slope instability is largely a result of the loss of support of the toe by river action and high groundwater conditions. In general, any remedial works must include toe protection of the river banks to ensure long term stability.

These remedial recommendations will form part of the slope management strategy. The recommendations are a combination of landslide protection and prevention. Ongoing regular monitoring is a vital part of the management strategy and is not detailed specifically in these recommendations.

Figure 4.2 identifies the area where engineering works are required and their location.

TABLE 4.3 SUMMARY OF REMEDIAL RECOMMENDATIONS

Section No.	Location	Relative Risk Rating	Nature of Hazard/ Risk	Remedial Recommendation	Timeframe for Remediation
Lloyds Coppice	Lloyds Cottage (Wesley Road Junction and area to east of Lloyds Cottage)	High*	Very high potential for further ground failure and severance of Lloyds Road. High risk to persons and property as building lies directly on landslide block. Potential for slide to extend to lower slopes and partial damming of river (resulting in consequential accelerated erosion on the opposite bank).	Further ground investigations to identify slip surface profile and local ground conditions. Surface crack and ground behaviour mapping. Detailed topographic survey. A combination of river bank toe protection, mechanical slope stabilisation and drainage to maintain present road alignment and infrastructure.	**Urgent** attention required to reduce risk
	Old School	High	High potential for similar type failure to Lloyds Cottage.	Further ground investigation to identify subsurface condition. Further monitoring, ground behaviour mapping and site inspections.	Dependent upon further studies, which are required within one year
	Lloyds House	Medium	Potential for shallow ground slippage and translational ground movement in isolated areas. Current activity is unrecorded although this is likely to occur as the lower slopes are eroded by river action. Failure of the sheet pile wall may result in rapid ground movement	Continued monitoring and updating of ground behaviour map	Further studies to be undertaken within one year and continued monitoring, especially of the failed sheet pile wall area
Jackfield	Jackfield Tile Museum	Medium	Potential for main slip area to extend laterally, resulting in further damage to Museum. Also potential for curtaining wall failure and consequential ground movement damaging the Museum.	Continued monitoring and updating of ground behaviour map. If the Jackfield slip area is left untreated, there is the potential for ground failure to extend into this area	Further studies to be undertake within one year; continued monitoring and structural survey.
	Salthouse Road (Jackfield Slip Area)	High*/ High	Active ground movement currently occurring as a result of toe erosion and high groundwater levels. Potential further displacement of road if left untreated and possible total loss. Potential for damage to properties and other buildings.	Ultimately, this area will require remedial works to arrest downslope movement. The rate of movement is slow, but may accelerate with time. This area requires interim real-time ground instrumentation prior to the remedial works toe protection and slope drainage. Should the area be untreated for some time, mechanical stabilisation may be required in addition as the failure retrogresses.	Installation of site specific subsurface instrumentation within 6 months, preferably before Winter 2003/4. Remedial works within 2 years.
	Salthouses	Medium	Potential for downslope movement as a natural consequence of valley development. Potential displacement of road. Potential for damage to buildings.	Although data shows less ground movement than at Salthouse Road, the area has been active in the past. The number of properties in the area causes some concern, although this area does not appear to have the recorded deposits of mine waste on the slopes as the Jackfield slip area	Further studies to be undertaken within one year and continued monitoring
	Tuckies	Medium	Potential for downslope movement as a natural consequence of valley development. Potential displacement of road. Potential for damage to buildings.	Although data shows less ground movement than at Salthouse Road, the area has been active in the past. The number of properties in the area causes some concern, although this area does not appear to have the recorded deposits of mine waste on the slopes as the Jackfield slip area	Further studies to be undertaken within one year and continued monitoring
Lloyds Head	Lloyds Head	High	Potential for further river bank erosion. Most properties are a suitable distance away from the river from immediate threat of damage, however, further erosion will reduce safe construction work space for future remedial works. Further subsidence/ compaction is likely to occur possibly as a result of mining and from the washout of fines as the unconsolidated river bank is eroded. Any delay may result in damage to roads and property within the area.	A combination of river bank protection and ground stabilisation to prevent further subsidence.	**Urgent** crack mapping and sub surface investigation to enable remediation within c.2 years

4.9 Telford & Wrekin Management Plan

The Telford & Wrekin Management Plan identifies the Ironbridge Gorge area as a World Heritage Site, based on Ironbridge and the legacies of its industrial past, and as an Area of Special Landscape Character (ASLC).

ASLC's are non-statutory designations and are considered for areas where normal planning policies cannot provide sufficient protection to the area. Any development, which is likely to adversely affect the characteristics of the area, either directly or indirectly, is unlikely to be permitted unless it can be demonstrated that benefits will far outweigh the loss of character of the area.

The Management Plan also states that any loss of habitat must be "… fully compensated for by the creation or enhancement of other habitats of equal or greater value in the local area."

4.10 Programme

It is recommended that the design and necessary studies and surveys (including planning requirements, highway notices and licences, etc) should be undertaken immediately for the Lloyds Cottage area, with a view to commencing work as soon as is feasibly possible (Refer to Table 4.3). Ideally, the mechanical slope stabilisation work should be completed before the rainy season expected during the winter of 2004/05.

Special permission should be sought from EA regarding working near to the riverbank, and possibly due to the time of year.

With regard to the study area as a whole, it is necessary to continue monitoring borehole instrumentation and undertake regular inspections of the slopes especially during Winter and Spring, or following prolonged and/ or heavy rainfall. Monitoring should be undertaken on a regular basis until a trend can be identified and subsequent monitoring can be reduced or increased as necessary. All studies and surveys recommended in Table 4.3 should be undertaken by the end of 2004.

It would be advisable to undertake the geomorphological mapping to establish ground behaviour in the Spring before vegetation develops.

The ground investigation at Lloyds Cottage should be undertaken as soon as possible to confirm the profile and extent of the slip plane and the ground conditions in the area; should funds be available it would be economically advisable to undertake the remaining boreholes recommended in this study at the same time.

The early warning instrumentation recommended at the Jackfield slip area is recommended to be installed as soon as possible in order that any ground movement this winter can be monitored.

The Lloyds is the major highway access for residents and tourists through the World Heritage Site, and major works are not recommended in the height of the tourist season.

Consideration will have to be given to construction plant access. Should reinforced concrete bored piles be the preferred option a number of cement lorries and large plant will require access to the Lloyds Cottage; this may require discussion with the planning authority and the residents and businesses of Ironbridge.

It would be preferable to undertake riverbank protection works during the summer when stream levels are low, although it is not impossible to construct such measures during periods of high water.

4.11 Health & Safety

The following points are the principle considerations that must be given to any works in the study area from design stage onwards, as part of the Construction Design and Management (CDM) regulations

- working on unstable slopes
- near water and potential flooding events
- working near roads
- plant access
- provision for workforce and members of the public safety

- site safety

As part of any works full risk assessments must be provided during the tender period.

4.12 Study Uncertainties

A number of uncertainties have been identified during the Study, including:

- slope instability and potential deep-seated failures of the valley slopes, which threaten the flow of the River Severn, infrastructure and present a risk to public safety. The timing of these one-off events is extremely difficult to predict. Nevertheless, the potential for a significant deep-seated failure during the immediate future at Lloyds Cottage, has been recognised and the ongoing downslope movement at Jackfield.

- the failure of the river banks as a result of flooding and lateral erosion of the toe of the slopes. This risk is increased at times when river levels are high, which often coincides with storm conditions. The failure and erosion of river banks is more prominent on the outside of a bend or where a failure has occurred on the opposite bank causing river narrowing. It is also of concern where man-made deposits within the river has resulted in turbulent flow (eg at the canoe club).

- The breach and subsequent failure of the retaining wall structures along the river and along The Lloyds. This could lead to a dramatic increase in ground failure and further instability upslope as support is lost.

- Loss or closure of The Lloyds road as a result of landsliding (currently partially closed at Lloyds Cottage). It is anticipated that this would lead to significant traffic disruption losses and create major re-routing problems for the highway authority.

Key areas of uncertainty associated with the identification of suitable management strategies for risk reduction are summarised in Table 4.4. These uncertainties generally relate to the need to base many aspects of the appraisal on expert judgement of the current and future risks and, in the absence of reliable information, the need to make assumptions about the anticipated consequences of particular events. Clearly these uncertainties need to be further addressed and would be incorporated into a quantitative risk assessment.

TABLE 4.4 SUMMARY OF STUDY UNCERTAINTIES

Area of Uncertainty	Issue
Problem Definition	• Reliance on expert judgement to assess the likelihood/timing of slope failure and of erosion • Reliance on engineering judgement to assess the likelihood of river bank failure • Uncertainty over the effect of climate change on the level of risks • Uncertainty as to whether all potential failure models have been identified
Data Provided	• Reliance on third party studies • Accuracy and determination of mapping • Ground conditions determined from boreholes represent regional site conditions • Certainty of borehole logging • Lack of sub surface detail in some boreholes • Accuracy and methodology of testing • Accuracy and validity of inclinometer monitoring • Incomplete mining records • The structural integrity of the retaining walls throughout the site (e.g. Jackfield Tile Museum and Lloyds Cottage gabion walls)
Appreciation of Processes	• The interaction between river levels and slope performance • The significance of internal slope processes (e.g. weathering, groundwater levels, mining) and the role of drainage failure in promoting landslide events • The potential for small slides to expand and trigger large, deep-seated landslides
Performance of existing riverbank protection	• The flooding performance during low probability conditions (e.g. high river levels) • The vulnerability of the river defences to a combination of intense rainstorms (i.e. rapid surface water runoff) • No monitoring data on the failed sheet pile wall near Lloyds House
Environmental	• The sustainability of the important tourist and public access routes in areas of potential ground failure • The acceptability of the necessary improvements to the slopes and river banks
Timing and Planning	• The prioritisation of urgent works is based on a desk study and monitoring data (year 2003) without a recent geomorphological survey of the area and a quantitative risk assessment. Either or both of these factors could change in the future

Furthermore, detailed information is missing from some borehole logs where open holing has been the preferred method.

The nature of the ground in which boreholes have been sunk has been mined at different levels. The returns from particular levels of gravels, voids, highly fractured core, may possibly be worked horizons. When cross-checked with the stratigraphy some of these horizons are not compatible with known recorded mining levels. It is understood from the data provided that mining records are not complete, and that mining has not always been accurately or spatially recorded. This is likely to affect slope stability analysis that has largely been calculated on known horizons.

5 SUMMARY AND CONCLUSIONS

A desk study has been undertaken of the Ironbridge Gorge Landslide areas and has included the interpretation of the recent ground investigation. The data provided has been made available by TWC.

The areas of ground movement have been identified and the types of failures have been determined, given the data provided.

It has been established that ground movement in particular areas is currently active and has affected most of the study area in the past. Ground movement is essentially the consequence of valley development, which has been accelerated through the end effects of a glacial period, relatively incompetent strata and human influence.

Ground movement has also coincided with areas where mining has been undertaken. Mining alone cannot be substantiated to have triggered ground movement in the study area. However, the effects and the method of mining any workable mineral as the shaft progressed is likely to have affected and disturbed the overlying strata.

The study area will continue to fail until the valley reaches maturity or remedial works are undertaken.

It has been determined that as a consequence of ground movement significant historic buildings will be damaged and ultimately demolished in response to Health & Safety requirements. This may affect the current designation of World Heritage Site status.

To maintain World Heritage Site status and to retain the current infrastructure it has been determined that remedial actions should be implemented. This has been undertaken by setting out the guidelines for a slope management strategy. The management strategy was achieved by assessing the hazard and risk across the study area and prioritising actions in order to either prevent further ground movement or protect persons/ property from ground movement.

The management strategy has recommended a number of actions ranging from continued monitoring to urgent remedial works. Table 5.1 summarises the remedial actions for the site areas described within the report and the basis for making these recommendations.

The slope strategy identified for the study area is summarised below and followed by site specific recommendations for the Jackfield, Lloyds Coppice and Lloyds Head areas:

- Undertake a quantitative risk assessment in conjunction with the updating of the ground behaviour mapping
- Continued monitoring of inclinometers, piezometers and monitoring pins on a regular basis to identify trends of movement;
- Continued monitoring of inclinometers, piezometers and survey plans;
- More regular existing piezometer readings in the active zones of the study area;
- A thorough diagnostic review of all inclinometer data;
- Liaison with utility services to identify the exact location of damage to services;
- The installation of a weather station to monitor rainfall;
- Updating the geomorphological map of the study area to confirm the ground behaviour of the slopes;
- Co-ordination with the Environment Agency to identify hydraulic processes of the River Severn with particular emphasis to the study area and its susceptibility to river erosion and potential remedial works;
- Co-ordination with land owners over riparian ownership of the riverbanks;
- Develop a contingency and action plan for areas where major failure or blockage of roads may occur, ie to ensure access for emergency vehicles and utility companies, short-term rehousing, meeting health & safety requirements, etc.

With regard to the Jackfield slopes, the slope strategy specifically recommends:

- The installation of real-time monitoring instrumentation to identify and measure the rate of movement and groundwater levels in the Jackfield slip. This can then be compared with weather data (ie effective rainfall);

- Ground investigation and the installation of borehole instrumentation up slope of the recent ground investigation in the Salthouse Road area in order that potential retrogressive failures and lateral ground movement can be identified and to identify the properties of the faults within the site area;

- Frequent inspections and structural survey of buildings and retaining walls in areas of relative risk of landslide movement for signs of ground movement (eg cracked walls, difficulty closing doors, tilting floors, etc), such as The Jackfield Tile Museum;

- Co-ordination with the service authorities who have services within and above Salthouse Road and other roads, to ensure any maintenance carried out does not have any adverse effects on slope instability;

- Develop an emergency remedial works strategy should failure occur and sever the Salthouse Road and its services.

With regard to the Lloyds Coppice site, the potential for road loss and access between Coalport and Ironbridge requires urgent remedial works at Lloyds Cottage. The ground movement observed and current rate of displacement is considered significant. There is a serious threat that the road might be severed in this location in the near future. Therefore, the site specific requirements are:

- **URGENT** updating of the geomorphological map of the study area to confirm the ground behaviour of the Lloyds Coppice slopes;

- **URGENT** further ground investigation and the installation of borehole instrumentation up slope of the recent ground investigation in the area of Lloyds Cottage to allow shear surfaces and lateral extent of ground movement to be determined, and to understand the faulting in the area;

- **URGENT** undertaking of a topographic survey of the Lloyds Cottage area;

- **URGENT** undertaking of detailed design of the remedial works to the Lloyds Cottage area of failure, including river bank protection and slope stabilisation measures, which could include mechanical stabilisation (eg piles) and drainage;

- Continued monitoring of inclinometers, piezometers and monitoring pins on a regular basis to identify trends of movement;

- Regular monitoring of the failed sheet pile wall at the Lloyds House riverbank with remediation/ replacement of the sheet pile wall as required by the monitoring results;

- more regular piezometer readings in any actively moving landslide zones of the study area (to be determined following geomorphological mapping);

- Liaison with utility services to identify the exact location of damage to services;

- Co-ordination with land owners over riparian ownership of the riverbanks;

- Use the weather station proposed at Jackfield to monitor rainfall, together with more regular piezometer readings in the actively moving landslide zones of the study area (ie Lloyds Cottage and the School House area);

- Develop a contingency and action plan for areas where major failure or blockage of roads may occur, to ensure access for emergency vehicles and utility companies, short-term rehousing, meeting health & safety requirements, road diversions, etc.;

- Co-ordination with the service companies who have services within The Lloyds, to ensure any maintenance carried out does not have any adverse effects on slope instability; and,

- Develop an emergency remedial works strategy should failure occur and sever The Lloyds.

With regard to The Lloyds Head the site specific details required as part of the strategy include:

- Continued monitoring and the implementation of a regular programme of crack mapping and spot levels to monitor ground movement and subsidence;
- Further investigations to identify the extent of any slip upslope by using inclinometers and mapping;
- Subsurface investigation into extent of tile waste deposits (ie by trial pits);
- Investigations into the most suitable method of river bank protection;
- Development of design strategy for the prevention of further subsidence (ie grouting);

- Develop action plan: emergency vehicle access, utility services, etc; develop remedial works strategy; and,
- Develop contingency plans for failure event: ie emergency works.

TABLE 5.1 SUMMARY TABLE OF REMEDIAL ACTIONS

Section No.	Location	Remedial Recommendation	Basis for Recommendations	Timeframe for Remediation
Lloyds Coppice	Lloyds Cottage	Further ground investigations to identify slip surface profile and local ground conditions and detailed topographic survey. Surface crack and ground behaviour mapping. A combination of river bank toe protection, mechanical slope stabilisation (eg piles) and drainage to maintain present road alignment and infrastructure.	The rate of ground movement is significant and the loss of The Lloyds is considered highly likely to occur in this area. The loss of The Lloyds in this area would be detrimental to the local infrastructure and tourism, with a major impact on the World Heritage Site. It is recommended that works should be undertaken **URGENTLY** before failure occurs.	**Urgent**
	Old School	Further ground investigation to identify subsurface condition. Continued monitoring, ground behaviour mapping and site inspections.	Movement in this area is considered localised to the area of The Lloyds where the road traverses to the lower reaches of the slope. There is no apparent evidence of ground movement observed within the road and it is necessary that further borehole instrumentation be installed to monitor any potential deeper-seated ground movement.	Completed within one year
	Lloyds House	Continued monitoring and updating of ground behaviour map Commence a programme of monitoring of the failed sheet pile wall area, where risk may change following acceleration of movement	Movement of the sheet pile wall is evident. Should failure occur in totality there is the potential for loss of The Lloyds and access between Madeley/ Coalport and Ironbridge. Without evidence for signs of ground movement in the area and no significant trend of movement from the monitoring pins it is only recommended that continued monitoring and updating of the ground behavioural plan be implemented.	Completed within one year
Jackfield	Jackfield Tile Museum	Continued monitoring and updating of ground behaviour map. Structural survey of retaining walls and building.	Currently there is no evidence to suggest significant ground movement in the area. However, this area is adjacent to Jackfield landslip area and further expansion of this failure to the west could affect the Museum. Furthermore, the structural integrity of the retaining walls needs to be established with regard to the slope above the Museum area. Monitoring is required to identify any transgression of the landslip into the Museum area.	Completed within one year
	Salthouse Road (Jackfield Slip Area)	Ultimately, this area will require remedial works to arrest downslope movement. The rate of movement is slow, but may accelerate with time. This area requires interim real-time ground instrumentation prior to the remedial works comprising of toe protection and slope drainage. Should the area be untreated for some time, mechanical stabilisation may be required in addition as the failure retrogresses. Continued monitoring and updating of ground behaviour map	Ground movement can be currently observed. Past movement has resulted in the realigning of Salthouse Road and the placing of utility pipes above ground level. The loss of Salthouse Road is highly likely to occur in this area without active intervention. Although movement is slow and funding for any works may not be forthcoming it is recommended that interim subsurface instrumentation be installed to monitor the rate of ground movement in real time which can be conveniently downloaded without the necessity for infrequent inclinometer and surveying.	Installation of site specific subsurface instrumentation within **6 months**, preferably before the Winter 2003/4. Remedial works within 2 years.
	Salthouses	Continued monitoring and updating of ground behaviour map	Currently there is no evidence to suggest significant ground movement in the area. However, this area is adjacent to Jackfield landslip area and further expansion of this failure to the east could affect the road and Salthouses. Monitoring is required to identify any transgression of the landslip into the Salthouses area.	Completed within one year
	Tuckies	Continued monitoring and updating of ground behaviour map	There is no evidence to suggest any trend of significant ground movement and therefore, it is considered only necessary to undertake monitoring and updating of the ground behavioural map.	Completed within one year
Lloyds Head	Lloyds Head	A combination of river bank protection and ground stabilisation to prevent further subsidence. Continued monitoring, crack mapping and sub surface investigation to the extent of tile waste deposits	The combination of subsidence and river erosion is currently threatening the short to medium term integrity of Lloyds Head road and the property between the road and the river. Subsidence is likely to damage property and erosion of the riverbanks threatens the safe use of property by persons.	Studies within one year and Remediation required within c.2 years

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FIGURES

PLATES

APPENDIX A
LIST OF INFORMATION PROVIDED BY T&WC

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Extracts of newspaper reports for 1952 landslide

Contact details for statutory undertakers

APPENDIX B
B1: INCLINOMETER PLOTS
AND
B2: PIEZOMETER READINGS
FOR
IRONBRIDGE GORGE STUDY AREA

APPENDIX C
LANDSLIDE EVENTS

APPENDIX D
LLOYDS COTTAGE LETTER

APPENDIX E
SLOPE STABILITY ANALYSIS