STRESS RELIEF ON HILLSIDES AND HILLSIDE EXCAVATIONS

B F Walker
Jeffery and Katauskas Pty Ltd, Gladesville, Sydney

ABSTRACT

The presence of high *in situ* horizontal stresses in the bedrock mass in Sydney is well established. The effect of stress relief during excavation into the bedrock mass is evident as horizontal movements as documented by a number of previous papers. This paper explores the likely stress relief on hillside slopes and the likely effect on movements during excavation. Two simple 2D block models are used to consider static equilibrium between the original *in situ* horizontal stress and the shear force possible on the base of the block. Published data in relation to stress reorientation or stress changes are summarised together with some observations in relation to site evidence of past movements which are indicative of stress relief on hillside slopes.

1 INTRODUCTION

Studies have shown that within bedrock of the Sydney Basin, in situ horizontal stresses are usually significantly greater than would be expected from the overburden pressure. The high *in situ* horizontal stresses are due primarily to tectonic compressive stresses. The major, or highest, stress direction is roughly in the north-south orientation within the near surface (0 to 20 m depth) rocks in Sydney city area.

The effects of this high *in situ* horizontal stress are evident in deep basement excavations where the phenomenon of stress relief causes movements adjacent to the excavations. Excavation causes a relaxation of the high horizontal stress and expresses itself as an inward movement of the walls of the excavation. The available monitoring data indicates that typical movements are of the order of 0.5 mm to 2 mm per metre depth of excavation (Pells, 1990; Braybrooke, 1992).

A past development proposal included a reasonably deep excavation into the bedrock mass on a steep hillside slope. A suggestion was raised, during the technical debate in relation to the development, that similar movements should be expected to occur on hillside slopes. This paper will explore the likelihood of high *in situ* horizontal stresses within hillside slopes based on a simple static block model analysis. Some published data in relation to stress reorientation or stress changes are summarised together with some observations in relation to site evidence of past movements which are indicative of stress relief on hillside slopes.

2 *IN SITU* STRESSES AND STRESS RELIEF MOVEMENTS

The existing high *in situ* horizontal stress has been measured at a number of sites in Sydney. Papers by Enever et al. (1990) and Enever (1999) have summarised the stress measurement results.

Pells (2002) suggests that for design purposes, the natural stress field within the Sydney area to depths down to about 100 m can be roughly taken as:

$$\sigma_1 = 1.5 + 1.2\sigma_3 \text{ to } 2.0\sigma_3 \text{ (MPa)} \quad (1)$$

$$\sigma_2 = 0.5\sigma_1 \text{ to } 0.7\sigma_1 \text{ (MPa)} \quad (2)$$

$$\sigma_3 = 0.024z \text{ (MPa), the total vertical stress at a depth z in metres.} \quad (3)$$

The orientation of the major principal stress can be taken as roughly in the direction north-south to about 20° east of north.

Enever (1999) summarises stress measurements to depths of up to 1200 m. The data are summarised against depth ranges of 0 to 20 m, 0 to 200 m, and 0 to 1200 m. Enever suggests that upper bound trends for stress values in each depth interval can be adopted for sites not influenced by topography. For the near surface interval (0 to 20 m), which is the interval of interest for most surface excavations, Enever's upper bound stresses are higher than Pells (1993) as shown on Figure 1. Enever's upper bound values for the major principal stress are:

For 0 to 20 m $\quad \sigma_1 = 2.5 + \sigma_3$ (MPa) $\quad$ (4)

For 20 to 200 m, $\quad \sigma_1 = 6.5 + \sigma_3$ (MPa) $\quad$ (5)

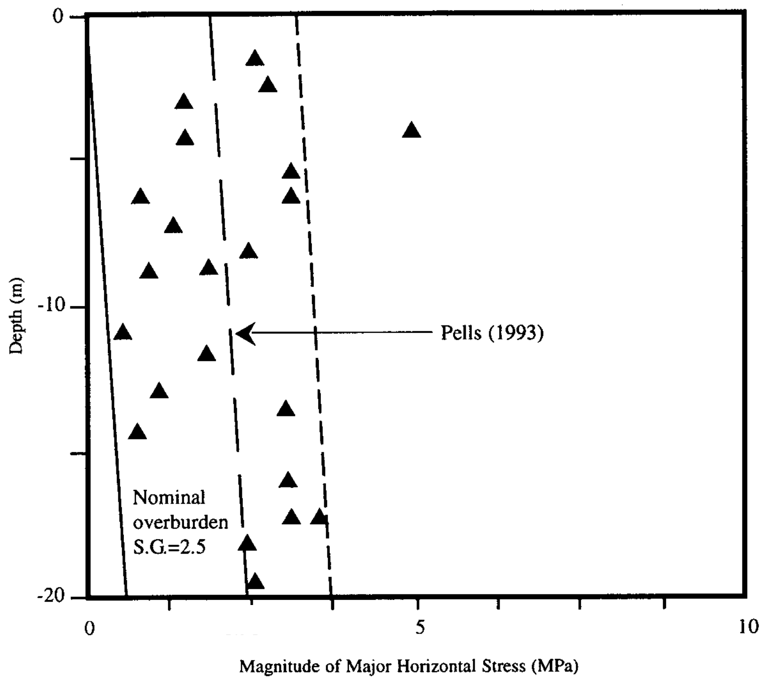


Figure 1: Summary of Magnitude of Major Horizontal Stress with respect to depth for 0 to 20 m depth in Sydney (after Enever, 1999).

In addition, Enever shows the ratio σ_1/σ_2 ranges from 1 to 2 within 0 to 200 m depth interval. The minor principal stresses are shown to be as low as the overburden pressure in most cases, with some results less than overburden thought to be affected by topography. It can be seen from Figure 1, that the Pells (1993) design value for the major principal stress (Equation 1) is reasonable for design purposes, but not the most conservative or upper bound.

Stress relief movements have been monitored primarily by use of inclinometers at a number of sites. Survey observations have also been used. Some results are given in Pells (1990). Braybrooke (1992) presents additional data, as shown in Figure 2, which shows movements of 0.5 mm to 2.0 mm per metre depth of excavation can be expected in practice.

Where detailed site measurements have been made using inclinometers it has been found that the movements do not necessarily occur uniformly with depth. Often the bedrock mass moves in a "block displacement" mode with the lateral movements being concentrated on major bedding planes or shale/clay seams. Usually the overlying rock mass above such partings or seams moves more than the underlying material. Examples of this form of movement have been presented by Braybrooke (1992) and Hewitt et al. (1999). It is considered that the step displacement observed occurs due to changes in modulus and shear strength within the bedrock mass, particularly at the sub-horizontal bedding defects.

Given the above evidence of an *in situ* stress field in the bedrock mass having high horizontal stresses which cause stress relief movements in excavations, the question arises as to whether the same should be expected for excavations on hillside slopes.

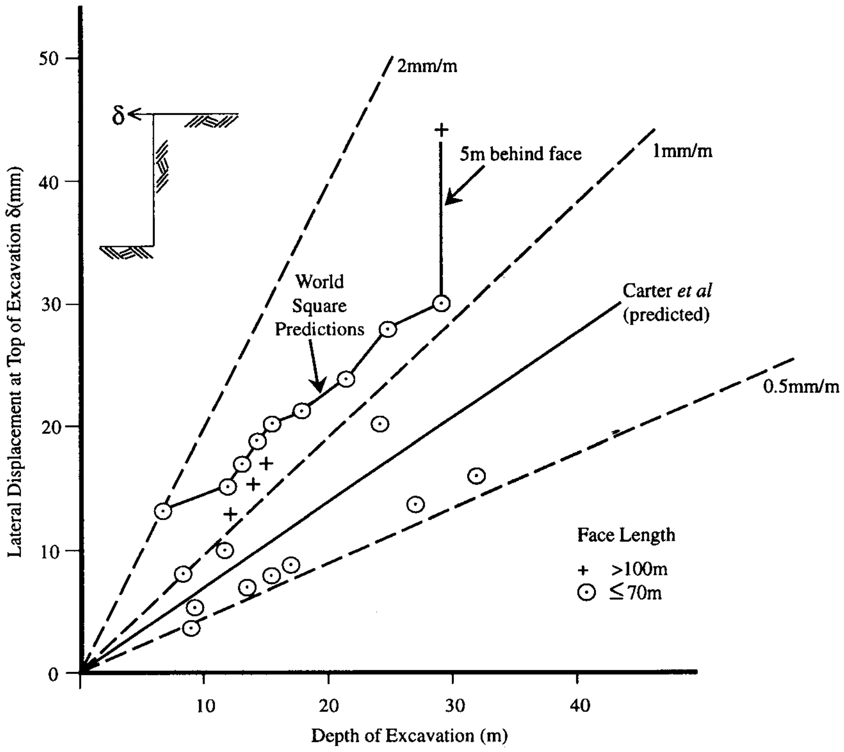


Figure 2: Lateral Displacement of Top of Excavation Versus Depth and Length of Excavation (Braybrooke, 1992).

3 STATIC EQUILIBRIUM WITHIN A HILLSIDE SLOPE

The possibility of stress relief on a hillside slope can be considered by using a simplified two dimensional block model of the hillside slope to evaluate the forces required for static equilibrium.

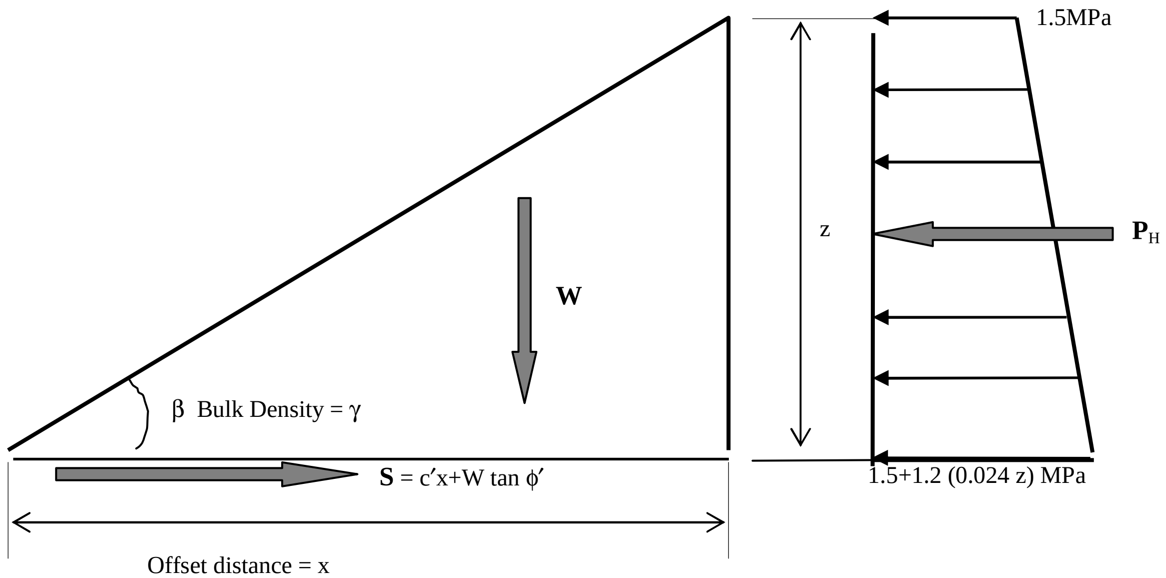
Two simplified block models are shown in Figure 3. Each block model considers the static equilibrium of a two dimensional block defined by a horizontal bedding defect and a vertical joint at some offset distance x from the outcrop of a horizontal plane. The self weight of the block, W, generates a shear force, S, on the base. This shear force is generated by the effective cohesion, c′, acting over the base of the block, and the effective friction angle, ϕ′, on the base of the block. The *in situ* horizontal stresses present on the embedded (or uphill) side of the block result in an applied horizontal force P_H to this vertical rear face. For ease of assessment the plane strain or 2-dimensional case is considered and shear forces on possible side release planes formed by orthogonal sub-vertical joints and the rear face, have been ignored. Also, for ease of calculation, pore water pressures have been assumed to be zero throughout the model, though the model could easily take into account positive water pressures from known ground water levels.

It is therefore possible to evaluate the static equilibrium of the block for different horizontal offsets x from the free surface and differing ground profiles. Two simplistic cases have been considered, being that of:

- Case A: a uniform infinite slope angle β to the horizontal;
- Case B: a uniform slope angle β for an horizontal distance X, then having a horizontal surface.

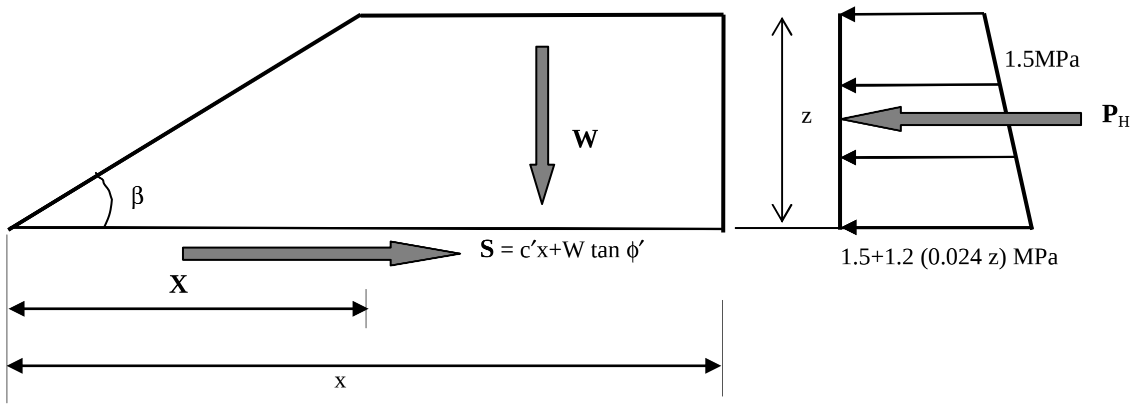
It is noted that often there may be a cliff line defining the change from the hillside slope to a more gentle slope which can be near horizontal. For simplicity, the presence of a cliff line has not been considered although it would be relatively easy to repeat the calculations taking into account a specific height of cliff and uphill surface slope angle.

At any offset distance x from the slope surface it is possible to evaluate the base shear force, S, and horizontal force P_H. from the *in situ* stress field assuming, say, the Pells (1993) value for the major principal stress (Equation 1) from the ground surface. The resulting ratio of S/P_H can be calculated as a function of offset distance x. The equations for static equilibrium (Factor of Safety = 1) are given on Figure 3.



$$\frac{S}{P_H} = \frac{\frac{c'}{\tan\beta} + \gamma \cdot \frac{x}{2}\tan\phi'}{1.5 + 0.0144x \cdot \tan\beta}$$

CASE A: Triangular Block Model.



$$\frac{S}{P_H} = \frac{c'.x/(X \tan\beta) + \gamma \,.\, (x - \frac{X}{2}) \,.\, \tan\phi'}{1.5 + 0.0144\, X \,.\, \tan\beta}$$

CASE B: Trapezoidal Block Model.

Figure 3: Block Models Adopted for Two Dimensional Static Equilibrium Analysis.

For comparative purposes, these equations have been evaluated for a range of shear strengths on the base of the block. It is considered likely the effective cohesion could vary from 0 kPa to, say, 200 kPa and the base friction angle could vary from 25° to, say, 45°. The lower end of these values could be occurring within bedding seams or planes which have been subjected to stress relief and weathering effects. The higher values are likely to apply within the bedrock mass that have not been significantly affected by stress relief. It is noted that the friction angle applicable to the base of the block may in reality be increased above the frictional strength of a clean joint due to waviness along the base defect resulting in dilation on shear at low confining stress levels. Hence a friction angle of greater than 45° would also be possible. The results of the calculations are shown in the attached Figures 4, 5 and 6.

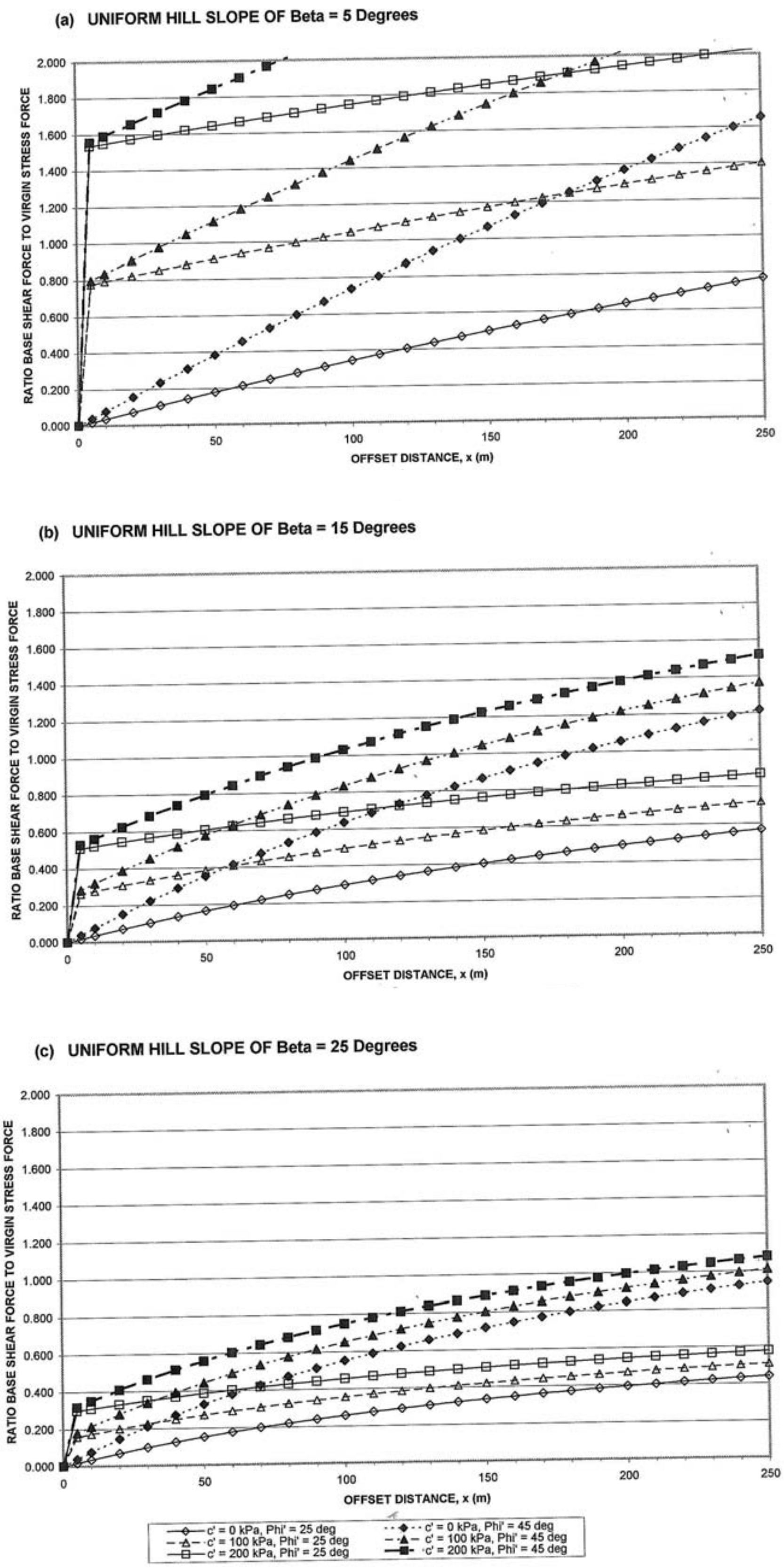


Figure 4: Results of Case A – Triangular Block Model Analysis.

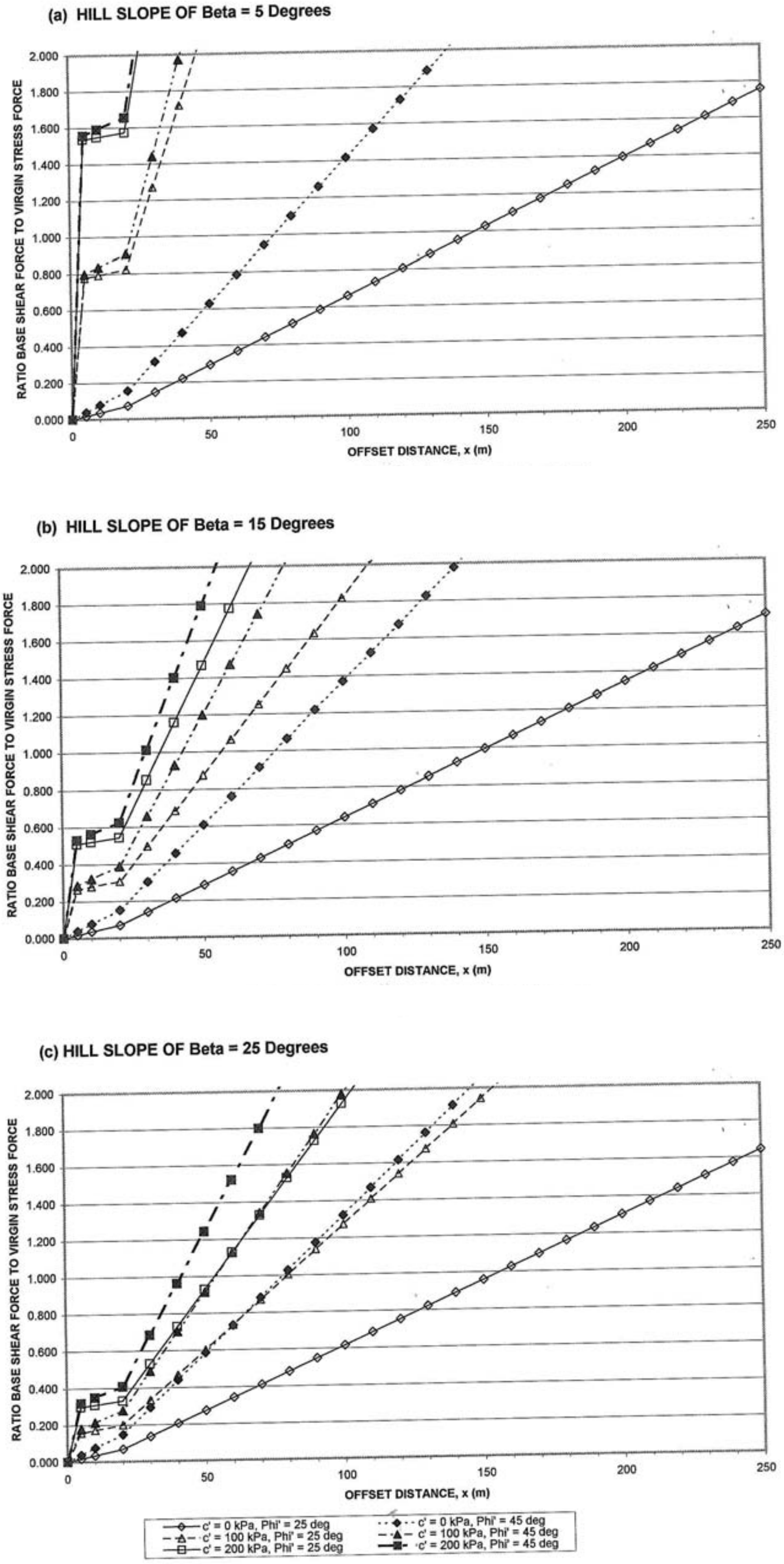


Figure 5: Results of Case B – Trapezoidal Block Model Analysis for Horizontal Slope at offset X=20 m.

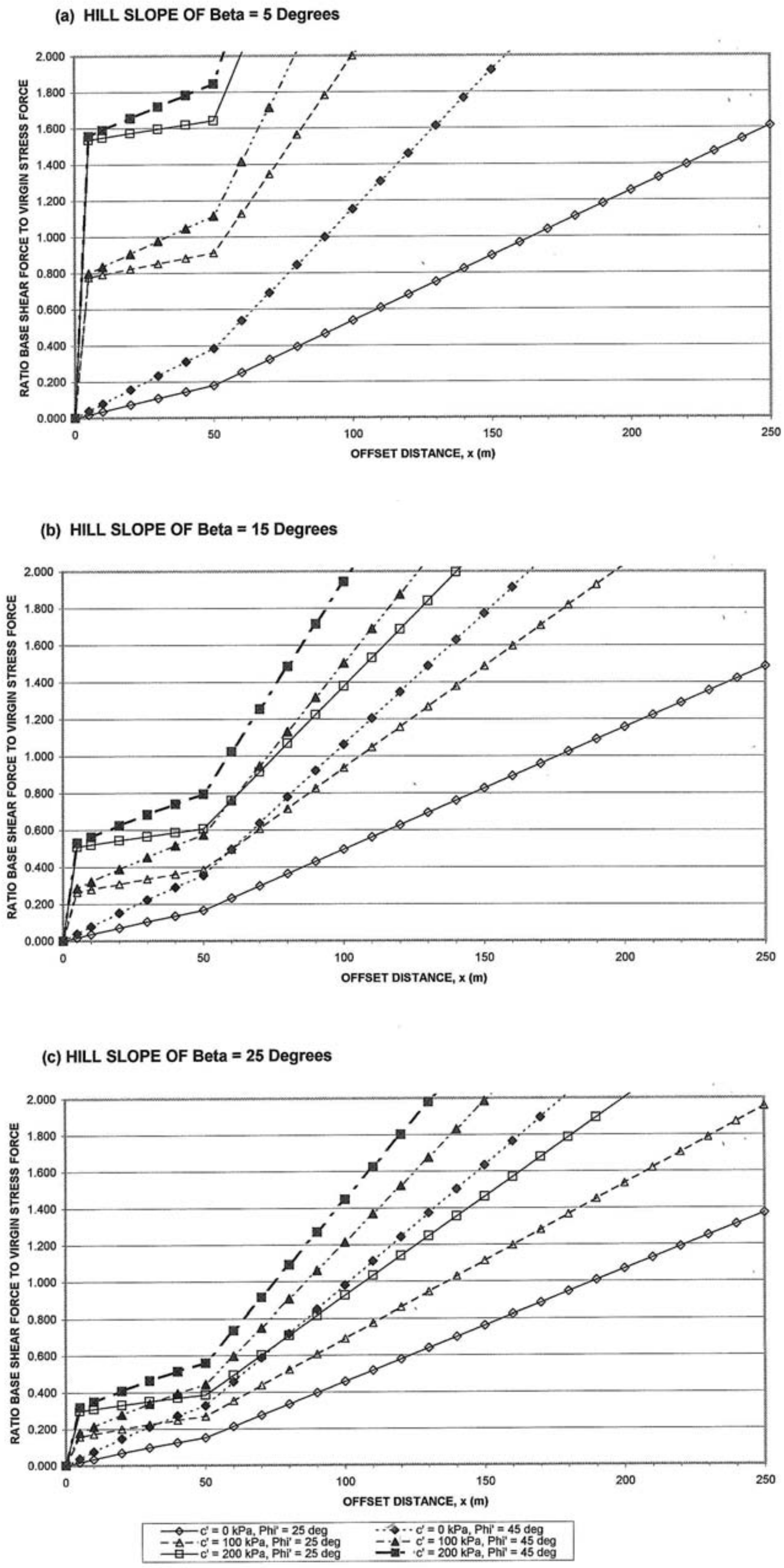


Figure 6: Results of Case B – Trapezodial Block Model Analysis for Horizontal Surface at offset X=50 m.

The significance of the ratio S/P_H is that where the ratio is less than 1, the horizontal force generated by the *in situ* stress field is greater than the shear resistance available on the base of the block. Therefore, where S/P_H is less than 1.0, movement of the block would be likely to occur until the horizontal force drops to equilibrium with the available base shear force. Thus, the ratio represents the proportion of the original *in situ* stress that can be resisted by the available shear resistance on the base of the block.

Hillside slope angles, β, of 5°, 15° and 25° have been considered to illustrate the results for the likely range of hillside slopes. The results of the analyses indicate that:

For the infinite slope model, Case A, the base shear force is less than the horizontal *in situ* force for offset distances of at least 200 m on the steep 25° slopes (Figure 4c) and about 100 m to 200 m, or more if there is no cohesion on the base, on the intermediate 15° slope (Figure 4b).

For the gentle hillside slope of 5°, Figure 4a shows that the magnitude of the cohesion on the base has a dramatic effect on the offset distance to equilibrium. If there is no cohesion on the bedding seam, then the base shear force is less than the *in situ* horizontal force for an offset distance of about 140 m to about 300 m. If there is significant cohesion, then the offset distance to full *in situ* horizontal force is reduced significantly. For a cohesion of 100 kPa the offset distance is about 30 m to 80 m. For a cohesion of 200 kPa, the offset distance would be less than 10 m.

For the trapezoidal block model, Case B, Figures 5 and 6 show that the offset distance to the slope break (X) has a significant effect, since at offset distances beyond the slope break, the *in situ* horizontal force remains constant, but the base shear force is increasing. The pattern of offset distances to full *in situ* horizontal force is similar to Case A, but the distances are reduced.

For Case B with low cohesion on the horizontal seam, the offset distance to equilibrium would be about 80 m to 150 m. At high cohesions, the offset distance would be less than 10 m.

Generally, it is found that bedding seams within the near surface bedrock mass (say for depths of less than 20 m) are weathered and/or are clayey such that shear strength would be expected to be relatively low, having cohesions of 0 to say 10 kPa. The friction will likely be closer to 25° than 45°, unless there is significant waviness which could cause dilation. Therefore, for the condition of low shear strength on the bedding seam, stress relief is likely to have occurred for offset distances of about 50 m to 150 m.

Similarly, these results suggest that at offset distances of less than say 50 m, the resulting *in situ* stress is probably only about 40%, or less, of the original *in situ* horizontal stress. For such cases, the expected horizontal movement resulting from an excavation would also be proportionately less than for the original *in situ* stress field. That is, for a 10 m deep excavation, horizontal movements of less than about 8 mm and probably more like about 2 mm or less would be expected.

The stress relief effects would occur over geological time during the formation of the hillside slope. Where there are high transverse horizontal stresses, such as found in ridgelines as discussed below, then there would most likely be sufficient side shear resistance to further reduce the offset distance applicable to stress relief on relatively uniform hillside slopes. Where deep gullies are present on the hillside slope, then local release of the transverse stress would also be expected such that the 2D conditions assumed above would be expected.

4 EVIDENCE OF STRESS RELIEF ON HILLSIDE SLOPES

The author does not know of any specific cases where lateral movements have been monitored adjacent to an excavation on a moderate to steep hillside slope. What will be presented below is an overview of some published cases and some site observations which reflect the likelihood of stress relief prior to excavation.

4.1 MEASURED CHANGES TO STRESS FIELD

The effects of topography and excavation on stress relief or reorientation of the major principal stress direction are discussed by Enever et al. (1990) and McQueen (2000). It would follow that if the regional stress field has been altered by formation of topographic features (over geological time) or by excavation, then there would also be associated strains / movements. Examples of changes in the stress field due to topographic effects given in the papers are:

4.1.1 Warragamba Dam

Enever et al. (1990) report that on the left abutment hill, the near surface stress measurements showed the major horizontal principal stress to be parallel to the hillside contours. At depth, the orientation was almost normal to this and was more closely aligned with the regional stress field. Below the gorge, stress concentration effects were evident with the major horizontal stress normal to the valley contours.

These data show that the topography has caused reorientation of the stress field. A reduced stress normal to the contours would be expected (though no data are presented in the paper to quantify the reduction).

4.1.2 D2 Excavation

Enever et al. (1990) report the results of stress measurements made from the western wall of the D2 car park towards the nearby existing rail tunnel. *"The results indicate both the stress concentration effect of the tunnel and the stress relief presumably associated with the D2 excavation."*

Pells (1990) provides further discussion of design aspects and monitoring of movements associated with the D2 excavation. Of interest is the report by Pells of the formation of vertical fractures within the intact sandstone at the base of the excavation due to stress concentration effects. A shale bed was present just below the excavation level and was penetrated by the footing excavations. The shale bed formed a release surface for the stress concentrations.

4.1.3 M5 East Motorway

McQueen (2000) reports on stress measurements below a paleochannel which indicated the major horizontal stress direction roughly at right angles to the regional trend which was shown elsewhere to be roughly parallel to the paleochannel. The change in major principal stress direction was thought to have been caused by stress concentration effects of the paleochannel

4.1.4 Hazelbrook Sewerage Tunnel

McQueen (2000) reports "*The first half of the Hazelbrook tunnel was constructed within a narrow ridge with adjacent valleys incised to below the tunnel level. Stress relief has occurred due to adjacent valley erosion, resulting in an open rock mass structure within the ridge."* McQueen also reports on poor tunnelling conditions for this section requiring heavy support.

"*The second half of the tunnel was within a wider ridge (Woodford to Hazelbrook) where the tunnel was more remote from the effects of lateral stress relief due to valley formation. The rock structure was generally tighter and groundwater was shallower."*

This case provides direct experience of stress relief due to the nearby valley form. It would be of interest to have further data on the location of the tunnels relative to the cliff lines so that the offset distances could be considered in relation to block models taking into account the cliff line topography.

4.2 CUTS THROUGH RIDGELINES

There at least two cases where horizontal stresses have been measured adjacent to an excavation through hillsides on a ridgeline.

At Kangy Angy, the F3 freeway cuts roughly orthogonally through a major ridgeline with excavation to about 25 m below the ridge line. Enever et al. (1990) report on stress measurements made normal to the main wall of the road cutting. The measurements were carried out due to the spalling of slabs of rock off the cut face. "*The results clearly indicate a substantial modification of the stress normal to the wall of the cut, from compression of approximately 1.4 MPa remote from the wall, through a state of approximate zero stress normal to the wall at the intermediate distance, to a significant tension in closer proximity to the wall."* The results show a redistribution of the *in situ* stresses due to the excavation.

McQueen (2000) reports *"The cutting was found to have closed up by 400 mm in places and horizontal movements of 100 mm along shale partings were measured"* as shown in a photograph in McQueen. These horizontal movements would appear to be towards the hillside slope (parallel to the road cut) possibly in response to removal of side shear forces on the block adjacent to the cut face.

At Mooney Mooney, the northern side of the F1 freeway rises up the hillside within a hillside cut again roughly normal to the hillside contours. M. McMahon (pers comm.) has advised that lateral movements into the road cut caused problems for the concrete bridge built over the freeway before the major cutting was made. *In situ* stress testing showed high *in situ* stresses in close proximity to the cut face. The cutting movement is also reported by McQueen (2000).

4.3 HILLSIDE EXCAVATIONS

4.3.1 Genting Centre, Sydney

Hewitt et al. (1999) have reported some movement monitoring results for the 29 m to 36 m deep basement excavation on the corner of Bathurst and George Streets, Sydney. Figure 7 shows a Section along Bathurst St, which runs roughly east west and at about right angles to the hillside contours based on the 1:2000 Orthophoto map (U1845-13, 1980). From Figure 7 the hillside slope is about 4°.

The basement excavation extends between George St and Kent St as shown by McQueen (2000). Excavation depths were about 35 m at George St and has been assumed to be about 25 m at Kent St based on the limited available data. Movement predictions reported by Hewitt et al. were made based on two dimensional finite difference model. The stress field adopted was based on Pells (1993) and the material properties used in the analysis are given in Hewitt et al. The analytical model is complicated by the presence of the rail tunnels beneath George St and by the site geology which includes Ashfield Shale, the Mittagong Formation and Hawkesbury Sandstone as shown in summary on Figure 7.

Limited data are presented in the papers, but these have been augmented by additional monitoring results kindly supplied by Paul Hewitt. Considering the east west section shown on Figure 7 the following summary has been prepared:

Location	**Kent St frontage**	**George St frontage**
Excavation depth	Assumed about 25 m	35 m
Horizontal offset distance at about RL5; i.e. at about the change from Mittagong Formation to Hawkesbury Sandstone	About 180 m	About 300 m
Assumed offset distance at base of excavation.	About 250 m to 300 m	About 370 m to 420 m
Predicted lateral movement into excavation for full depth excavation	Not given. By proportion to George St, about 21 mm to 23 mm	About 30 mm to 32 mm at tunnel level
Final observed lateral displacement into excavation	At station M21, about 2 mm	About 6 mm
Ratio observed / predicted movement	About 0.1	About 0.2

On the southern face, for which it is assumed the higher north south major principal stress (Equation 1) would apply, the observed movement at ground level was about 15 mm. No results are given for the predicted movement. A rough predicted estimate, based on the George St frontage prediction using the ratio of the total horizontal force from the *in situ* horizontal stresses, would be about 50 mm movement. This would probably be a conservative estimate as the George St frontage prediction takes into account the rail tunnel excavations which would likely reduce the predicted movement compared to a face not affected by the tunnels, such as on the southern side. Nonetheless, the rough estimate gives a ratio of observed / predicted movement of about 0.3.

Hewitt et al. conclude that the "*discrepancies between the numerical predictions and measured data could be due to stress relief effects caused by earlier tunnel construction and confining effects not accounted for in a two dimensional analysis.*" The author considers that additional causes for the discrepancy would be that the modulus values for the model could be in error, and the horizontal stress field could be affected by the stress relief effect resulting from the hillside slope and weathering of the Ashfield Shale and Mittagong Formation.

The Hewitt et al. prediction model was based on the scenario of the full *in situ* horizontal stress state for the full depth of the excavated profile. From the results in Figure 4(a), and considering the offset distances given above, it is possible that the *in situ* stresses at about RL 5 could be as low as about 60% of the original *in situ* stress state on the Kent St face if bedding defects are of low strength, and in particular have cohesion approaching zero. For stronger bedding defects, such as having cohesions of say 50 kPa or more, or having high friction angles, then stress relief prior to excavation would seem unlikely in the lower half of the excavated depth. On the George St frontage, stress relief prior to excavation is unlikely except at higher elevations say above about 15 m depth (RL7 mAHD), where the offset distance would reduce so that some stress relief effects could have occurred prior to excavation.

From the above it would be possible to consider stress relief due to the hillside slopes as another contributory cause of the over estimate from the analytical predication, but stress relief seems unlikely to apply to depths of greater than about 15 m on hill side slopes as flat as about 5°.

Figure 7: East-West Section along Bathurst Street.

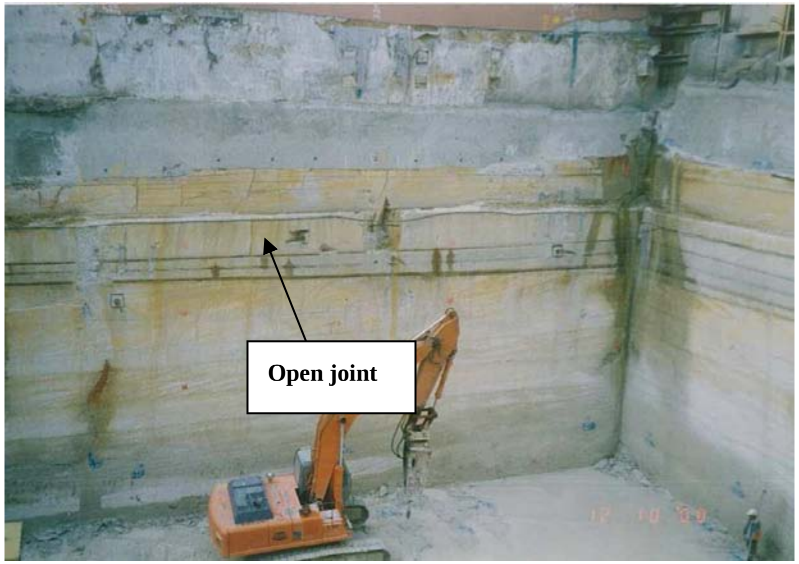


Figure 8: General view of UTS face at end of basement excavation showing location of open joint and subhorizontal laminite bedding seams.

Figure 9: Close up view of open joint terminating on laminite/shale bedding seam at base of photo.

4.3.2 ABC Site Harris St, Ultimo

The basement of the new ABC accommodation at Harris St, Ultimo was excavated to about RL-9 mAHD, that is about 20 m below street level. The Harris St face formed the south western boundary, and could be considered to follow very roughly the hillside contour. On this face, the weathered Hawkesbury Sandstone was encountered at about RL8 mAHD to RL9 mAHD (about 2 m to 3 m below street level), giving a rock excavation depth of about 17 m to 18 m. On the opposite side of the basement, there was past filling associated with the Darling Harbour Goods Line, over alluvial sediments associated with the swampy area at the head of Darling Harbour and residual soils over Hawkesbury Sandstone. The rock level was at about RL0 mAHD, a depth of about 9 m below the Goods Line. The drop in sandstone level was over a site length of about 70 m, giving an original hillside slope of about 6° to the north east.

Inspection of the north western face during excavation, found an open joint in the bedrock near the Harris Street frontage. The joint was open about 8 mm and was planar, subvertical, clean and had no infill. Similarly, some open joints were evident on the south eastern face (common to the adjacent UTS building). Figure 8 shows a general view of the face at final excavation. Figure 9 shows a close up view of the main joint which extended over a bed thickness of about 1 m and terminated on a sub horizontal laminate bedding layer at a depth of about 7 m below the top of sandstone (the upper most sandstone layers had been protected by mesh and shotcrete). The joint had some iron oxide infill, but was not completely infilled / healed. Within the over lying sandstone there were a number of joints as evident in Figure 8, but none were open to the extent of the lower joint. Another open joint was encountered to the right in Figure 8, and caused a wedge of rock to be removed during excavation of the face. These open joints were at horizontal offset distances of about 20 m to 40 m. As there was no sign of open joints below the laminite seams, it would appear that stress relief movements had been confined to the upper sandstone layers.

Instrument survey techniques were used to monitor the movement of the south eastern excavation face adjacent to the UTS building. The maximum horizontal movement into the excavation was measured at about 6 mm at full excavation depth. The implied accuracy of the instrument survey was about plus/minus 5 mm based on the scatter of results for individual survey targets.

The presence of the open joints clearly indicates that there would have been full stress relief to at least the depth of about 7 m. Figure 4(a) suggests the force ratio could be as low as 0.1 to 0.2. The small movement observed on the UTS face is consistent with stress relief.

4.3.3 Wharf Rd Gladesville

An excavation was formed into the foreshore hillside for construction of a dwelling stepped down the hillside. The maximum excavation depth for each bench was about 3 m. The lower of the two benches exposed an open joint in bedrock mass. The joint was located about 6 m back from the downhill edge and was parallel to the hillside contour. The joint was about 20 mm wide and could be probed by a hand tape to about 3 m depth. This open joint indicated full stress relief of the near surface bedrock mass.

Similar observations have been made in other hillside excavations in Balmoral and Whale Beach.

4.3.4 Collaroy

A basement excavation was made into a hillside slope of about 12° in Collaroy. The resulting excavation reached a depth of about 12 m below ground level on the uphill side. The exposed rock was predominantly weathered sandstone of the Narrabeen Series, with some minor interbedded siltstone layers. As the excavation neared the final depth and detailed excavation for footings was underway, a number of wedge failures occurred on the uphill face. The largest wedge was about 3 m high by 5 m long and had release plane at about 80° to horizontal. The release plane had clay infill to a thickness of about 5 mm to 10 mm. The side of the excavation (normal to the hillside contours) showed the steeply dipping joints to be present as a family of steep joints. Sub-horizonal bedding was evident with some bedding seams reasonably continuous along the side face. The excavation had a maximum horizontal offset distance of about 40 m.

From Figures 4(a) and 4(b), stress relief could be expected to extend further into the hillside, being for horizontal offset distances of 100 m or more. The presence of the clay infilled joints is consistent with such stress relief.

4.4 NATURAL WEATHERING EFFECTS

Fell et al. (1992) provide examples of and discussion of “valley bulging” where local uplift and /or shear failures are evident in valley floors in sedimentary rocks. Causes include high horizontal stress and unloading of the valley floor due to erosion. “Valley cambering” or opening of joints and distortion of the bedding is often present on the upper valley sides near the crest of the slopes. Fell et al. also give references to other papers documenting these phenomena.

Young and Wray (2000) present an interesting discussion on "block gliding" where sandstone blocks are thought to have moved many metres, in some cases without an obvious cause other than moving down dip on weak bedding planes. Stress relief may be an initiating cause. Young and Wray also refer to finite element model studies of steep valley slopes within high horizontal stress field. These studies predict tensile zones at the top behind vertical cliffs. They comment "*These models readily explain the widespread opening of joints behind clifftops throughout this region*" (referring to the Sydney Basin). The author is not aware of the details of these models. However, further studies taking into account the shear strength of bedding defects may be useful to explore the relationship between elastic stress relief and limiting shear strength on bedding defects.

5 CONCLUSIONS

There is widespread evidence of stress relief in valley sides as part of the natural hillside formation process over geological time. Most of the evidence is available as observation of open joints and larger scale effects, such as valley bulging and cambering. Stress measurements have confirmed that the high *in situ* horizontal stresses can be altered in direction and magnitude due to the weathering effects.

A simple 2D block model can readily demonstrate that there is insufficient shear resistance available on bedding defects within considerable distances from a hillside slope surface to resist the high *in situ* horizontal stress field. The model results suggest that stress relief is likely to be more extensive on steeper slopes, than on gentle slopes. The simplifying assumptions for the model, such as ignoring the shear forces on the sides of a block, may not apply in some cases and are likely to reduce the horizontal offset distances (or depths below the surface) to which stress relief effect would otherwise be predicted.

Monitoring of movements from excavations on gentle hillside slopes indicates that the amount of movement could be reduced from predicted amounts in part by the effects of near surface stress relief, though the data/evidence is limited. There appear to be no published site measurements documenting movements resulting from excavations on steep hillside slopes.

6 ACKNOWLEDGEMENTS

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