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Discontinuity Controlled Cut-Slope Failures on Weathered Low Grade Metamorphic Rocks along the East-West Highway, Grik to Jeli

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.**Abstract:** This paper describes the occurrence and mechanism of discontinuity-controlled cut-slope failures within the residual soil zone and the underlying weathered metasedimentary and metamorphic rocks, drawing on the experience gained from investigations of a number of landslides observed on the cut- slopes of the East-West Highway. These slope failures highlighted the important influence that discontinuities in residual soils and weathered rocks can have on slope stability. The slope movements recognised in the metasedimentary and metamorphic rock slopes along the East-West Highway are: - A) movements of rock-soil cover through: (i) movement of loose soil and weathered fragments, and ii) rotational sliding movements or slumps, B) movements of loosened blocks (rockfalls), C) movement of intact rocks along predetermined planes (slides), D) progressive complex movements. Slope failures are found to be largely controlled by the unfavourable orientation of discontinuities with respect to the slope face compounded by the weathered nature of the rock and the infiltration of water and continuous traffic flow that triggered movement down slope. The occurrence of landslides in slopes, which have been investigated and engineered, may be the result of inadequate attention to structural features in the weathered rock mass during site investigations and construction (design).

INTRODUCTION

The East-West Highway, coursing from Grik to Jeli (Figure 1) was constructed to provide access between the northwestern region and the East Coast states of Peninsular Malaysia. The highway cuts across variably dipping, sedimentary rocks, low-grade metamorphic rocks and granitoids. The East-West Highway is one of eight locations, which has been declared and identified by the Malaysian government as a high-risk landslide activity area.

Within recent times numerous landslides have developed in the cut-slopes composed of soils developed from the *in situ* weathering of rocks as well as the less weathered rocks along the East-West Highway. Many of these landslides are only a few cubic metres in size, but some are large enough to have interrupted the free flow of vehicular traffic. Many of the landslides, which occur in the residual soil and weathered rock zones, are directly or indirectly controlled by relict discontinuities (Tajul Anuar Jamaluddin, 1991). This paper describes the occurrence and mechanism of discontinuity-controlled slope failures within the residual soil zone and the underlying weathered metasedimentary and metamorphic rocks, drawing on the experience gained from investigations of a number of landslides observed on the cut-slopes of the East-West Highway.

GEOLOGY

The highway cuts through a plethora of rock types and lithologic units. Based on the Geological Map of Peninsular Malaysia (Santokh Singh, 1985), Jones (1970) and detailed engineering geologic mapping by Tajul Anuar Jamaluddin (1991) the western segment of the highway is under-lain by a shale-sand-stone sequence intercalated with minor tuffs and cherts belonging to the Baling For-mation. These rocks have undergone both low-grade regional and dynamic meta-morphism to phyllites, slates, schists, metatuffs

Figure 1. Road map showing the location of studied slope cuts along the East-West Highway

and quartzites. The entire sequence has been complexly folded and faulted. Phyllite beds are either intact or occur as friable layers exhibiting distinctive brown and red brown hues. The beds vary in thickness up to 0.5 metres and possess a well-developed cleavage oriented sub-parallel to bedding. Thin clay layers often exist between phyllite beds. Some bedding surfaces are slickensided.

The Main Range Granite outcrops at the center of the highway. It consists predominantly of fine to medium-grained biotite granite and medium to coarse-grained porphyritic granite. The Cretaceous hornblend biotite granite (Santokh *et. al.*, 1984) is exposed near Batu Melintang and Pergau on the eastern end of the highway. Sandwiched between the granites are exposures of low-grade greenschist facies to amphibolite facies rocks such as quartz mica schist, mica schists, phyllites, slates, amphibole schists, quatzites and gneisses.

The rocks are affected by faulting dating way back to the Palaeozoic and Mesozoic to the Tertiary. The most dominant and persistent fault directions are NW–SE and N-S, and NE–SW. Most fault surfaces are slickensided. A moderate to strong degree of schistosity is developed in the metasedimentary and metamorphic rocks as a result of regional metamorphism. Usually, four to five well-defined major sets of joints are found in the rocks at any locality.

SLOPE STABILITY ANALYSIS

Although the cut-slopes on the metasedimentary and metamorphic rocks are of relatively small height, they present special stability problems due to their complex geology and structural characteristics. Slope instability is always a serious problem along the East-West Highway because of steep topography and cut-slopes, unfavourable geological condition and adverse climate. Abdul Ghani Rafek and Ibrahim Komoo (1987 and 1989) and Tajul Anuar Jamaluddin (1991) conducted detailed discontinuity surveys and analysis along the highway. Ahris Yaakup *et. al* (2000) monitored part of the slopes through GIS method. Common failure modes of rock slopes along the highway deduced from the studies are composed of planar, wedge, toppling and circular failures typical of cut-slope failures in hilly and mountainous terrains (Raj 2004).

This report presents the result of field assessments of selected slope failures along the East-West Highway. The study involved:

Engineering Geologic Analysis

The field data gathered from our surface geologic mapping was compiled on the project base maps. The results of the engineering geologic analysis are summarized in the accompanying engineering geologic maps for each section and tabulated in Figure 2.

Slope Stability Kinematic Analysis

The discontinuity data was analyzed statistically through the use of *ROCKPAC III* program (Watts, 1997). The susceptibility of each slope to undergo planar, wedge or toppling failure were analyzed using Markland's tests (Markland, 1972) for failure. The characteristics of the slope material are summarized below.

WEATHERING PROFILES

The low-grade metasediments and metamorphics are either partially decomposed or deeply weathered. The following four major zones (Figure 3) characterized the typical weathering profile in the metasediments and metamorphic rocks along the road cuts in the area (Little, 1969).

Zone I (Residual soil)

Made up of completely weathered bedrock (grade VI). Characterized by a mantle of structureless soil. the upper part of which may be transformed into laterite. The residual soil cover is generally thin or missing,

Zone II (Decomposed rock)

Made up of highly to completely weathered bedrock (grade III to V). Equivalent to the highly and moderately weathered rock mass of BS 5930 (British Standards Institution, 1981). Characterized by soil-like material, which retains features of the original rock structure and fabric. It may contain less weathered corestones. The zone may extend to thicknesses of over 20 m in many weathering profiles. When the rocks weather to the consistency of a soil, the structural and lithological features are preserved as relict discontinuities.

Zone III (Partially decomposed rock)

Made up of slightly to moderately weathered rock (grade II), consisting mostly of rock material separated by friable soil-like material along discontinuities or a continuous network of rock separated by seams of soil of varying thickness.

Zone IV (Fresh rock)

Made up of unweathered rock (grade I).

The weathering grades are after *International Society of Rock mechanics*, ISRM (Brown, 1981). A description of the geophysical characteristics of the weathered rocks at KM 67 of the highway can be found in Abdul Ghani Rafek *et al.*, (2001).

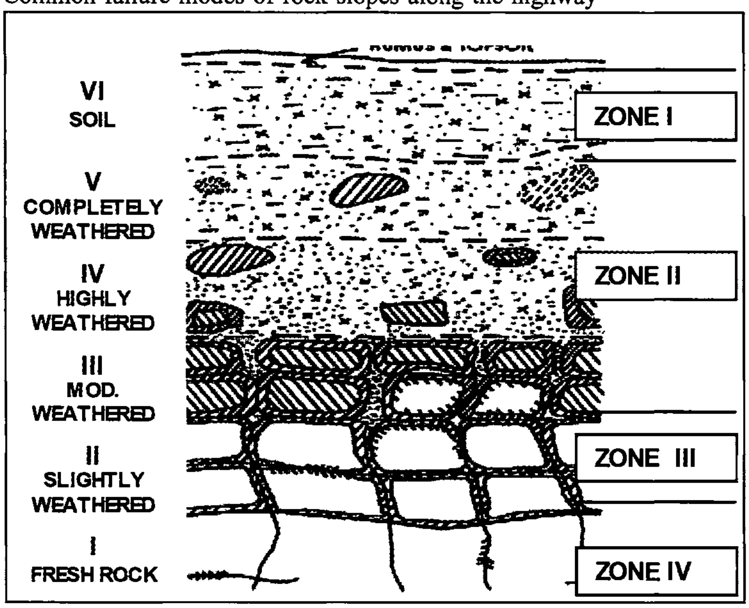

Figure 3. Schematic weathering zonation in the area. (Modified from Little, 1969)

Figure 2. A table showing the characteristics of slope failures along the East-West Highway

Slope	Slope steepness	Geologic conditions Soil and Bedrock	Type of failure	Shape of failure	Discontinuities	Structural control of failure
19.8	Steep (70 degrees)	Fresh to Moderately weathered foliated quartzitic slates sequence. Thick soil cover, orangey red silty CLAY	Geological induced slides: Rock and debris slides	Translational: Planar wedge	S1)340/40E Faults F1:280/40N F2 330/62 E F3 074/70 N Joints : J1) 033/34 W J2) 142/90 J3) 068/80 S J4) 092/26 S	Sliding surfaces/Planar failure: Along J1,
28.0	Steep (70 degrees)	Moderately to highly weathered foliated slates sequence. hick soil cover, orangey red silty CLAY	Geological induced slides: Rock and debris slides	Translational: Planar Wedge toppling	S0) 022/20-80N J1) 300/84 W J2) 243/42 W J3) 017/72 E J4) 118/85 S	Sliding surfaces/Planar failure: Along N dipping foliation, faults and joint surfaces. wedges with releasing joints: J3 and J4 toppling along J5
34.6	Steep	Filled gravelly to sandy material	Gulley erosion	-	-	Erosion induced failure.
43.1	steep (70 degrees)	Moderately to highly weathered well foliated Quartz schist with slaty horizons. Thick soil cover, orangey red silty CLAY	Geological induced slides: Rock and debris slides	Translational: Planar wedge	Foliation: S1: 017/56 E 168/10 E 155/59 E Joint: J1) 164/70 W J2) 030/60 S J3) 245/80 W J4) 075/80 S	Sliding along NS foliation surfaces and along weak slaty horizons parallel to foliations. Sliding facilitated by EW cross joints acting as releasing joints giving rise to wedge plunging S.
55.4	Steep (70 degrees)	Moderately to highly weathered and highly foliated schist with quartz lenses. Thick soil cover, brownish red silty CLAY	Geological induced slides: Rock and debris slides	Translational: Planar wedge	S1) 028/41 E J1) 220/40 W J2) 250/20 W J3) 010/30 W	Failure/sliding occur along Soil/rock contact defined by foliation and joint surfaces. Sliding surfaces/Planar failure: Along S1, J1, J2 J3 and J4
60.5	Steep (70 degrees)	Moderately to highly weathered biotite microgranite Thick soil cover, brownish red clayey SAND	Geological induced slides: Rock and debris slides	Translational: Planar wedge	S1) 009/40 E F) 330.60 E J1) 003/59 E J2)142/70 W J3)253/68 W J4) 060/56 E	Sliding along EW joint surfaces.
77.9	steep (70 degrees)	Moderately to highly weathered and highly foliated sshists with quartz lenses. Thick soil cover, brownish red silty CLAY	Geological induced slides: Rock and debris slides	Translational: Planar wedge	J1) 060/56 E J2)104/80 E J3)255/68 W J4)348/84 E F1)332/45 W F2)148/65 E S1)010/40 E	Sliding along NS foliation surfaces sub parallel to the slopes, Sliding facilitated by EW cross joints acting as releasing joints giving rise to wedge plunging S.
109.8	Moderately steep (50 degrees)	Damp Gravelly SAND	Tension fractures along road surface, subsidence Slumping on embankment	Circular	Tension cracks on road surface: 090/90 110/90 100/90 085/90 060/90 105/90	Failure on road embankment induced by infiltration of ponded water on the opposite side of the road.
114.1	Steep (70 degrees)	Moderately to highly weathered and highly foliated QUARTZITE with quartz lenses. Thick soil cover, brownish red silty CLAY	Geological induced slides: Rock and debris slides	Composite	S0) 082/30S J1) 068/78 S J2) 220/82 W J3) 163/71 W J4) 080/80 N	Sliding surfaces/Planar failure: Along J1, wedges with releasing joints: J3 and J4 Likely ponding on the opposite side of the slope.
119.7	Steep (70 degrees)	highly weathered to completely weathered granite. Thick soil cover, brownish red silty CLAY	Rock and debris slides	Translational: Planar Wedge toppling	J1) 128/58 E J2) 090/64 N J3) 022/57 E J4) 224/75 W	**Planar sliding planes along:** Moderately NORTHERLY dipping joints **Toppling:** Inward slope sw dipping joints **Wedge failure** Northwest plunging wedges.

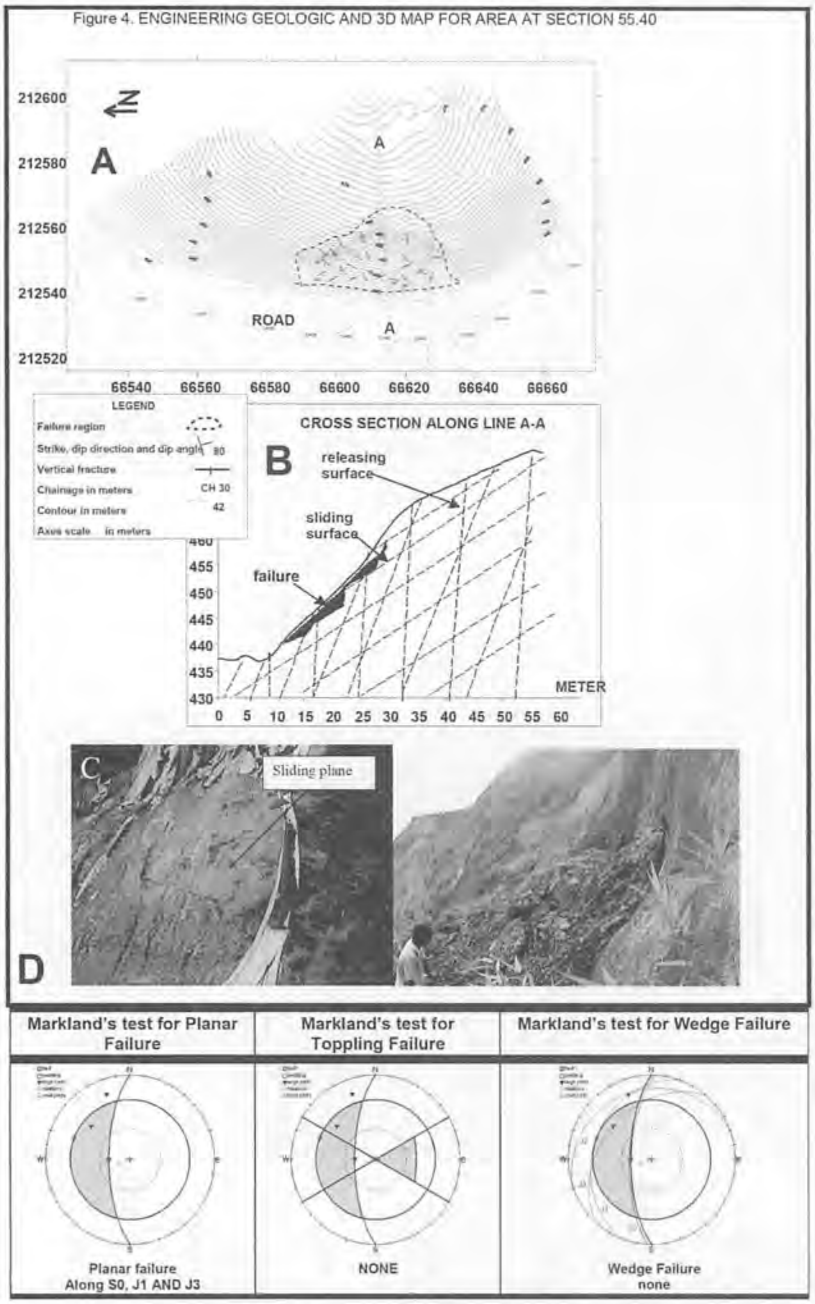

Figure 4. Characteristics of slope failures at km 55.

A) geologic map showing the Movement of loose soil and weathered fragments
B) cross section showing Movement of loose soil and weathered fragments
C) photographs showing the Movement of loose soil and weathered fragmentsalong the slope parallel sliding planes.
D) slope stability kinematic analysis results.

DISCONTINUITIES

Most of the sediments have been metamorphosed to slates, phyllites and schist. These rocks are characterized by the present of at least one set of foliation or cleavage. Weathered foliated metasediments are inherently weak. Foliation/cleavages, like bedding planes and joints, are natural planes of weakness. There is therefore, a greater propensity for sliding to occur along these surfaces. This sliding potential is enhanced in the metasediments as the rock sequence is thinly bedded and cleavage is well developed. Also, because cleavage is sub-parallel to bedding, the number of potential sliding surfaces in the direction normal to the strike of the beds is increased. This accounts for the repeated occurrence of planar sliding in the metasediments and metamorphics.

Joints and faults cut the rocks. Many types of mineral infillings and coatings may be present along joints and other discontinuities. The main types of infillings found along discontinuities are those formed as a result of weathering processes. They normally have a similar mineralogy to that of the weathered rock. Some discontinuities may be polished or slickensided as a result of internal deformation in the slopes. When the rocks weather to the consistency of a soil, the structural and lithological features are preserved as relict discontinuities.

DISCONTINUITY CONTROLLED SLOPE MOVEMENTS

Four types of mass movement have been identified:-

A) MOVEMENT OF RESIDUAL SOIL COVER

i) Movement of loose soil and weathered fragments.

Residual soil and fragments of weathered phyllite and quartzite move down slope gradually and accumulate as talus at the slope toe (Figure 4). The displaced debris represents loose soil and fragments, which have weathered from the surface layers of the parent material and have remained unstably positioned on the slope. Observation of these landslides has indicated that the downward movement occurs either along one plane of weakness that are either joint or bedding planes. The volume of material, which moves at any time, is generally small (a few cubic metres). However, other such unstable material can move down slope subsequently and add to the volume of the fallen mass. Typical examples of this type of movement are described as case 1.

Case 1 SECTION 55.4

The landslide is located along a westward facing road cutting that trends northerly and sloping 70^0 eastward

(Figure 4 A). It occurred on the top to the bottommost bench of the road cut. The slope is underlained by schistose sequence belonging to the Lower Palaeozoic unit. The rocks are well foliated with foliation parallel quartz veins. The beds are deeply weathered to clayey soil. The rock weathered to brownish red silty CLAY. They are highly fractured. Bedding/folia-tion is steeply dipping along the slope and can be distinguished from relict joints and fractures. The failure occurs as surface movement of soil and weathered materials. Failure occurs by sliding along the rock-soil contact, which is defined by bedding, and foliation planes (Figure 4 B, C and D).

Results of kinematics stability analyses (Figure 4 D) indicated that the moderately to steep westerly dipping foliation planes and NW dipping bedding planes are identified as the critical planes of weakness in the slope. These discontinuities meet the condition where planar failure is kinematically possibly.

The residual soil and weathered material already had some potential for swelling and surface creep. However, the creep movements observed at this site is considered to be initially controlled by the bedding planes and relict joints parallel to the slope face in the weathered material. They would have started opening up due to stress release subsequent to excavation. This mechanism, coupled with the swelling of clay minerals, would have resulted in the more rapid disturbance of the upper portion of the soil mass. Once disturbed, the mass would then have continued to deform at a slower rate with further weathering resulting in reduced shear resistance of the soil mass.

ii) Rotational sliding movements or slumps

In closely jointed weathered rocks and residual soil, in which failure is not controlled by one or two dominant discontinuities, but where the joints contribute to a general weakening effect on the soil mass, slope failure commonly occurs along an irregular or roughly arcuate surface. Many of the failures which occur in closely jointed highly to completely weathered metasedimentary rocks and residual soil are circular (rotational sliding or slumps) or, in the general case, of non-linear type when there is no strong control by one or other sets of discontinuities. Typical examples of this type of movement are described as case 2.

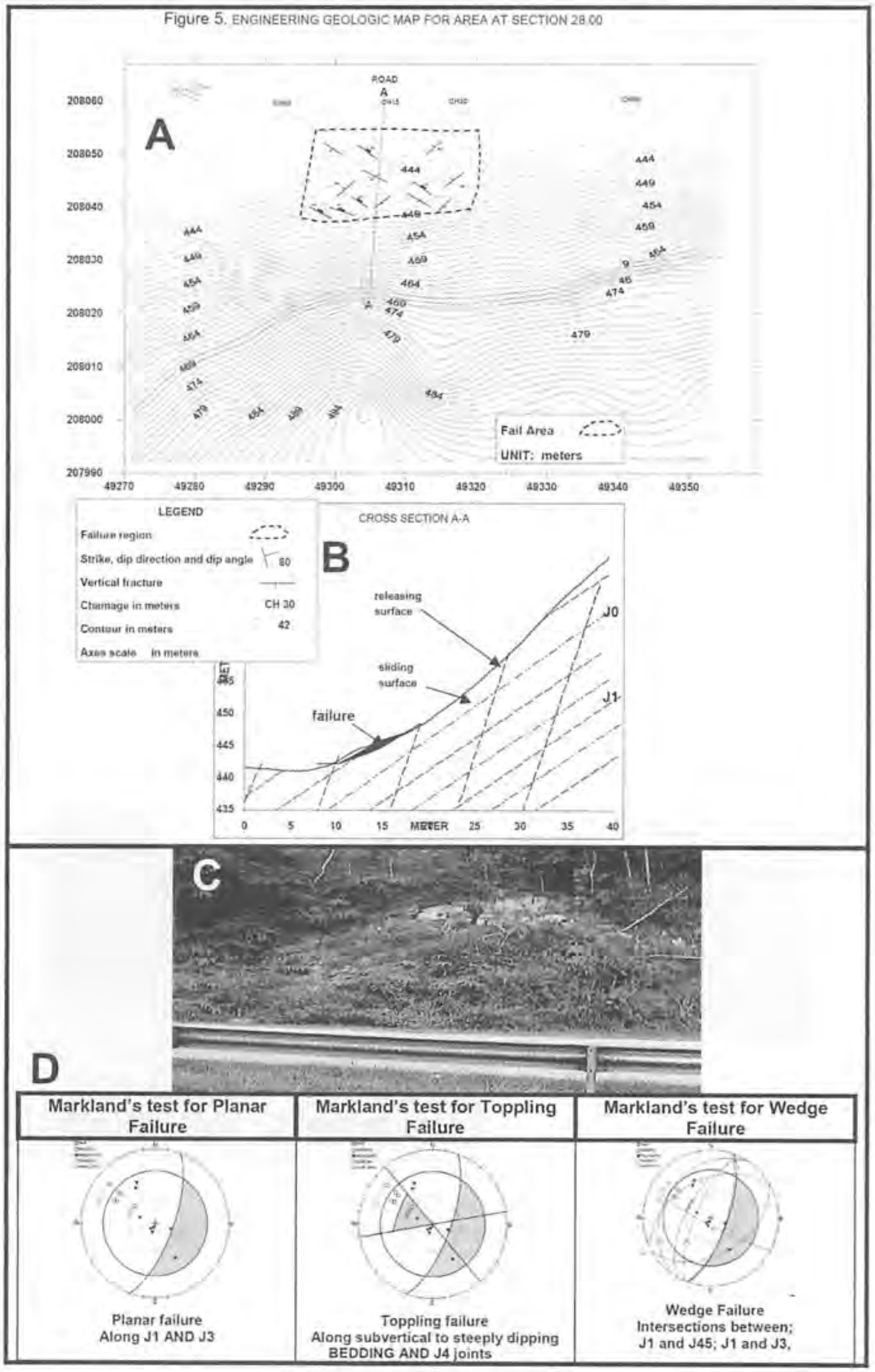

Figure 5. Characteristics of slope failures at km 28.00

A) geologic map showing the circular failure in soil slope.
B) cross section showing Movement of loose soil and weathered fragments
C) photograph showing the circular failure controlled by joints
D) results of slope stability kinematics analysis.

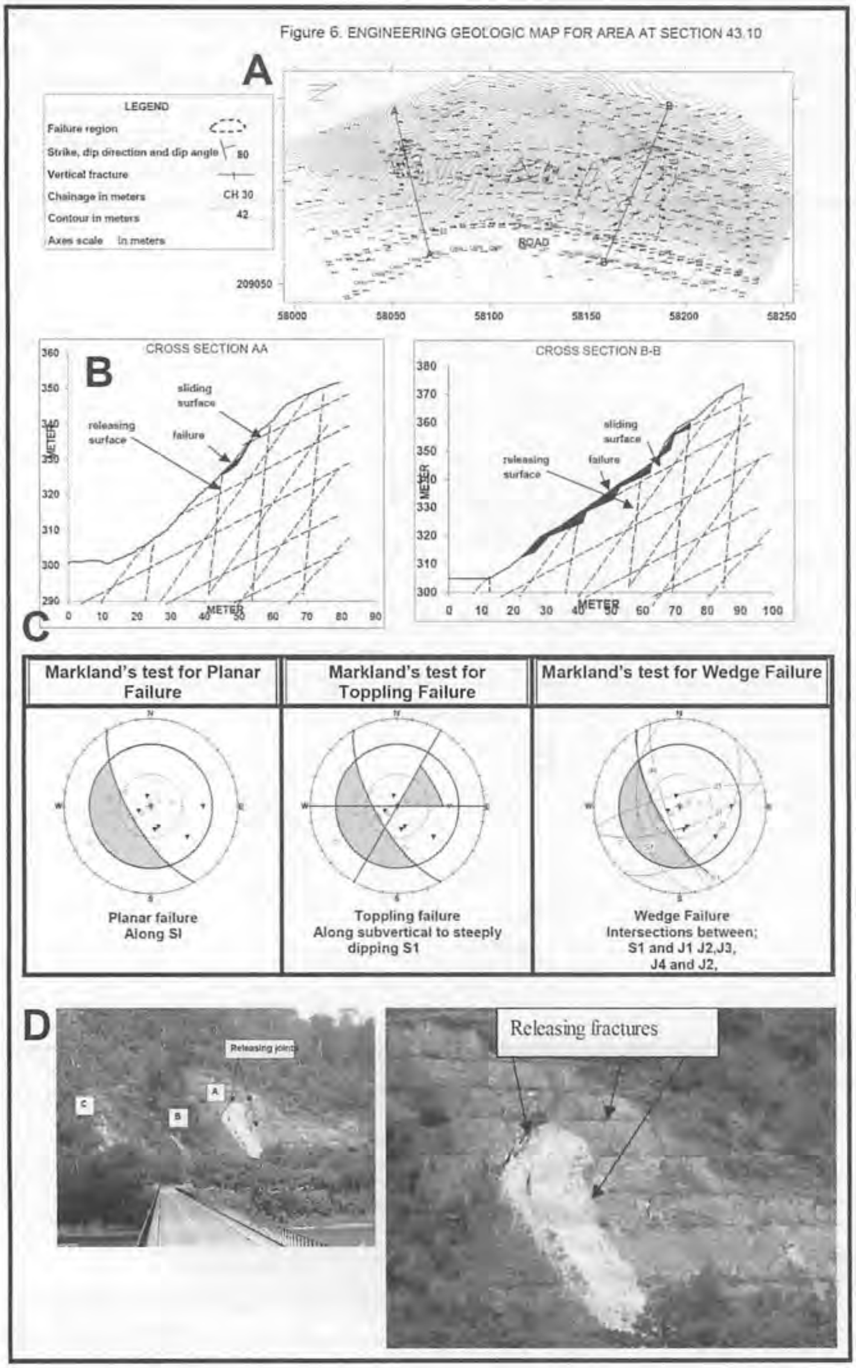

Figure 6. Characteristics of slope failures at km 43.1

A) geologic map showing the discontinuity controlled slope failure geometry.

B) cross section showing the sliding planes

C) slope stability kinematic analysis results.

D) photographs showing the releasing fractures and sliding planes.

Case 2 SLOPE 28.0

(Rotational sliding movements or slumps)

The landslide (Figure 5 A and C) is located along an eastward facing ($020^0/70^0$ E) road cutting that trends northerly and sloping 70^0 E. The failure took place in well-foliated slates with well-developed slaty cleavage (foliation surfaces), grading from completely to slightly weathered rock, with the depth of weathering being much greater in the upper portion of the slope. The rocks have been deeply weathered to clayey residual soil. The rock weathered to orangey red silty CLAY. At the bottom of the bench fresh slates rocks are exposed. They are highly fractured. At least 4 sets of major fractures are recognized (Figure 5 B).

The upper part of the landslide consisted of a deep rotational slip along a clay-filled relict joints joining with a translational planar slip along relict foliation in the lower part. Water seepage occurred along bedding/foliation surface at the head scarp region.

The moderate to steeply southeast-dipping bedding and east dipping fracture surfaces were utilized as the planes of sliding during the failure event (Figure 5 B and C). Failure also occurred along a well-developed set of southeast dipping fracture surfaces. The east and southeast-dipping fractures and bedding acted as sliding surfaces, while the sliding rock mass is allowed to separate from the slope along a third set of more steeply inclined northerly dipping fracture planes that bounded the slides which are used as releasing surfaces. Another releasing surface that facilitate the sliding is the westerly slope inward dipping joints

Based on the field observations and slope stability kinematics analysis (Figure 5 D):

- The slope failed by circular failure aided by discontinuities,
- Planar sliding planes along moderately south-easterly dipping joint planes
- Wedge failure along northerly and south-easterly joints

The presence of relict foliations and clay-filled joints at shallow depth within the weathered rock mass was a major contributory factor. Seepage reduces the stability of a slope by making it easier for the soil particles to slide over each other during failure. Similarly, pore water pressures associated the water saturated soil reduce the inherent strength and stability of the soil mass.

B) MOVEMENT OF LOOSENED BLOCKS (ROCKFALL)

Fragments of residual soil, and weathered phyllite and quartzite blocks exposed on the surface of the slope become detached from the rock mass and tumble downslope at a rapid rate. An example of this behaviour was observed at the huge sub-vertical cut-slope near the bridge on Pulau Banding. Fragments of residual soil, and weathered phyllite and quartzite, rolled from a height of more than 100 metres onto the roadway, where it disintegrated into smaller fragments of varying sizes. Observation of these landslides indicated that failure occurs either along one plane of weakness or between two planes and their line of intersection. In the latter case the unstable mass is confined in a wedge. In both cases the failure surface dips onto the slope face. This type of movement is uncommon and a typical example of this type of movement is described below.

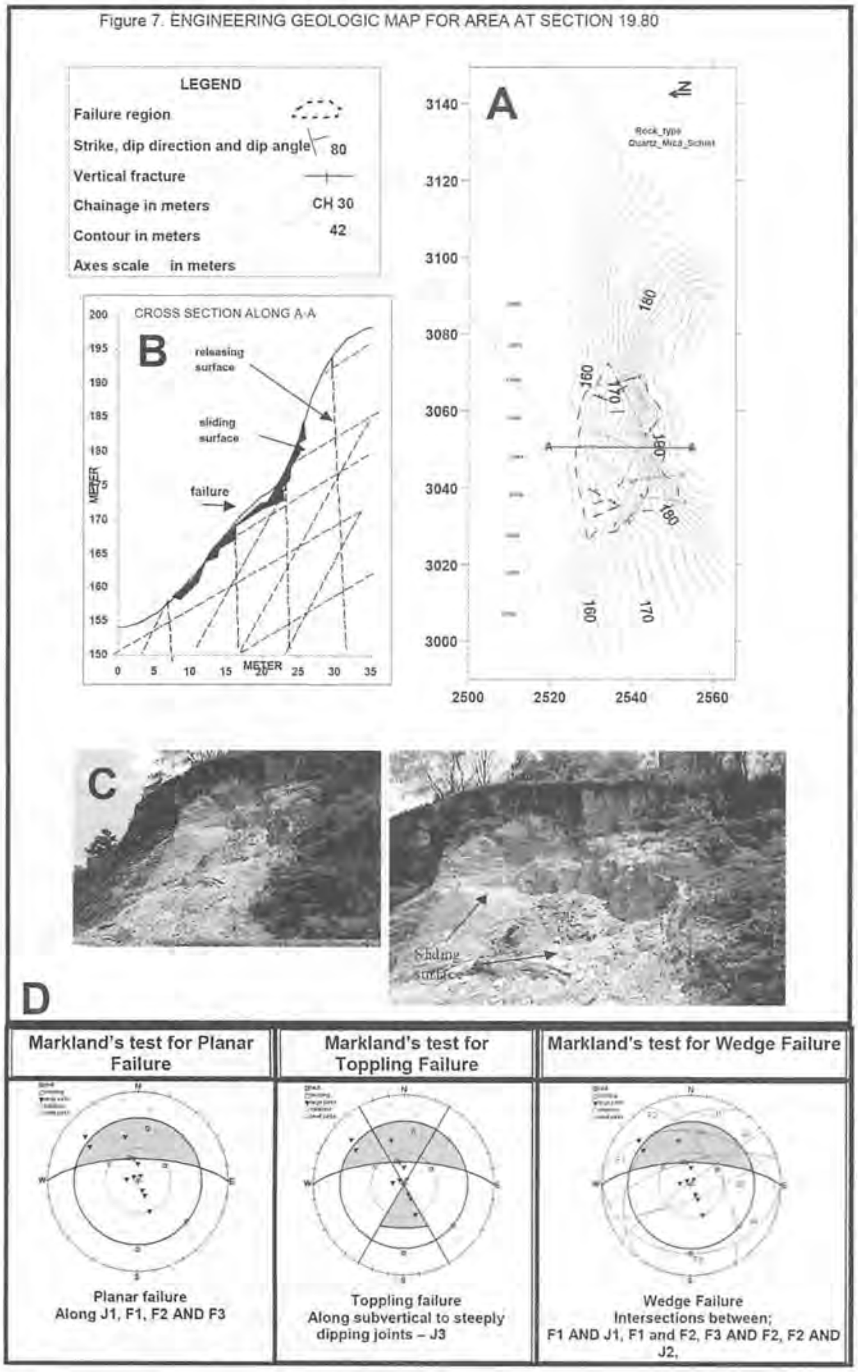

Figure 7. Characteristics of slope failures at km 19.8

A) geologic map showing the discontinuity controlled slope failure geometry.
B) cross section showing sliding planes
C) photographs showing the discontinuity controlled slope failure
D) slope stability kinematic analysis results.

Case 3 SLOPE 43.1

The cut-slope on Pulau Banding (Figure 6 A and D) is underlained by quartzite and phyllites/slates interbedding sequence belonging to the Lower Paleozoic unit. The rocks are well-foliated. The beds are deeply weathered to clayey soil. The rock weathered to orangey brown silty CLAY. They are highly fractured. Bedding/foliation is steeply dipping along the slope and can be distinguished from clay-filled relict joints and fractures.

This is a very large slope that has three separate failures (Figure 6). The landslides are located along a westward facing road cutting at Pulau Banding that trend northerly and sloping 70^0 westward. The 3 landslides are very similar to each other and will be described together.

Releasing and sliding fracture surfaces (Figure 6 A and D) are exposed in the portion of the slope that formed the head scarp and the sliding planes. Surrounding all the three failures there are over steepened slopes that are critically unstable. The head scarp is over steepened at a slope of 90 degrees. Presently, the entire head scarp region is extremely unstable. The head scarp geometry is controlled by the major fractures presence. The head scarp is bounded by a releasing fracture as shown in Figure 6 D. These releasing fractures are clay-filled major joint surfaces that strike easterly, southeasterly and northerly with moderate to steep day lighting dip.

In the upper slope, sliding is controlled by the location and orientation of the bedding and bedrock fractures (Figure 6 B and C). The foliation and bedding surfaces are sub-parallel to each other. They show contortions giving rise to warping of the strata. Although the strata are irregular, they generally dip southwesterly to westerly ranging from moderate to steep. Planar failure occurred along these strata. Where the strata dipped steeply inward of the slope (east dipping), failure in the upper slope region occurred by toppling. The moderate to steeply east-dipping bedding surfaces that dipped inward into the slope were utilized as the planes of toppling during the failure event.

Failure also occurred by sliding along wedges (Figure 6 C and D) that plunges southwesterly due to the intersection between fracture surfaces and bedding or between differently oriented joint surfaces followed by rapid tumbling of the failed mass down slope.

Based on stereographic projection shown in Figure 6 C, the discontinuities in slope 43.1 comprises beddings and at least of 4 sets of joints labelled J1 to J4: Based on the analysis as shown by the Markland's tests for failure: Failure occurred along south-westerly dipping foliations aided by variably oriented releasing joints that give rise to planar, wedge and toppling failures.

C) MOVEMENT OF INTACT ROCK ALONG A PREDETERMINED PLANE (SLIDES)

These are by far the most dominant, result in the largest slides and offer the greatest potential danger. The moving material consists of a mixture of slabs of weathered phyllites, quartzite blocks, weathered rock fragments and residual soil. The material is translated down slope en masse along a discontinuity, such as a bedding plane or cleavage surface. Because of the very weathered nature of the rock, the unstable material tends to break up at the slope toe. Such slides are invariably hundreds of cubic metres in dimension and, where they occur, invariably block the roadway. Observation of these landslides has indicated that failure occurs either along one plane of weakness or between two planes and their line of intersection. In the latter case the unstable mass is confined in a wedge. In both cases the failure surface dips onto the slope face. Typical examples of this type of movement are described as case 3.

Case 4 SLOPE 19.8

The slope is made up of fresh to moderately weathered well-foliated quartzite-slate sequence of Lower Palaeozoic age. The quartzite and slate beds weathered to clayey soil. The rock weathered to orangey red silty CLAY. They are severely fractured.

Figure 7 A - D illustrates slope at section 19.8. The failure includes rockslides and rock flows. The moderate to steeply northwest-dipping and northeast-dipping fracture surfaces was utilized as the planes of sliding during the failure event. Failure also occurred along a well-developed set of northwest-dipping foliation surfaces.

Our investigation has confirmed that the northeast and northwest-dipping fractures which act as sliding surfaces, while the sliding rock mass is allowed to separate from the slope along a third set of more steeply inclined easterly dipping fracture planes which are used as releasing surfaces. Presently, the movement at the toe of the landslide has been stabilized by the presence of a gabbion wall. Surrounding the failure there are over steepened slopes that are critically unstable. The head scarp is over steepened at slope angles of up to locally 90 degrees. Presently, the entire head scarp region is extremely unstable. In the upper slope, sliding is controlled by the location and orientation of the bedrock fractures. Releasing and sliding fracture surfaces are exposed in the portion of the slope that formed the head scarp and the sliding planes.

Based on the analysis as shown by the Markland's tests for failure (Figure 7 D). The slope is susceptible to planar, toppling and wedge failures.

D) PROGRESSIVE COMPLEX MOVEMENTS

Complex planar and wedge-type sliding conditioned by foliation, bedding planes and faults occur in slopes cut into complex folded metamorphic rocks. The complex slope failures involved relatively deep-seated/penetrative shear planes or zones conditioned by complex weathering and alteration conditions, and discontinuity patterns. This type of movement is uncommon and a typical example of this type of movement is described below.

Case 5 Slope 77.9

This slope (Figure 8 A – D) has been remedied several times but failures keep on occurring especially after heavy rain. Complex slope failures involving relatively deep-seated shear planes or zones conditioned by complex weathering and alteration conditions, discontinuity patterns, have occurred in cut slopes at section 77.9. The failure of these slopes, which had relatively gentle profiles of less than 60°, took place progressively with significant movements occurring during or shortly after rainfall, but not always heavy rainfall.

The slope is made up of schist sequence deeply weathered to clayey soil. The rock weathered to brownish red silty CLAY. They are highly foliated and fractured. Foliation is variably oriented and generally is moderately dipping along the slope and can be distinguished from relict joints and fractures.

The schist is well foliated and highly weathered. Weathering and erosion followed by continuous slope failures created a V-shaped valley. The axis of the valley is made up of a 2m wide zone of intensely weathered schist (Figure 8 D). Here the schist has been weathered to whitish clayey residual soil. The intense weathering occurs along a zone that parallels the schistosity planes and a major fault plane trending NS. The fault zone provides the weak zone where water seeped into the ground. Therefore e intense weathering preferentially occurs along the zone.

Less intense weathering occurs along the zones bounding the above zone of intense weathering. The schist was weathered to dark brownish silty clay exhibiting well-defined relict schistosity. Away from the central zone weathering is less intense.

The slope failure occurred along a V-shaped slope (Figure 8 D) that have undergone continuous failures as indicated by the fallen drains and disrupted benches. Continuous failures are concentrated along the fault zone parallel intense weathering zone giving rise to a V-shaped valley.

All failures occur along the V-shaped, oversteepened slopes. These slopes are critically unstable. At the main landslide the headscarp (slope B) is oversteepened at a slope near to 90 degrees. Presently, the entire headscarp region is extremely unstable. Erosion is continuously taken place along the intensely weathered zone. Sliding occurred along moderate southerly dipping joint planes and wedge failures occur as a result of intersection of foliation with releasing joint surfaces giving rise to southerly plunging wedges.

Erosion and failures along the axial weathered zone resulted in undercutting of the over steepened slopes. These result in the side slopes (slope A and C) to fail. Failure along these side slopes occurred by sliding along foliation planes and day lighting wedges created by intersection between foliation and joint surfaces.

Based on the analysis as shown by the Markland's tests for failure (Figue 8 C), the slope is susceptible to planar and toppling failures. Wedge failure may occur along the intersection of joints.

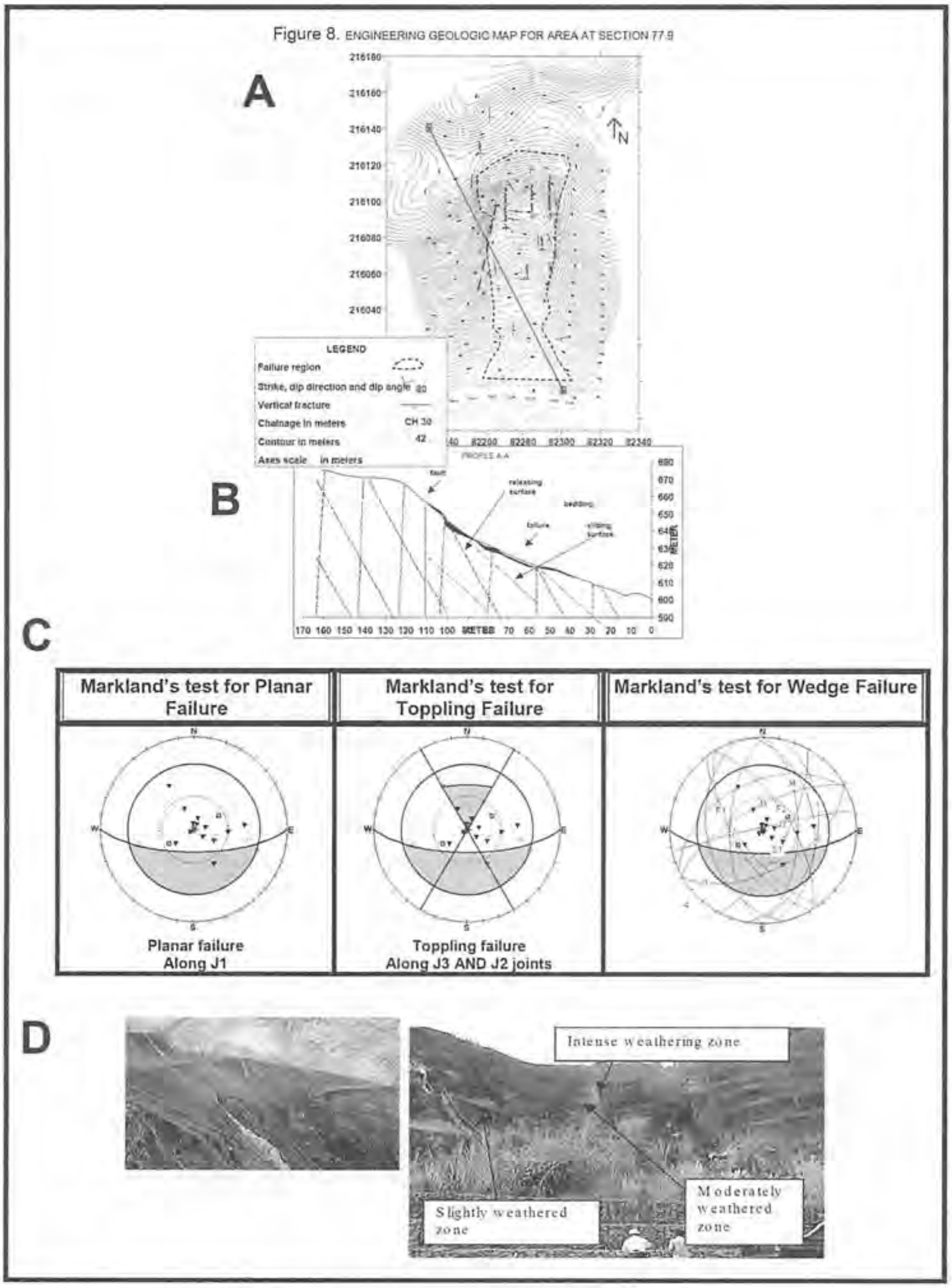

Figure 8. Characteristics of slope failures at km 77.9

A) geologic map showing the slope failure geometry and distribution of discontinuities.
B) cross section showing sliding planes
C) photographs showing the discontinuity controlled slope failure
D) slope stability kinematic analysis results.

DISCUSSION

A number of factors influenced the slope stability for the rock slopes within the metasediments and metamorphic rocks along the East-West Highway. These are:-

A) Weathering

The deeply weathered nature of the dominantly metasediments and metamorphic rocks is a major factor affecting its stability. These cut slopes have been subjected to mechanical and chemical alteration over time. The degradation due to weathering has resulted in a reduction in the strength of the material forming the slope. These increased the susceptibility of the material to slide.

B) Discontinuities

Unstable conditions resulting from weathering are compounded by the presence of numerous discontinuities. Discontinuities such as bedding, lamination, sedimentary horizons, lenses, fault or joint systems dipping toward the free-face of the slope (dip-slope) at about the same angle of the slope, constitute a well-known slope failure-prone condition. In the study area, regardless of the lithological type, discontinuities provide the slopes with a strong mechanical and hydrogeological anisotropy that controls the geometry and development of failures.

The dominant cause of slope instability however, is due to the existing relationship between the orientation and inclination of the slope and the bedding, foliation and joint directions. The steep slope face encourages gravity sliding by increasing the driving force causing down slope movement. Where such steep slopes occur in conjunction with beds and foliations, which intersect the slope face, the tendency is for the material above the planes to move down. Joint surfaces have the effect of breaking up the rock mass into individual blocks. Since many of the joints have clay infillings, the frictional resistance between joint surfaces is at a minimum and separation between blocks and subsequent failure results. Along dip-slopes (day lighting discontinuities) landslides initiate as translational or compound slides and transform into earthflow, mudflow or disrupted block slide.

C) Infiltration of Water

Unstable conditions resulting from discontinuities are compounded by the infiltration of surface water along these discontinuities. The numerous fissures in the rock, both those inherent in the rock and those caused by loosening of the rock structure as a result of its decomposition, give to the rock a high permeability. This facilitates rapid water infiltration. Infiltration is often to appreciable depth, since these structures extend deep into the slope. Water entering small cracks, joints, bedding and cleavage surfaces contribute to, deep chemical alteration of the slope material and encourages even deeper infiltration.

In addition, water causes swelling of clay beds and lubricates sliding surfaces. More importantly ingress of water triggers slope movement as it causes a rapid build-up of pore and joint water pressure in the weathered rock and residual soil.

D) Traffic Flow

Continuous traffic flow resulted in vibrations that contributed to failures by increasing shearing of the rock mass and sliding along the pre-existing sliding surfaces.

CONCLUSION

The slope movements recognised in the metasedimentary and metamorphic rock slopes along the East-West Highway are :- A) movements of rock-soil cover (i) Movement of loose soil and weathered fragments, ii) Rotational sliding movements or slumps, B) movements of loosened blocks (rockfalls), C) movement of intact rocks along predetermined planes (slides), D) non-linear mass creep and complex movements.

Slope failures are largely controlled by the unfavourable orientation of discontinuities with respect to the slope face compounded by the weathered nature of the rock. This accounts for the abundance of planar slides in the metamorphics. Infiltration of water and continuos traffic flow also contributes to slope failures by triggering movement down slope.

The occurrence of landslides in slopes which have been investigated and engineered may be the result of inadequate attention to structural features in the weathered rock mass during site investigations and construction (design).

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