

A Brief Overview of the Development of a Landslide Prediction and Management System for the East-West Highway, Malaysia

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Summary

This paper presents a brief overview of the development of a landslide prediction and slope management system for the East-West Highway in northern Peninsular Malaysia. The collection and effective utilisation of large amounts of data is discussed along with the development of landslide hazard and risk ratings for over 1,000 embankments and cuttings along the highway.

1.0 INTRODUCTION

The East-West Highway is located in the northern states of peninsular Malaysia and forms the only significant transport link between the east and west coasts in the northern section of the country. The highway is 112.6 km long and was opened in 1982 after a construction period of twelve years. The highway traverses the rugged Main Range mountains which, in the past, have formed a barrier to cross peninsular communications and commerce.

Even prior to opening, the highway had been affected by large landslides. This instability has continued with some landslides requiring road closures of up to a week. Fatalities due to landslides have occurred. Between 1982 and 1995 approximately 521 million Ringgit (roughly 250 million AUD at 1995 exchange rates) had been spent specifically on landslide remedial works on the highway.

There are several contributing factors that have lead to the development of widespread slope instability on the highway. These include:

- the rugged nature of the terrain (steepness, dense primary jungle);
- high rainfall;
- deep residual soil profiles; and
- an active communist insurgency during construction. Guerrilla activities resulted in the adoption of high embankments and steep cuts to avoid the sabotage of tunnels and bridges. The unrest also put a premium on speed and resulted in minimal forward planning i.e. selection of the best corridor. In addition construction was under armed guard and the surrounding jungle was mined.

In an effort to reduce its long term expenditure on landslide remediation, the Government of Malaysia

commissioned the "East-West Highway Long Term Preventive Measures and Stability Study" to provide a rational basis for the allocation of funds for landslide prevention, remediation and slope maintenance works along the highway. The team for this project was comprised of the Government of Malaysia, Perunding Zaaba (Malaysia), Soil and Rock Engineering (Malaysia), the University of Bristol and the University of Strathclyde.

The three year study was completed in September 1996 and resulted in delivery to the Malaysian Public Works Department of a prioritised listing of the risk of landsliding for all the slopes (1,123 slopes comprising 464 cuts, 577 embankments and 82 natural slopes) along the highway. This risk rating was then used to prioritise landslide prevention works. In addition a computerised database with a facility to allow updating of the conditions and the risk rating at each slope was handed over to Public Works Department.



Figure 1: East-West Highway Location

2.0 STUDY METHODOLOGY

The steps involved in producing the prioritised list of landslide risk ratings was:

1. Data collection and database development;
2. Development of a hazard rating for each slope; and
3. Converting the hazard rating of each slope into a risk rating.

Each of these steps are briefly discussed in the following sections.

3.0 DATA COLLECTION AND DATABASE DEVELOPMENT

Initially the data collection phase of the project involved obtaining, reviewing and cataloguing all previous documentation relating to the highway. The documents included site investigation reports remedial works reports and drawings, monitoring data (rainfall, piezometer, inclinometer etc) and other miscellaneous references. Note that no design drawings or completion reports were made during the original construction of the highway.

A six month field data collection programme collected slope specific data for all 1,123 slopes along the highway and involved up to four teams of geologists, geotechnical engineers and geomorphologists. A standard proforma was developed to capture what were considered to be potentially critical parameters influencing the stability of the slopes. The proforma required collection of up to 600 parameters under 13 main groupings. These groupings were:

1. Location;
2. Geometry;
3. Cover;
4. Pavement;
5. Geology;
6. Artificial Drainage;
7. Natural Drainage;
8. Erosion;
9. Side Slopes;
10. Instrumentation;
11. Current Stability
12. Comments; and
13. Sketches

Figure 2 shows one page from the seven page data collection proforma.

The data collected was entered directly into a computer database via the use of laptop computers in the field. This involved developing a set of protocols to ensure that the data was entered accurately and that the data was sensible. This was accomplished by a set of standard queries and alarms in the database package to ensure that extreme or unlikely values were not entered e.g. excessively high slopes, slope angles greater than 90 degrees, etc.). In addition cross referencing to other sources of information was undertaken where possible.

EAST-WEST HIGHWAY LONG TERM PREVENTATIVE MEASURES AND STABILITY STUDY Field Data Collection Proforma: EMBANKMENTS, CUTS, GRADES, NATURAL SLOPES

| | | | |
|------------------------------|--------------|--------------|-----------------|
| Feature Number | <u>157</u> | Feature Type | <u>1</u> |
| Primary or Secondary Feature | <u>1</u> | Age | <u>3</u> |
| Logged by | <u>SJNAJ</u> | Date | <u>29/03/94</u> |

NOTE: Some data will be better estimated from desk studies (eg: aerial photos etc). Enter a field estimate with a ? and modify in the office if necessary.

1) LOCATION

| | | | |
|-----------------------------------|---------------|----------------------|-----------------------|
| Position: Left/Right side of road | <u>2</u> | Up/downslope of road | <u>2</u> |
| Chainage: Start | <u>25.520</u> | Finish | <u>25.610</u> |
| Reduced Level | <u>453.56</u> | | |
| Associated Primary Feature No.s | <u>293</u> | <u>295</u> | <u>292</u> <u>296</u> |

2) GEOMETRY

| | | | |
|-------------------------------------------------------------------------|------------|-------------------------|-----------------------------------|
| Recorded Configuration | <u>1</u> | | |
| Slope height | <u>1.4</u> | Slope type | <u>2</u> Feature area <u>2500</u> |
| Feature aspect | <u>130</u> | Slope angle | <u>28</u> |
| Number of benches | <u>1</u> | Bench width | <u>2.5</u> Batter height <u>7</u> |
| Slope cross section | <u>4</u> | Slope plan profile | <u>2</u> |
| Ratio of crest length to edge length | <u>0.9</u> | Distance to ridge/gully | <u>0</u> |
| Distance from centreline of highway to toe of slope/crest of embankment | | | <u>70</u> |

| | | |
|----------------|--------------------------------------------------|-------------|
| For cuts only: | Relationship between road cutting and topography | <u>9999</u> |
|----------------|--------------------------------------------------|-------------|

Is there a secondary feature above/below the feature being logged? Y/N? N. If no, ignore the contents of this box. If yes, complete additional NATURAL SLOPE, CUT, EMBANKMENT, or GRADE proforma as required. Enter reference number of Data Sheet following 9999 (enter feature number prefixed C for cut, E for embankment, etc.). In addition the following data should be recorded for upslope features:

| | |
|-------------------------|----------|
| Upslope catchment area: | <u>0</u> |
|-------------------------|----------|

Is there structural works at the slope? Y/N? N. If no ignore the contents of this box. If yes complete STRUCTURAL SUPPORT proforma reference S 9999 (enter feature number).

3) COVER

| | | | |
|--------------------------------|-------------|-------------------------------|-------------|
| Feature Uncovered (%) | <u>0</u> | Main Cover Type | <u>3</u> |
| Vegetation cover (%) | <u>100</u> | Vegetation cover tree (%) | <u>100</u> |
| Artificial cover (%) | <u>0</u> | Condition of artificial cover | <u>9999</u> |
| Weepholes in artificial cover: | <u>9999</u> | Weephole Flow | <u>9999</u> |
| Logging on feature? | <u>9999</u> | Distance to tree line (m) | <u>9999</u> |

FOR CALCULATION PURPOSES ONLY:

| | | | | | | | | | | | | | |
|------------------|------------|----------|---|---|---|---|---|---|---|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Batter height(m) | <u>6</u> | <u>8</u> | | | | | | | | | | | |
| Bench width(m) | <u>2.5</u> | | | | | | | | | | | | |

Figure 2: Field Data Collection Proforma

Running simultaneously with the slope data collection programme was a survey of the entire highway length including a minimum 300 metre corridor on either side of the highway. Note that the only existing survey of the highway comprised 1:50,000 topographical maps which were of limited use. The survey was completed using an Airborne Laser Survey which utilises a laser pulsating 2000 times per second from a helicopter platform to penetrate dense foliage and return true ground data. The helicopter is located in real time by continuous reference to GPS earth stations established prior to flying. The helicopter flew flight lines at 40 metres separation over a minimum 600 metre wide corridor. Vertical and spatial accuracies were within one metre. An additional benefit of the laser survey was to provide coordinated and elevated video images of the entire highway length.

4.0 THE DEVELOPMENT OF HAZARD RATINGS FOR EACH SLOPE

For the East-West Highway project hazard was defined as the probability of slope instability during the lifetime of the highway. Note that this definition contains no reference to the size of the failure.

The full dataset of 1,123 slopes was split into two subsets, embankments and cuts. natural slopes were included in the cuts subset.

In addition the data set was subdivided into "environments" where slopes considered to be similar were grouped for analysis. Environments were created based on geology, elevation and terrain units.

A total of six different predictive slope stability models were used to derive a hazard rating for each slope with two of these methods giving the best results. These two methods were:

1. A statistical Discriminant Analysis; and
2. A Factor Overlay Analysis.

These two methods are discussed in the following sections.

4.1 Discriminant Analysis

Discriminant analysis is a statistical method of representing the separation between two or more groups of data belonging to a common set of variables. For the purposes of this study the Discriminant Analysis may be used to categorise the slopes into stable and failed groups by producing a discriminant function that models the data set. This model is of the form:

$$Y = a_1X_1 + a_2X_2 + \dots + a_n X_n + b$$

where, a and b = constants; and

X = variables (e.g. slope height etc.)

Variables considered statistically insignificant when discriminating between failed and stable slopes were excluded by the SPSS software package used for this analysis. The stability of a new slope can be evaluated by substituting the appropriate variables into the model function and determining its discriminant score Y_1 . If Y_1 is greater than the mean discriminant score the slope is classed as potentially unstable. These scores can be interpreted as the probability of a slope failing and therefore can be ranked and a relative hazard rating assigned.

A stepwise Discriminant Analysis was performed on the data set to rank the variables in terms of their statistical ability to discriminate between failed and stable slopes. Tables 1 and 2 show variables from this analysis ranked in terms of their statistical ability to predict failures for geological environments.

The results in Tables 1 and 2 indicate that:

- Erosion is a key indicator of potential instability. Note that for the results to be meaningful it is essential that the field recording programme differentiates between failure caused by erosion and failure causing disruption to drainage which then results in erosion;

There are a number of apparent contradictions with the variables in these lists. For example the number of drains variable for embankments (NO_DRAIN)

suggests that as more drains are placed on the slope, the more likely it is to fail. What must be kept in mind is that the Discriminant Analysis is selecting these variables purely on a statistical basis. With the NO_DRAIN variable an increased probability of failure may reflect that the drains are blocking or breaking and thereby introducing water to the slope. Alternatively, the NO_DRAIN variable may have been selected by the Discriminant Analysis in combination with all the other variables as a good discriminator between stable and failed slopes i.e. on a purely statistical basis and not on the number of drains on the slope;

Table 1: Significant Variables - Cuts

| GEOLOGICAL ENVIRONMENT | | |
|-------------------------------------------------|-----------------------------------------------|-------------------------------------------------|
| Granites | Metasediments | Sediments |
| Erosion | Erosion | Slope height |
| Bench drains | Number of water courses adjacent to the slope | Erosion |
| Relationship between the cutting and topography | Distance to ridge behind the slope | Distance to tree line behind the slope |
| Distance to ridge behind the slope | Plan profile of the slope | Relationship between the cutting and topography |
| Elevation | Batter height | Culverts |
| Vegetation cover | Rock Condition profile | Horizontal Drains |
| | Slope angle | Slope angle |
| | Slope height | |

Table 2: Significant variables - Embankments

| GEOLOGICAL ENVIRONMENT | | |
|-----------------------------------------------|-----------------------------------------------|------------------------|
| Granites | Metasediments | Sediments |
| Erosion | Erosion | Erosion |
| Vegetation cover | Age | Vegetation cover |
| Age | Number of water courses adjacent to the slope | Slope height |
| Slope height | Distance to ridge behind slope | Slope cross section |
| Horizontal drains | Batter height | Number of drains |
| Bench drains | Bench Drains | Upslope catchment area |
| Number of water courses adjacent to the slope | Slope height | Feature area |
| Culverts | Number of benches | |
| Elevation | Culverts | |
| Slope area | Vegetation cover | |
| Distance to ridge behind the slope | Ratio of crest length to edge length | |
| Number of drains on slope | | |

- For cuts, variables reflecting external influences such as erosion are dominant with variables reflecting slope geometry (eg. slope height) also significant; and
- For embankments, variables reflecting external influences such as erosion are dominant with variables reflecting material properties also significant. Material properties are reflected through the AGE variable which is the years since construction of the embankment. Embankments that have been reconstructed since the highway opening in 1982 (due to road realignments or landslides) were generally constructed to higher standards than the original embankments. This reflects the difficulties experienced during the initial construction of the highway.

There is some overlap in the variables listed in the Tables 1 and 2. For example, the material properties will influence the susceptibility to erosion hence the high ranking of the erosion variable may be at least partially influenced by the material properties.

4.2 Factor Overlay Analysis

To derive a hazard rating for the slopes, the Factor Overlay Analysis method involved the following steps:

1. Selection of significant parameters believed to contribute to instability. These were selected based on the ranking of variables that the Discriminant Analysis determined were statistically the best indicators of instability.

2. A maximum weighting of 2.0 and a minimum weighting of 0.1 was assigned to each parameter.
3. The parameters were subdivided and each division was assigned a weighting based on the number of known failures. An example of this process is shown on Figure 3.
4. For any slope a hazard value is then calculated by summing the sub-parameter values. These were converted to hazard ratings of very high, high, moderate, low and very low based on a linear split of the maximum and minimum hazard values.

Various methods of selecting parameters and assigned weightings were trialed in an attempt to refine the Factor Overlay Analysis method to produce the best results.

4.3 Other Methods of Determining Hazard Ratings

Several other methods of determining hazard ratings for the slopes were trialed in the project. These included a method proposed by the Geotechnical Control Office of Hong Kong. This method was modified slightly for the conditions on the East-West Highway and involved a process similar to the Factor Overlay Analysis method except that the significant parameters were as used in Hong Kong, as was the sub-parameter weightings.

An Applied Engineering Judgement method was utilised where the project team selected what they considered to be the most significant parameters causing instability based on their understanding of the conditions on the highway. Sub-parameter weightings were then selected between the

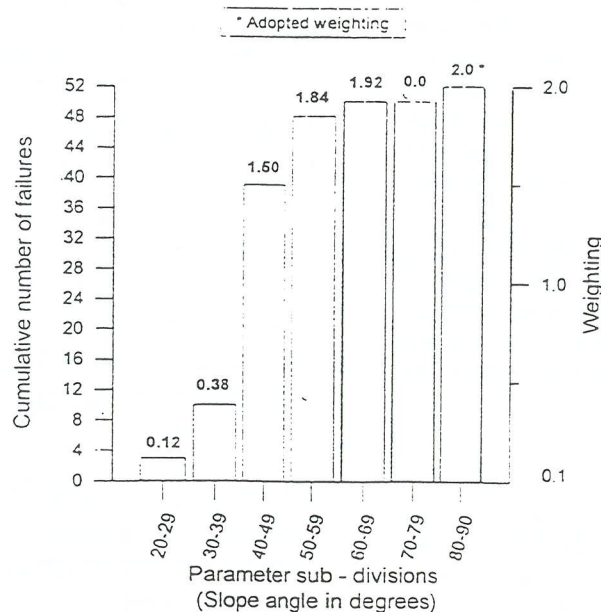


Figure 3: Factor Overlay Sub-Parameter Weighting

Figure 4.

ranges of 0.1 to 1.0 or 0.1 to 2.0 dependent on how influential that parameter was thought to be. In addition, some multipliers were utilised to allow for parameters that could not be applied to all the slopes. For example, if the presence of a black shale was observed in a cutting the hazard value would be multiplied by 1.5.

4.4 Selection of Hazard Rating Method

A method to compare landslide hazard maps produced by different assessment methods was proposed by Gee (1992). The method involved comparing different hazard rating classes (very low to very high) within each method. The method that gives a good separation between the high and low hazard classes, with the majority of the known failures in the high class, being the best method.

This method was adapted to the East-West highway project to compare the various hazard rating models.

Under the method proposed by Gee the statistical Discriminant Analysis method was the best performing hazard rating model and the results of this method were used to derive the final hazard ratings. The Factor Overlay Analysis method was the next best performing method although it should be noted that the Factor Overlay Analysis method in part used the Discriminant Analysis result to select significant parameters. Note that the methods based on engineering judgement performed least well.

5.0 RISK RATING

For the East-West Highway project risk was defined as the probability of failure multiplied by the consequences of failure. The probability of failure is obtained directly from the hazard rating as described in Section 4.0. The consequence of failure was calculated as follows:

For embankments = $S + V + R$;

For cuts = $S + P + R$;

where, S = size of failure;

R = time required to re-route the road;

V = vulnerability (a measure of the degree to which the expected failure would affect the road e.g. a slip affecting one lane of a four lane highway would pose less of a problem than a slip affecting one lane of a two lane highway; and

P = proximity of the cutting to the road.

A numerical weighting was applied to each of these parameters (S , V , R and P) and a consequence of failure calculated. An example of the weightings for the re-routing parameter is shown in Table 3. From these weightings a final risk value was obtained by multiplying the consequence value by the hazard value. These risk values were then rated as very high, high, moderate, low and very low on a linear split between the highest and lowest values. Plans showing the risk rating of each slope on the highway were then produced and an example of one of these maps is shown on Figure 4.

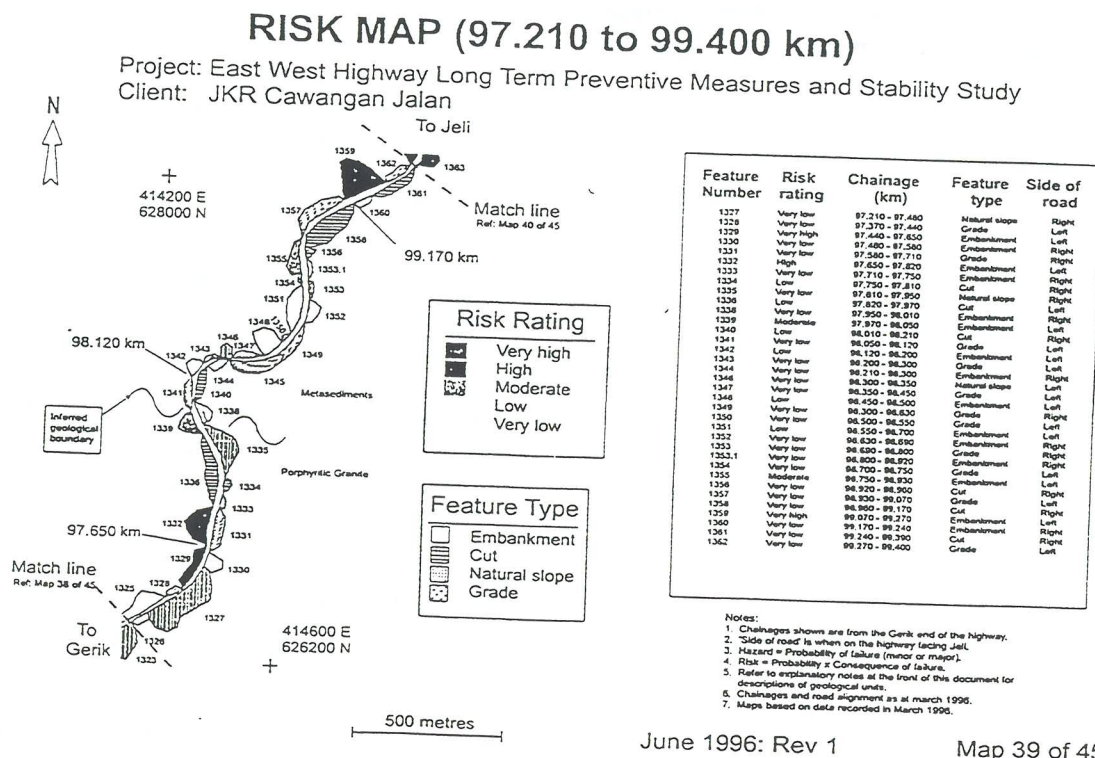


Figure 4: Example Risk Rating Map

June 1996: Rev 1

Map 39 of 45

Table 3: Numerical Weighting for Re-routing

| Days to Re-route | Numerical Weighting |
|------------------|---------------------|
| 4 days or more | 4 |
| 3 days | 3 |
| 2 days | 2 |
| 1 day or less | 1 |

6.0 CONCLUSIONS

The methodology developed for the East-West Highway Long Term Preventive Measures and Stability Study Project provides a rational basis for evaluating the risk of landsliding along the Highway. The method does not rely on subjective assessments of the probability of landsliding and the methodology could equally be applied to landsliding anywhere, including Australia.

One of the key findings of the study was that a statistical approach can be effective in identifying instability provided that data of sufficient quality and quantity can be collected and that careful selection of data subsets is undertaken. In addition, the dataset must continually be updated if it is to continue providing a useful tool in evaluate the risk of landsliding.

7.0 ACKNOWLEDGMENTS

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