

Investigation on Slope Stability Using Monte Carlo Simulation: A Case Study of Ulu Jelai Hydroelectric Project



Abdul Rahman Nurul Umibaiti

Abstract Slope safety and its monitoring are major concern for dam owners, especially if the slopes are adjacent to public highway or roads that experiences increase in traffic volume each year. If no proper assessment and maintenances are being done, there is potential for loss of life of public users. Deterministic design methods for the slope stability often depends on the interpretation of the geotechnical investigations by the geologist and civil engineers involved with the project. This method usually adopts conventional value of ground parameters and which then gives large safety factors. By performing probabilistic approach by utilising Monte Carlo Simulation, designers or owners are more confident with the results given and it will help in the decision-making, such as in deciding the best solution for the long-term maintenance and monitoring of the slopes at critical area. This paper described the probabilistic procedure and gave a distribution of Factor of Safety (FOS) rather than only one single calculated FOS for that critical slopes. The case study for the paper is the Ulu Jelai's dam located in Cameron Highlands, Malaysia. The analysis is done using both excel and software. At the end, proper mitigation plans are proposed for the critical slopes [1].

Keywords Factor of safety · Slope stability · Highway · Dam
Monte Carlo simulation

1 Introduction

Analysis of slope stability is usually consist of many uncertainties, which range from lack of accurate geotechnical parameters, inherent spatial variability of geo-properties, change of environmental conditions, unpredictable mechanisms of failure, simplifications and assumptions used in geotechnical models.

A. R. Nurul Umibaiti (✉)

Department of Civil Engineering, Universiti Tenaga Nasional,
43000 Kajang, Selangor, Malaysia
e-mail: nuruluar@tmb.com.my

Typical and conventional way of slope stability calculations usually will not consider many uncertainties in the process of getting the results. Also, several conservative safety factors are used to cover some uncertainties which in most cases are more than required, and in some cases are less. Actually, it is not possible to distinguish the accurate effect of these safety factors on safety level. By contrast, in probabilistic approaches the safety determination applies more accurately and clearly.

Monte Carlo Simulation is a useful tool that available for applying the probabilistic approaches in many fields. An iterative process using deterministic methods of slope stability analysis are applied in this technique. This method consists of five steps as follows:

- Selection of input variable for the calculation.
- Select a random variable for each input variable chosen earlier as per assigned probability density function.
- Calculate the factor of safety (Fellenius, Bishop Simplified Method, Janbu, etc.) based on the selected figure in Step 2.
- Step 1–3 is repeated for 500, 1000 or 1500 depends on the engineer.
- Determining distribution function of factors of safety and probability of failure.

The left bank of the Ulu Jelai Dam located in Malaysia has been considered as a case study, analysis has been accomplished using both software and excel calculation [2].

2 General Geology of Cameron Highlands

Ulu Jelai is located at the Cameron Highlands, Pahang, Malaysia. Cameron Highlands is located within the central part of the Main Range, which is underlined by Main Range Granite. The Main Range Granite consists predominantly of Late Triassic intrusive biotite granite and roof pendants of Lower Paleozoic sedimentary rocks intruded by minor quartz dykes. The main range granite crystallise in late Triassic is about 207–230 Ma (Fig. 1).

3 Salient Features Ulu Jelai Hydroelectric Project (Ulu Jelai HEP)

Ulu Jelai's dam was constructed on Susu river at Bertam Valley, Cameron Highlands, Pahang, Malaysia. The salient features of Ulu Jelai's Dam are represented in Table 1.



Fig. 1 General geology of Cameron Highland

Table 1 Salient features of dam

Item	Details
Dam type	Roller compacted concrete
Crest length	512.5 m
Maximum water level (MWL)	EL 548
Dam crest width	5 m
Reservoir gross storage	18.62 mm ³
Maximum operating level (MOL)	EL 548
Dam's height	88 m
Full supply level (FSL)	EL 540
Extreme minimum operating level (EMOL)	EL 524
1 in 100 year flood level	EL 548

4 JKR Road—Highway Adjacent to Dam

During the early stages of the design of Ulu Jelai’s HEP, it was identified that drawdown of the reservoir during operation could possibly influence upon performance and stability of the Pos Betau—Lembah Bertam Road. This road is a highway class single carriageway road and wide shoulder in each direction. It

transverses along the rim of the Susu reservoir. The road completed in 2010, and it is under the responsibility of the Malaysian Jabatan Kerja Raya Authority (JKR). After this, the road is referred as the 'JKR Road'.

The slope on which the JKR Road has built are steep with local relief of several hundred metres. The height from the JKR Road to the bed of Sg. Bertam is about 100 m at the Susu Dam right abutment to about 20 m at the upper reach of the planned reservoir.

The road is about 60–80 m above the riverbed. These intervening slopes are at natural gradients of 20–40°. Normal operation of the Ulu Jelai HEP will result in rapid drawdown of the reservoir. There is potential that some of the slopes adjacent to the JKR Road, road embankments and road retaining structures are expected to be affected by the filling and operation of the reservoir.

4.1 Potential Modes of Instability for the Slope

The fluctuations from the reservoir could possibly affect the highway in a number of ways

- Undercutting of the toe of embankments and walls;
- Slope instability of road embankments;
- Instability of retaining structures;
- Differential settlement of the road;
- Culvert inundation may cause piping erosion of backfill.

Depending upon the setting, slope conditions, material types and the slope profile the modes of failure will vary. The following main modes of instability are considered possible:

- Rotation (or circular) slope failure;
- Non-circular slope failure;
- Retaining structure failure;
- Differential settlement;
- Debris (or mud) flow.

Rotational slope failure would be limited to generally uniform soil profiles where the slide surface does not reach the bedrock surface. Such a scenario could be on the long slopes both above the road and below the road, but both sites would likely have different driving mechanisms. A failure above the road may be due to the undercutting or removal of the supporting toe of the slope, whereas a failure below the road could be due to a raising of the groundwater table and consequent pore water pressure increase. Where the bedrock level is intersected by a failure surface the mode would change from a circular failure to a non-circular failure or a planar slide surface. Where large boulders are present in the slope face the failure mode could be due to a toppling mechanism or a rock fall.

If a retaining structure failed this may lead to a slump or driving wedge where a mass of material loads a lower part of the slope thus leading to a type of progressive failure. This may also be the case where differential settlement of the road surface causes a transfer of load down the slope and thus induces a type of progressive failure. The performance of this road is potentially affected by the filling of the reservoir and the fluctuations of reservoir level during operation of the dam. The raised water level and drawdown operation of the reservoir will affect the groundwater levels, causing increased pore pressure within the soil and weathered rock that can result in instability, in the slopes below and above the road and the road bench itself.

The road in its present state has exhibited significant signs of instability once groundwater or storm water increases the degree of saturation in the existing slope.

4.1.1 Design Considerations, Uncertainties and Limitations

It is considered that slopes that are flatter than 2H:1 V may experience some instability during reservoir operation but are unlikely to impact immediately on the performance of the JKR road.

In establishing a factor of safety criteria, a literature review has been undertaken of relevant references for highway and dam projects. The findings from this review include

- I. JKR Guidelines for Slope Design Table 2, Reinforced or treated slopes FOS = 1.5.
- II. Wilson and Marsel (1979—ICOLD)—Table 2:

Table 2 Geotechnical investigations and results of laboratory tests of the JKR’s road

Material	Average thickness encountered along JKR road (m)	Interpreted seismic velocity (m/s)	Typical SPT N—Value range (blows/300 mm)	Results of laboratory tests
Fill	9	0 to 400	0 to 10	Sandy silt—sandy clay
Residual soil	5	0 to 800	0 to 10	Sandy silt—sandy clay
Completely weathered granite 1	5	800 to 1200	10 to 30 (with minor cored section)	Sandy silt or sandy clay, with gravel, cobbles and boulders
Completely weathered granite-2	6	1200 to 1600	20 to 50 (with numerous cored sections)	Bouldery silty sand
Granite bedrock	—	Greater than 1600	Continuous coring	—

- FOS = 1.5 using effective strength parameters and estimated flow net drawdown piezometric surface (as carried out in our JKR road stabilisation designs).
 - FOS = 1.2 sudden drawdown from spillway crest—not considering flow nets calculating drawdown of piezometric surface during drawdown.
- III. FHWA-NHI-10-024 ‘Design and construction of Mechanically Reinforced Stabilised Earth Walls and Reinforced Soil Slopes’:
- FOS = 1.5 for slopes where limited and variable geotechnical information is provided or slopes support structures or where consequences of failure of supported structure are severe, (i.e. full or partial closure of a highway class road).
 - FOS = 1.3 for slopes not supporting structure/slopes above infrastructure and only minimal to minor consequence of failure, i.e. movement of a sign foundation.
- IV. United States Society on Dams USSD (Feb 2007)—‘Strength of Materials for Embankment Dams’, considering effective strength parameters:
- USACE—FOS = 1.3 for Sudden drawdown from Max storage pool crest.
 - USACE—FOS = 1.4 to 1.5 Sudden drawdown when routine operating conditions.
 - USBR—FOS = 1.3 rapid drawdown from normal pool.

The considerations and limitations of the design inputs and analyses that have been included in developing the determination of FOS and its slope treatment, but are not limited to

- I. The JKR road slopes are supporting public R5 standard highway road infrastructure of 80 km/h speed limit.
- II. The original JKR road is understood to have been designed for a FOS of 1.5 in accordance with JKR guidelines.

4.1.2 JKR Road Investigations Results

See Table 2.

5 Geohazard Map—Further Assessment on Potential Instability of the Slope

Susu Dam fo the Ulu Jelai HEP has a hilly topography. Due to the construction of the dam, some slope within the study area had been cut for access road during the development of the dam. The cutting of a few slopes is steep with angle more than

45°. The minimum elevation of access road is 525 m around the dam crest area while the maximum elevation of the access road is 546 m located around kg Leryar. As the project advanced, geohazard mapping has been performed to further assess the potential instability and the most hazard areas that need particular attention.

From the map, it is found that no major fault is identified in the study area. The overall study area is underline by granite bedrock, weathered granite, residual soil and boulder at top of layer. While at certain areas of sub-surface there are areas with highly water content zone. kg Leryar, the nearest settlement, is not affected as it was not located at potential geohazard area and it is quite far from the potential geohazard area. Basically, the location potential geohazard area is, where there is cutting of slope more than 45° without proper erosion protection. Potential geohazard is identified at level 530–540 m due to fluctuation water level.

6 Factor of Safety (FOS) Results from SLOPE/W

The stability analyses using Slope/W have been carried out to find the factor of safety for the slope. The Morgenstern Price Analyses has been adopted in the analysis with the assumption that the soil will be saturated at the levels of MWL (EL 548). Short term and long-term slope stability analyses were carried out at 10 selected location (Fig. 2). The selected locations is in Appendix 1.

The minimum global FOS obtained was 1.989 at slope Slope L. The minimum global term FOS obtained was 1.475 at slope Slope C. Output from SLOPE/W

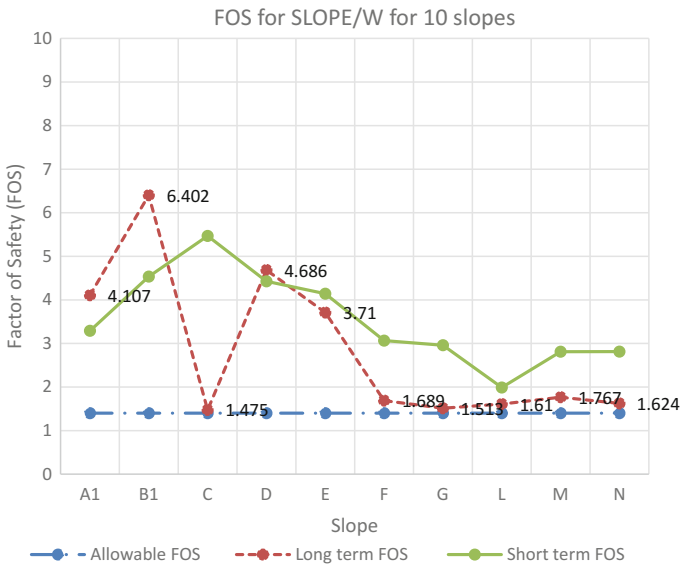


Fig. 2 FOS from SLOPE/W at 10 selected locations

shown that when the consolidated drained samples were soaked for 14 days suggest a decrease in the friction angle. From the experiment conducted, all slopes have sufficient stability, even with a drawdown of 6 ft/hr at extreme operation conditions, i.e. from MWL (548 m) to Extreme MOL (524 m). With intense rainfall of 100 mm/h for 1.5 days duration however, Slope C and L has FOS values, which are lower than allowed for slope stability. Thus, it is critical for Slope C and L to carry out further investigation on the slope stability using probabilistic approaches.

6.1 Variables of Pore Pressure

Pore pressure is determined from hydraulic tests result, and in some cases the result differ from the real values. Pore pressure is a direct reflection of variability in permeability, while permeability is usually highly uncertain. Below is the assumed drawdown scenario selected for the assessment (Figs. 3 and 4).

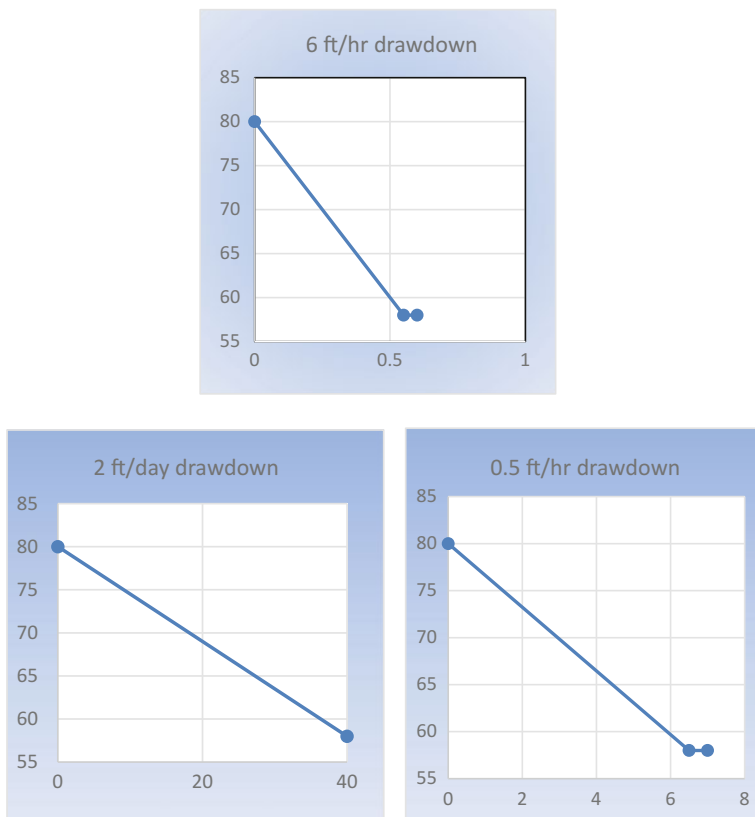


Fig. 3 Assumed drawdown scenario adopted for assessment

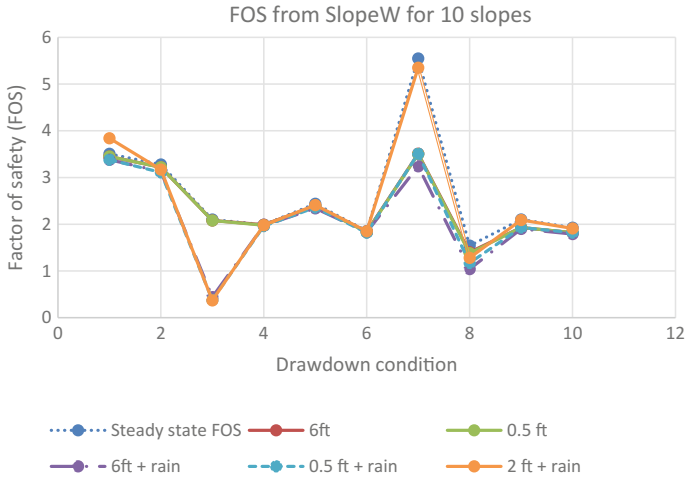


Fig. 4 Factor of safety relates to the drawdown scenario

7 Probabilistic Approach—Monte Carlo Simulation Method

Factor of safety (FOS) defined as

$$\frac{\text{Resisting forces}}{\text{Driving Forces}} = \frac{\text{Shear strength}}{\text{Shear Stress}} \tag{1}$$

In deterministic calculation, such as adopting SLOPE/W, often-single fixed values (mean values), strength parameters are used as the input in the calculation. Such calculations does not able to take into consideration for variation in slope parameters. The limits and assumptions used may pose some uncertainties in the result. Confidence of the decision maker to the output/results will be limit to that certain assumptions made.

Meanwhile, MCS simulation able to check the assumption made for the calculation (is it valid/not?) and explore the sensitivity of the results to the input parameters.

7.1 Material Properties

The strength envelope parameters obtained from site investigations for the left bank rim as in the Table 3.

Table 3 Strength envelope parameters

Parameters	Range	Mean	Standard deviation
cohesion	15–338	86.8	8.22
ϕ	22–75	29.75	7.6
τ	8–64	63.5	0.86
σ	6–98	33.9	24.27

8 Results

8.1 Monte Carlo Simulation (MCS) Output Analysis

Figures below is the probability of failure and the histogram data for the most critical slope, Slope C and L after 500 Monte Carlo trials using software RiskAmp (Figs. 5, 6, 7 and 8).

Referring to U. S Army Corps of Engineers (2006), for embankment dams, slopes with reliability index of more than 3 is stable. The probabilistic analysis gave a high reliability index (Fig. 9; Table 4).

9 Discussion

Based from the result of MCS output and previous assessment, the discussion came to these important points

- Slope stability is more sensitive to parameter—cohesion, but less sensitive to parameter—friction angle. As can be seen from the probability of failure graph

Fig. 5 Range of FOS (Slope L) related to the 500 MCS iteration for friction angle

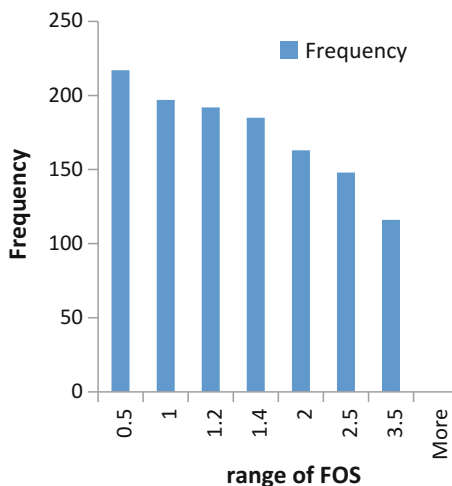


Fig. 6 Range of FOS (Slope C) related to the 500 MCS iteration for cohesion

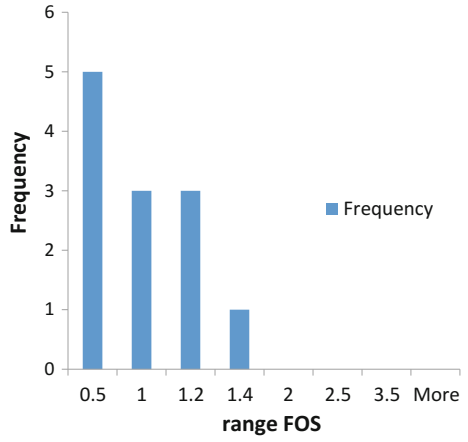


Fig. 7 Probability of failure Slope L 500 iterations of MCS

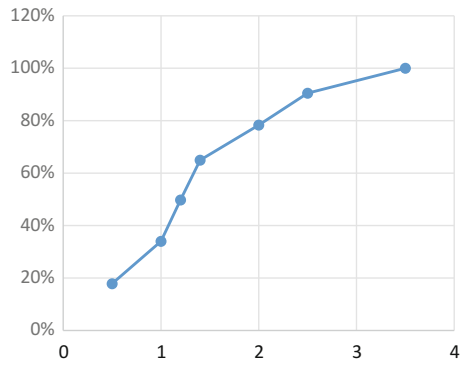


Fig. 8 Probability of failure Slope C 500 iterations of MCS

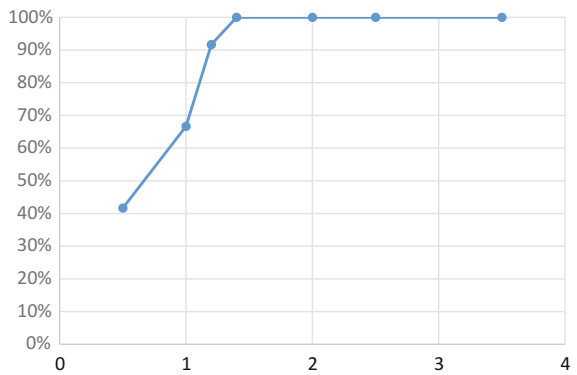


Fig. 9 FOS for different drawdown scenario

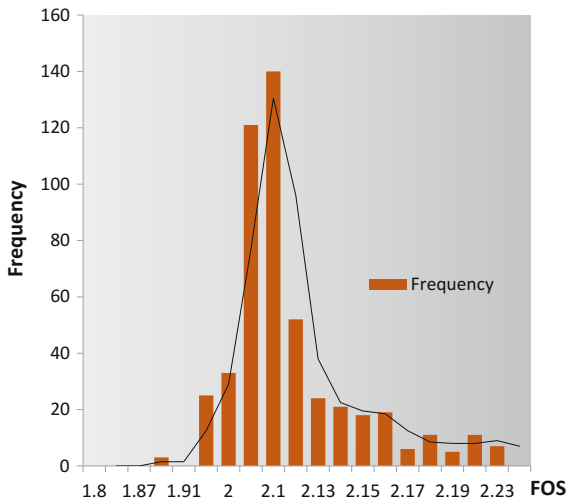


Table 4 Probabilistic analysis results and reliability index

Probabilistic analysis results	Number of trials	500
	Min. FOS	1.94
	Max. FOS	2.12
	Mean FOS	2.076
	Standard deviation	0.068
	% failure	0
	Reliability index	15.705

for variables in cohesion, the probability of getting a FOS of less than 1.0 is more than 60%, compared to only 30–40% of obtaining FOS less than 1.0 for variables—friction angle. The decrease in the cohesion has negative effect on slope stability.

- a. When the soil is saturated, the friction decreases and affected the shear strength of the soil. However, since the toe protection and sub-surface drainage have been installed before reservoir filling, the pore pressure is reduced and it increases back the shear strength.
- b. The slopes throughout the study area are still intact with major areas still covered by thick trees and vegetation. Thus, the existing trees and vegetation helped with the overall stability of the slopes. The existing of deep roots from the trees will act as slope anchors deep into the hard layer and thick vegetation leaves will prevent heavy surface runoff from penetrating into the soil layer, which will weaken the soil. All these mitigations help to maintain the shear strength of the soil [3, 4].

10 Recommendation of Mitigations

Slopes next to watercourse need proper treatment and safety measure. Proper design of riprap or other protection measures is important due to fluctuating water levels. The exposed slopes (if exist) must be treated from running water and provide proper drainage.

10.1 Maintenance and Monitoring Program for Slope

Even though the slope conditions are safe based on the current conditions, the following recommendation are to be look in order to avoid the future risk of the area:

- To carry out inspection and maintenance of the slopes periodically;
- To monitor inclinometers and piezometers periodically; and
- To avoid any future development along the slope of the area as much as possible.

Follow complete guide for slope maintenance and monitoring shall be in accordance to JKR Cerun 1—Guidelines on Slope Maintenance in Malaysia. Remote sensing (RS) is possible to be considered for early warnings of slope failure.

10.2 Evaluation of Slope Stability

In the future, prove the slope repair had improved the stability of the slope, by checking/evaluating the stability of the left abutment slope by tool/software. The safety of the left abutment can be further verified. [5] Such database is valuable, and it is more economical to the dam owners, in making planning for slope maintenance in the future.

10.3 Conflicts of Development

Often if there is conflict of development, or there is other development concurrently with each other, communication and timing is an important thing to avoid waste of resources (time and money) fixing the damages that could be avoided if a proper plan and proper communication have been made.

When there is conflict of highway and dam, information that need to be pass to JKR are

- Elevation of the dam and the reservoir level along the important alignment adjacent to the reservoir;
- Slope characteristics—for rapid drawdown scenario;
- Operation rules of the dam need to be passed on those designing the highway;
- Early engagement and involvement in development of the highway with proper documentation as future reference, to cater for changing of the person in charge from time to time.

It is important for the dam operators/design team to be part of the highway design team, so that they can be actively involved in the design, as meetings, discussions and letters are not efficient in passing information that essential to avoid conflicts later. Sharing and discussing on the standard used for design is also an important thing to do. Maintain transparent and communicate often among all involved in the planning, design and construction of dams. Assessment of past event is essential so that the lesson learnt from past project is not repeated.

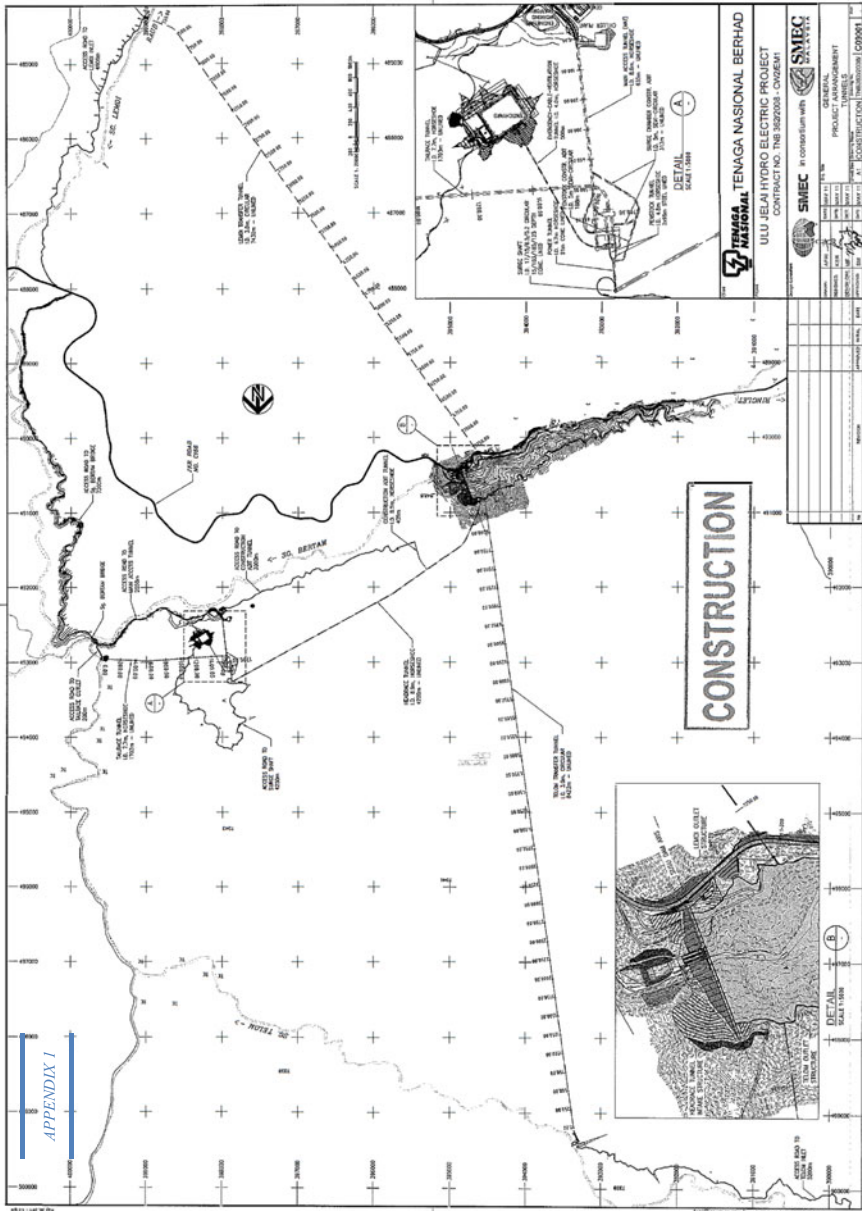
11 Conclusion

The model from the MCS is able to answer questions such as these:

‘What if the parameters is such and such what will be the FOS of the slope?’
or ‘Given all these parameters, what is the risk of slope failure?’

Its good to keep in mind that, the simulation will only be good as the estimates one made, like any other forecasting model. The simulation represents probabilities and not certainty. However, the Monte Carlo Simulation is one of power tool that useful when forecasting and unknown future [6–8].

Appendix 1



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