EFFECTS OF SUBLIATION ON STEEP TOPOGRAPHY AND CLIFF LINES

By

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ABSTRACT

A two year study into the effects of coal mining induced subsidence on cliff lines was undertaken by the Department of Mineral Resources with the support of a grant under the National Energy Research, Development and Demonstration Program. A new monitoring technique, using an Electronic Distance Meter and acrylic reflectors attached to the cliffs, provided safety for the surveyors and extensive and accurate three dimensional displacement data on the movement of the cliffs as they were being undermined.

The study report included many graphs showing the measured vertical and horizontal displacements, differential subsidence, tilts and strains and included analysis of these movements with various parameters, such as, seam thickness, depth of cover and distances between the reflectors, topographic and the edge of the main pillar. Some of these graphs are presented in this paper and could be used, with caution, to predict subsidence movements around other cliff lines, after allowing for differences in geology and mining layout.

A mechanism is suggested as an explanation for the observed high horizontal movements around the cliff lines. Sixteen percent of the overall lengths of cliffs that were undermined during the monitoring study fell and the contributions of various factors that appeared to influence the cliff falls are discussed. It is concluded that no single factor dominated as the major cause of the cliff falls and, rather, many factors combined to cause cliff face instability.

BACKGROUND TO STUDY

A significant proportion of the coal reserves in New South Wales lie under areas of steep slopes and cliffs. Several large mining induced cliff falls have occurred in NSW and since then mining has been restricted to within conservative angles of draw from all significant cliff lines. In November 1988 the Commonwealth Minister for Resources advised that financial support of up to $50,000 would be provided, through the National Energy Research, Development and Demonstration Council, towards a two year research study that has been titled "EFFECTS OF SUBLIATION ON STEEP TOPOGRAPHY AND CLIFF LINES". The N.S.W. Department of Mineral Resources supported the study and allocated the required staff resources to complete the study.

The objective of the study was to improve the understanding of strata mechanisms involved when cliffs are undermined and to formulate appropriate methods to predict ground movements near such topography. To achieve this the study included the following stages:

i) related research literature was reviewed;
ii) a detailed monitoring programme was initiated to measure the ground movements around the cliffs and adjacent steep slopes as they were being undermined;
iii) all monitoring results were graphed and analysed;
iv) two and three dimensional mathematical modeling of cliff line displacements was undertaken;
vi) the monitored movements, at the time of the cliff falls, were analysed in detail to assess the influence of various parameters on the observed cliff falls, and
vii) a detailed study report was prepared.

The literature concerning the effects of mining induced ground movements on slopes and cliffs was found to be surprisingly scarce. Some overseas and local papers have discussed mining-induced cliff fall occurrences and some have discussed using mathematical models to examine the effect of mining near the cliffs. The most notable of these papers were Pells et al (1987) and Pells (1981), which provided valuable historical data on previous mining-induced cliff falls within the Sydney Basin.

However, no literature was found that presented data on monitored cliff face movements as the cliffs were being undermined. Hence the papers that were found that discussed possible cliff failure mechanisms were based on pre-mining and post-collapse observations and none of the mathematical models in these papers were calibrated against actual cliff movements.

MONITORING PROGRAMME

Because cliff falls represented a serious injury risk to the surveyors, a new monitoring technique was pioneered that allowed the cliff face movements to be measured remotely whilst the cliffs were being undermined. Inexpensive reflectors were attached to the valley floor, cliff face and plateau areas before mining and then, during and after mining, the positions of the reflectors were tracked using a precise Electronic Distance Meter, that was set up at locations that were away from where falling rock or debris could injure the surveyors.

This new cliff monitoring technique proved successful and accurate data was collected on the existing and moving coordinates and the reduced levels of each reflector for each of the surveys. Extensive cliff monitoring was undertaken by the Department's subsidence survey team over an eighteen month period. Six separate areas, including nine lines of cliff faces and two steeply sloping areas, were monitored at the Balloara...
Cotter, which is approximately 150 km from Sydney in the Western Coalfields of N.S.W. The surveyors attached 510 reflectors over the six monitoring areas and 2,310 sightings were taken over 26 separate survey expeditions.

The Collie矿 used the Lithgow Seam using 211 m wide longwalls and extruded coal thicknesses varying from 2.3 to 2.6 m. Strata cover over the seam varied from 43 to 212 m. The vertical height of the monitored cliffs ranged from 5 m to 60 m and these cliffs were located away from any and effects of the commencing and existing ribs of the longwalls. The cliff lines were generally oriented across the longwall panels at angles of 80° to 100° to the direction of mining.

MONITORING RESULTS

The study report includes approximately 300 graphs showing the monitored vertical and horizontal displacements, fits and strains. To present the distribution of these movements around the panel and the influence of topography, these movements are shown as superimposed scales and vectors on topographical contour plans, as shown in Figs 1 to 3. After producing the tilt and strain graphs, it was decided to concentrate the detailed analysis on the vertical and horizontal displacement data as these graphs showed clearer trends and included fewer abnormalities.

Fig. 1 - Subsidence of reflectors over Longwall 6 at East Bone Colliery on 23-7-00 and 8-1-01.

Fig. 2 - Horizontal movements of reflectors over Longwall 6 at East Bone Colliery on 23-7-00 and 8-1-01.
observed angles of draw from the longwall panel edge to surface points of 20mm subsidence were noted to vary significantly and, within the central zones of these longwall panels, subsidence varied in response to the changing depths of cover. Graphs, such as Figs 4 and 5, were prepared to assist in predicting the vertical subsidence of any surface point over these longwall panels based on the ratio of panel width to cover depth, and distances between the surface point and the longwall face and the edge of the chain pillar.

In reviewing the distribution of monitored ground movements over these longwall panels at Baa Bone Colliery, it is important to appreciate that, because the chain pillars between the longwalls were relatively wide compared to their depth, i.e. 25m wide at depths ranging from 43 to 212m, the surface areas over these chain pillars only subsided by small amounts, i.e. up to 0.1m. As the central regions of these panels subsided up to 1.5m, the lateral difference in subsidence caused large and permanent lateral tilts, strains and horizontal movements, which were found to be of comparable magnitude to the longitudinal or temporary or travelling tilts, strains and horizontal movements.

HORIZONTAL MOVEMENT OBSERVATIONS

Although little has been published on the horizontal movements occurring from mining under flat terrain, it is clear from the monitoring in this study that the subsidence induced horizontal ground movements were significant near the cliff faces and steep slope areas and were influenced by the changes in surface topography. The maximum horizontal movement measured was 1.75m, which is greater than the maximum monitored vertical subsidence of 1.5m.

The direction and magnitude of the horizontal movements of each reflector were calculated and plotted. Then these horizontal movements were broken down into two components, i.e. parallel and perpendicular to the direction of mining. Because the cliff lines were generally orientated across the longwall panels the observed horizontal movements, that were;

i) parallel to the direction of mining, were movements perpendicular to the cliff lines, and

ii) perpendicular to the direction of mining, were movements along the cliff lines.

The movements parallel to the direction of mining were particularly interesting. It was noticed that irrespective of the direction that mining approached the cliff faces, the observed horizontal movement components, that were parallel to the direction of mining, were generally directed towards the valley.

In the case where the cliffs were mined from their valley sides first, i.e. the base of the cliff was undermined first, significant horizontal movements of the cliff faces were observed towards the valley, which in this case was also towards the excavated areas (goaf). However, when cliffs were mined from their plateau sides first, it was noticed that the cliff face still moved towards the valley and it should be noted that this direction was away from the mined out goaf areas. This observed horizontal movement towards the valley occurred consistently even though the plateau area above the cliff line was subsided before the cliff, i.e. as the cliff was being tilted back towards the goaf centre, the top of the cliff face moved away from the goaf.

Although the average horizontal movements, that were perpendicular to the direction of mining, were directed along the cliff line and away from the chain pillar, many reflectors were noted to move towards the chain pillar whenever this direction was towards a valley.

Fig. 3 - Slope and strain between reflectors over Longwall 6 at Baa Bone Colliery on and 8-1-91.

SUBLINCE OBSERVATIONS

The observed vertical subsidence pattern around the cliffs and steep slopes was slightly modified but not significantly different from the subsidence behaviour expected over flat terrain. The maximum vertical subsidence observed in the central regions of the panels ranged from 1.2 to 1.5m, representing up to 65% of the seam thickness mined. Comparing the maximum observed subsidence for these longwall panels with the maximum subsidence predictions using the empirical methods outlined in Hota (1981), it can be seen that the difference in observed and predicted maximum subsidence was only 5%. However, the

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Accordingly, this study has found that the horizontal movements around the dip faces are significant and are occasionally opposite to the expected subsidence behaviour over flat terrain. The observation can also be seen in the strain graphs, where as well as the usual spread of tensile and compressive strains around the longwall panels, areas of higher compressive strains were noticed at the bottom of valleys and higher tensile strains were observed on top of ridge lines and behind dip faces.

Graphs were then prepared to analyse the horizontal movements. These graphs, such as Figs 6 and 7, have shown that, for the areas monitored in this study, the extent of these 3D movements depends primarily on the seam thickness, depth of cover and the location of the reflector with respect to the longwall, panel edges, and the steep slope. These graphs could be used to predict similar ground movements at other collieries, after allowing for the influence of both changing mining layouts and the geomechanical properties of the overburden, as these factors were predominantly constant over the monitoring areas examined at Basi Bima Colleye.

**STRATA MECHANISM EXPLAINING HORIZONTAL MOVEMENTS**

The following strata mechanism is suggested as an explanation for the observed "anomalous" horizontal movements around the dip face. The mechanism is based on assumed horizontal movements within each strata layer, from the seam level upwards.
After a coal seam is extracted, the immediately overlying strata layers fall predominantly vertically into the void. However, these strata blocks that overlie the edges of the excavation experience mainly horizontal displacements and tilting towards the void, as shown in Fig. 6. Some of these strata blocks break off and fall into the void whilst others remain overhanging into the void. As these blocks move and tilt towards the void, it is reasoned that they exert a horizontal force on the strata layer above, (by horizontal shear transfer), causing localized tension and compression zones, fracturing, horizontal movements and tilting within that strata layer. This horizontal “dragging in” of strata over the goaf edges is envisaged to continue upwards through each strata layer to the surface and, although it is shown in Fig. 6 in two dimensions, it is a three dimensional phenomenon as it occurs over each edge of the goaf area.

Where surface areas are flat, the surface strata is relatively constrained and monitored horizontal displacements are usually directed towards the centre of the panel, with maximum displacements occurring where the change in ground slope is near its maximum and the horizontal strain is approximately zero.

However, where there are cliff lines, a different pattern of horizontal thrusts is developed within the strata layer that includes the cliff face and its surrounding plateau regions. Considering the cliff face and the square mining layout shown in Fig. 6, horizontal forces should develop within this cliff strata that:

1) are located above the right hand edge of the extracted area, (these forces would be directed towards the valley), and
2) are located over the two edges of this excavation that are perpendicular to the cliff line and these forces would be directed along the cliff line and towards the centre of the excavation.

However because the strata have been eroded away to form the valley, no significant horizontal thrust is developed from this direction. As a result there is an apparent net horizontal thrust towards the valley and since this strata layer is less constrained, significant horizontal movements are generated perpendicular to the cliff line and towards the valley.

This mechanism also indicates that as the longwall moves the magnitude and directions of the horizontal forces within the cliff horizon strata will change. Consider first the westwards facing cliffs monitored at Bael Bona Colliery. After the longwall had travelled under and past these cliff lines, the main horizontal forces developed within the plateau strata and near the cliff line, would be those across the panel or along the cliff line. These opposing horizontal forces would compress the cliff line laterally and, if it is reasoned that the observed horizontal movements at the top of these cliffs towards the valley could have resulted from a compressive buckling of this strata.

A different positioning of horizontal forces would have acted within the eastern facing cliff lines strata. No horizontal forces would have developed within this strata until after the longwall had mined past the cliffs and under the plateau. At that time not only would opposing forces be generated across the longwall panels, but a tumbar horizontal force would develop above the longwall face and combine to cause horizontal movements towards the valley. As the longwall moves further away from the cliff face the location of the horizontal force over the longwall will move and will have less impact on the cliff edge movements.

As explained in the study report, this mechanism has been applied successfully to explain:

1) why the monitored horizontal displacements around the steep slope areas were observed to be directed down slopes and perpendicular to the contour lines rather than towards the centre of the extracted panel as would be expected in the flat surface terrain,
2) why the largest tall occurred where it did and why that cliff moved towards the south east rather than due east, and
3) why the largest tall of the Nietal North Gallery occurred where it did rather than at the other undermined cliff strata along the Burragorang Valley.

CONCLUSIONS FROM CLIFF MATHEMATICAL MODELLING

Although preliminary two dimensional modelling of cliff line displacements was undertaken, most of the modelling effort for this study concentrated on using available three dimensional models as it was clear the above strata mechanism is a three dimensional effect. This modelling work was undertaken by MINGAD Systems, who modified their 3D program, SUBSOIL, so that it realistically modelled steep cliff line topography.

After calibrating the three dimensional model to the movements monitored in one of the valleys at Bael Bona Colliery, two “what if” scenarios were examined which showed that:
Displacements about the cliff lines were significantly reduced when the depth of cover was increased, and negligible differences in predicted displacements occurred between the case of a valley with two opposing cliff lines and the case of a single escarpment.

Details of this work are described in another paper presented at the conference by Dr. L. Ward and K. McKee.

**EFFECTS OF SUBSIDENCE ON THE MONITORED CLIFFS**

The surface areas over the longwall panels at Baal Bone Colliery are part of a State Forest and contain rugged, undeveloped terrain. Exposed sandstone areas and cliff faces dominate the landscape. The mining-induced subsidence movements caused extensive surface cracking over the plateau and sandstone areas. The average crack width was 85mm and the widest crack was 600mm. Many of these surface cracks were several hundred metres long and the total length of all the observed surface cracks was approximately 7km.

Although many cliff faces were observed to fall over the longwalls at Baal Bone Colliery, these falls were small compared to other reported mining-induced cliff falls. Of the fifty-eight cliffs or rock faces that were observed to fall over the Baal Bone Colliery during this study, nineteen involved rock volumes of less than 10m³ each and could be considered minor rock slides. The average cliff fall size was 9m long, 6m high and 1.4m deep and the largest cliff fall was 30m long, 20m high and 5m deep. The 307 tonnes of cliff falls that fell in the areas monitored during this project represented 16% of the 1320m of rock faces that were undermined in the monitoring areas.

**WHY CERTAIN CLIFFS FAIL**

Why these did only 16% of cliff faces fall when the surrounding 84% of cliff faces were just high and were exposed to similar mining-induced ground movements.

In order to answer this question, a review was undertaken of all the factors that appeared to influence the cliff falls, including: the state of weathering, shape and geology of cliff face, existing jointing and mining-induced surface cracks, position of falls with respect to the longwall face and the chain pillar, direction of mining towards the cliffs, magnitude of ground movements (vertical and horizontal), magnitude of differential ground movements, magnitude of lifts and the magnitude of strains.

**NATURAL WEATHERING AND SHAPE OF THE CLIFF FACE**

Cliffs are formed when weaker rock units weather and erode first leaving more resistant strata. Natural cliff failures in the Sydney Basin are attributed to the weathering of claystone and siltstone layers that are typically below the sandstone cliff faces. As the cliffs are undercut, high tensile stresses develop in the overlying rock mass eventually leading to surface cracking or the dilation of existing joints behind the cliff face. After further weathering and softening of the base layers, commonly following a period of intense rainfall, the centre of gravity of the overhanging mass shifts and eventually cliff toppling occurs. This ongoing process of cliff face development and natural cliff falls can be observed at various locations around the Sydney Basin.

Logically, if a particular cliff face had weathered considerably and was close to a natural failure, then it would be more liable to fall from mining-induced movements than those cliff faces that are not in as advanced stages of weathering. Indeed most of those cliffs that were naturally undercut, fell. However, the "state of weathering" of the cliff was not the only factor influencing cliff falls as many other cliff faces fell, which were not undercut.

**MAGNITUDE OF GROUND MOVEMENTS**

Although the effect of mine subsidence on cliffs is similar to the above weathering process in that it also causes removal of the base support for cliffs, the cliff monitoring during this study has shown that the undermined cliffs were subjected not only to vertical subsidence but also horizontal movements both across the panel and longitudinally along the longwall panels.

An analysis was undertaken of the ground movements at the cliff face, valley floor and plateau areas above the cliff at the time of the cliff falls. The minimum vertical subsidence monitored at a cliff face when it fell was 83mm. However, at this time, significantly higher ground movements were being recorded in the adjacent valley floor regions. That is, although the subsidence level at the time of the fall was small, the cliff was experiencing high differential subsidence or lift levels. The mean cliff face subsidence at the time of the cliff fall was 320mm for the cases where mining approached the cliff from the valley and 441mm from the plateau side respectively, as shown on Fig. 10.

![Fig. 10](image)

Mean movements at the time of the cliff falls when the plateau area was mined before the valley.

Mean movements at the time of the cliff falls when the valley area was mined before the plateau.

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The mean horizontal movements, at the time of the cliff falls, were approximately half of the vertical subsidence, however certain cliff faces moved horizontally more than they subsided vertically particularly where the cliffs and slope areas moved "en masse" down the slopes and towards the valley.

**Fall Position in Relation to Goaf Edges**

No cliffs fell before they were undermined.

Most cliff falls were observed after the longwall had mined 0.2 to 1.0 times the depth of cover past the cliff face, as shown in Fig. 11. This location corresponds to where the longitudinal subsidence wave was monitored to cause the highest tilt, horizontal movements and strains, as was shown in Fig. 5.

The observed distribution of cliff falls across the longwall panels was also interesting. Most falls were located in the region from 0.2 to 0.5 times the depth of cover inside the panel from the chain pillar, which is also where the high values of tilt, horizontal movements and strains were observed across the longwall panels. However, as can be seen on Fig. 12, there were also many falls in the panel centre and some falls were located over the chain pillars. (This figure shows the number of cliff falls occurring within set 2.5m wide segments across the panel, and thus wide cliff falls were counted across several such segments.)

**Direction of Mining**

Before this monitoring study it was generally believed that cliffs would be less likely to fall when the mining approached the cliff from the plateau side rather than the valley side of the cliff. The main logic in this belief was that when mining the plateau side first, the cliff face would be tilted backwards rather than towards the valley. As no cliff face monitoring had been undertaken at the time of mining this assumption had not been tested.

However monitoring during this study revealed:

i) The magnitude of monitored ground movements (both vertical and horizontal), at the time of the cliff falls, was generally greater when mining approached a cliff face from the plateau side rather than the valley side.

ii) The differential subsidence, between the cliff face and the valley area, was generally greater, at the time of the fall, when mining approached a cliff face from the valley side rather than the plateau side.

iii) When mining approached from the plateau side, subsidence was greater at the cliff face than in the valley; and, when mining approached from the valley side, subsidence was greater in the valley than at the cliff face.

iv) When mining approached from the plateau side, the plateau surface areas subsided more than the cliff face, however the tops of the cliff faces were monitored to move towards the valley and away from the goaf.

Regardless of the above, the monitoring revealed that the proportions of cliffs falling at East Bone Colliery were similar for both these mining directions.

**Existing Jointing and Mining-Induced Cracks**

As mentioned previously up to 7km of surface cracks were mapped around the cliff lines at East Bone Colliery. As these surface cracks appeared to influence the location of many of the cliff falls a study of their occurrence was undertaken, which revealed that:

i) the orientation of cracking around cliff areas and within 50m of the chain pillars was principally east-west, which is parallel to the direction mined, whilst

ii) the orientation of cracking around cliff areas and in the centre of the panels was principally north-south, which is perpendicular to the direction mined, and

iii) in both areas another set of minor cracks was monitored parallel to the cliff lineament directions.

Accordingly, most cracks predominantly followed new mining-induced paths although away from the cliff face some existing joints were opened. Because the surveys were not able to monitor the site continuously and because it was dangerous for the surveyors to be close to the cliff edge during undermining, it is not clear whether the surface cracks or the cliff falls occurred first.

In 25 out of the 27 cliff falls studied at East Bone Colliery, mining-induced surface cracks could be seen continuing through the cliff face and/or above the cliff into the plateau region. Not one of the cliff falls occurred off existing joints, as all the exposed rock surfaces showed clean freshly fractured sandstone without any signs of secondary mineralogy, fillings, or weathering. Unlike natural cliff falls or the larger mining-induced cliff falls that are reported in the literature, the rock falling from the cliffs over the East Bone Colliery generally originated from within one sandstone unit and these falls were not associated with base...
strata weaknesses or topping. In fact the cliff collapse mechanism at Biall Bone Colliery appeared to be more a result of shear and tension failures within the cliff face horizon.

Why did the surface cracks propagate where they did? It is suspected that the location, size and spacing of these mining-induced surface cracks is influenced by: the location and size of the fault, the geology and caving properties of the immediate roof beds, depths of cover, native stress fields, a propensity of the strata to crack along preferred alignments, surface topography and the rate of mining. However, despite detailed plotting of the development of surface cracks at the adjacent Angus Place Colliery and during this study, it is not possible yet to predict in advance where these surface cracks will occur.

**NEED TO DEVELOP A CLIFF FALL PROBABILITY FACTOR**

Because many factors appear to influence cliff falls, rather than trying to predict whether a particular cliff would collapse, it may be better to discuss the probability or frequency of falls occurring within a cliff face area. (The extent of cliff damage within an area can be quantified by accumulating the total length of all the cliff falls within an area and then expressing this total length as a percentage of the total length of cliff lines that were undermined.)

It has been noticed that 10% of the undermined cliff lines fall during this monitoring study. However, this percentage is higher than the 6% of cliff faces falling over the previous longwall mined at Biall Bone Colliery. It has generally been observed that increasing percentages of cliff falls have occurred along various cliff lines over Tower, Biall Bone, Angus Place and Hailtail North Collieries with increasing cliff height and increasing mining-induced ground movements. It is envisaged that, given further field data, an empirical graph could be developed which would show the "probability of cliff collapse" in relation to these quantifiable factors contributing to cliff falls.

**LIMITATIONS TO STUDY**

Extensive cliff monitoring data was gathered at Biall Bone Colliery. However, the depth of cover over the monitoring areas only ranged from 100m to 210m and all longwall panels were extracted at the same width of 211m. Mining at other collieries with different geology, mine layouts and depths of cover could therefore generate other cliff fall mechanisms. Hence it is difficult, if not impossible, to draw general conclusions on why mining-induced cliff falls occur based on monitoring over only one geological and mining environment.

The study has shown that the presence of mining-induced surface cracks over the plateau region influences cliff falls. However, a related and important issue that could not be addressed in this study is whether these surface cracks will cause increased weathering and hence lead to subsequent cliff falls. Future monitoring of these surface cracks and cliff areas would identify if this happens.

This study monitored, for the first time, the mining-induced movements of cliff faces and steep slopes before, during and after mining. However, the cliff lines that were monitored were all located near the central regions of the longwalls. Further studies could reveal how close mining could be permitted to significant cliff crest so that they would not fall. Such a study would be less dependent, could use the results of this study and other historical data, and should consider both the complexities of movements around the ends of longwalls and the above secondary effects of mining on the cliff face stability.

**CONCLUSIONS**

The objectives of this study were achieved after successfully executing and analyzing the results of a detailed monitoring programme specifically designed to assess the ground movements around the cliff face and steep slope areas during mining. In particular, it is concluded that:

i) the observed vertical subsidence pattern around the cliffs and steep slopes was only slightly different from the subsidence behaviour expected over flat terrain;

ii) the horizontal movements around the cliff faces are significant and are occasionally opposite to the expected horizontal movements over flat terrain;

iii) a mechanism, based on assumed horizontal forces within strata layers from the eastern limit upwards and over the edges of the extracted areas, can explain why monitored horizontal displacements around cliff lines and steep slopes are often directed down slope rather than towards the centre of the panel;

iv) no cliff falls before they were undermined;

v) most cliff falls were observed after the longwall had mined 0.2 to 1.0 times the depth of cover past the cliff face;

vi) most cliff falls were located 0.2 to 0.5 times the depth of cover inside the panel from the chain pillar;

vii) the fall locations mentioned above correspond to where the monitored longitudinal and lateral subsidence profiles were steepest, i.e., where the horizontal movements are largest;

viii) widely varying ground movements were observed at the time of these cliff falls. (The minimum vertical subsidence monitored at a cliff face when it fell was 28mm, although at this time the cliff face was experiencing large lifts);

ix) the monitoring revealed that the proportion of cliffs failing at Biall Bone Colliery when mining approached a cliff face from the valley side was similar to the proportion of cliffs failing when mining approached from the plateau side;

x) the surface cracking, that was monitored around the cliffs, mainly followed new mining induced paths although away from the cliff face some existing joints were opened and not one of the falls occurred off existing joints, and

xi) no one factor controlled all cliff fall occurrences and further empirical studies over cliff line areas may confirm trends of increasing cliff fall occurrences with increasing cliff heights and increasing mining-induced ground movements.

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