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Static and Dynamic Slope Stability Analysis for Non-Commercial Nuclear Power Site

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Abstract

This paper discuss slope stability problems both static and dynamic analysis in Non-Commercial Nuclear Power site. Soil exploration and number series of test were made to assist in preparing design, carried out input parameter for SLOPE/W model with Morgenstern-Price method. Morgenstern-Price method considers both shear and normal forces, satisfies both moment and force equilibrium, and allows for a variety of user-selected interslice force function. Slope stability analysis results in static modeling conditions relatively safe with the number of safety factors are 2.937 for normal condition and 2.292 when ground water table increase. In the condition of earthquake loads of the 1000-year period with a ground level peak acceleration value of 0.406 g, safety factor value analysis dropped to 0.914. Dynamic Slope stability analysis results pore water pressure shows a different pattern compared to the initial conditions at 0 seconds, total stress pattern does not change, while the vertical effective stress and displacement pattern changes very significantly.

Keywords: Slope Stability; Static Analysis; Dynamic Analysis; Morgenstern-Price Method

1. Introduction

Geotechnical investigation was done in order to attain the data needed to evaluate the site for Non-Commercial Nuclear Power Site, as such has been conditioned in head of BAPETEN regulation No. 5 year 2007 about the safety control of Nuclear Reactor Site Evaluation.

One of the geotechnical disasters is landslide, which is why geotechnical aspect and site evaluation are highly required for the sufficiency analysis based upon the geotechnical hazard potential. Soil Exploration and number series of test were made to assist in preparing design. Certain general subsurface information is generated by state agencies in this collaborative research report. Description of soils, water levels, bedrock locations, topography, geophysical logging, and laboratory data obtain very detail and contained very useful information to evaluated landslide potential [1]–[3].

The invention of computers has led to the development of more sophisticated techniques. Currently, software like GeoStudio and Geo5 are used to carry out the majority of slope stability evaluations. The integrated of the software suite enables you to assemble many analyses performed using various products into a single modeling project. For example SLOPE/W can efficiently assess a variety of slip surface shapes, pore-water pressure conditions, soil parameters, analytical methodologies, and loading circumstances for basic and complex situations. Quake/W is also a powerful finite element software product for modeling earthquake liquefaction and dynamic loading which determines the motion and excess pore water pressure that arise due to shaking, blast or sudden impact factor.

In this paper we use SLOPE/W and QUAKE/W to evaluate the static and dynamic slope stability analysis in Non-Commercial Nuclear Power Site in Serpong.

2. Methodology

SLOPE/W may use a wide range of soil models to use limit equilibrium to describe diverse soil types, intricate stratigraphic and slip surface geometry, and varying pore-water pressure conditions. Both deterministic and probabilistic input parameters can be used for analyses [4], [5].

For the most thorough slope stability study currently possible, stresses calculated using a finite element stress analysis may be utilized in addition to the limit equilibrium computations. SLOPE/W can assess virtually any slope stability issue you will run into in your geotechnical, civil, and mining engineering projects because to its broad range of capabilities [4], [6], [7].

Since slope stability is a statically indeterminate problem, engineers have a variety of analytical techniques at their disposal. The finite element method (FEM), limit analysis method, limit equilibrium method (LEM), and finite difference method can all be used to analyze slope stability [8], [9]. The majority of limit equilibrium approaches rely on slice techniques, which can be either vertical, horizontal, or inclined [10], [11].

In contrast to a strict mechanical premise, the first slice approach by Fellenius was more based on engineering intuition. Bishop, Janbu et al., Lowe and Karafiath, Morgenstern and Price, and Spencer all made significant contributions to the rapid development of the slice methods in the 1950s and 1960s (1967) [12], [13]. The numerous 2D slice limit equilibrium analysis techniques have been thoroughly reviewed and condensed by Fredlund and Krahn, 1984; Nash, 1987; Morgenstern, 1992; Duncan, 1996. Zhu et al. have outlined the common traits of the ways of slices [13], [14]:

(a) A finite number of slices make up the sliding body over the failure surface. Although the slices are typically cut vertically, some studies have also used horizontal and angled cuts. The vertical cut is currently used by the majority of engineers since the variations between other ways of cutting are generally not significant.
(b) To get the sliding body into a limit state, the strength of the slip surface is mobilized to the same extent. That indicates that only one safety factor is used throughout the entire failure mass.
(c) To make the problem deterministic, inter-slice force assumptions are used.
(d) Equations for force and/or moment equilibrium are used to calculate the factor of safety.

The ratio of the ultimate shear strength divided by the mobilized shear stress at incipient failure is typically used to define the factor of safety for slope stability analyses. The factor of safety F can be formulated in a variety of ways [6], [15], [16]. The most typical formulation for F is defined with reference to the force or moment equilibrium and assumes that the factor of safety is constant along the slip surface:

(1) Moment equilibrium: Rotational landslide analysis is frequently employed. The factor of safety Fm defined with regard to moment is given by when a slip surface is taken into consideration

$$F_m = \frac{Mr}{Md} \qquad (1)$$

where Mr is the sum of the resisting moments and Md is the sum of the driving moment.

(2) Force equilibrium: usually used to describe slip surfaces made up of polygonal or flat shapes that fail in translation or rotation. The force-related definition of the factor of safety Ff is provided by:

$$F_f = \frac{Fr}{Fd} \qquad (2)$$

where Fr is the sum of the resisting forces and Fd is the sum of the driving forces.

3. Study and Analysis

3.1. Soil characteristics

Analysis of layer characteristics is carried out by combining result geotechnical data and geophysical testing. Geotechnical data includes observations of core rock and SPT values obtain by soil investigation with deep borehole and open cut as shown in Figure 1 and Figure 2.

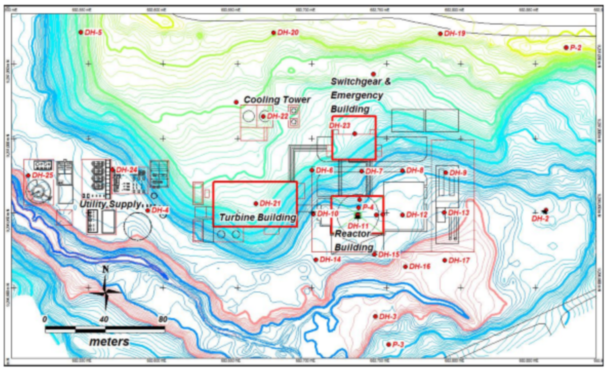


Figure 1. Point of soil investigation by deep borehole on site

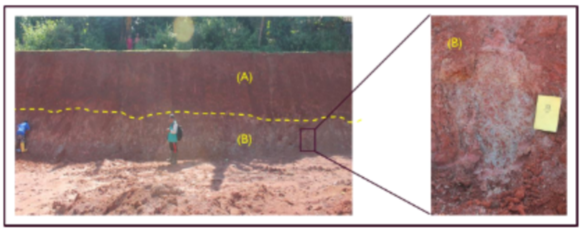


Figure 2. Stratigraphy and layer characteristics on site

Groundwater level data obtained from manually measuring results. Maximum groundwater level conditions obtained from the results of assumptions and extrapolation based on groundwater level monitoring data on the site. Laboratory analysis is carried out at the soil mechanics laboratory and rock mechanics laboratory according to the material being analyzed. Laboratory analysis is divided into two types; physical / index properties, and technical properties [17] Physical / index properties include gradation analysis, percentage of fine grains, atterberg limits, specific gravity, moisture content, relative density, and compacting. Technical properties include consolidation, permeability, salinity, direct shear, unconfined compressive strength, triaxial UU, CU, CD, and cyclic Triaxial.

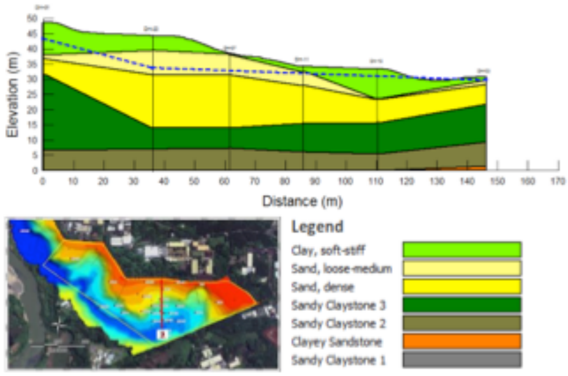


Figure 3. Slope section A-A with ground water table

Data input for soil parameter in SLOPE/W analysis for Morgenstern and Price method is shown in Table 1.

Value of bulk density and saturated is determined from the average value of the sample in the same layer and CU triaxial analysis in effective conditions. Data on the effective shear strength of the clay soft-stiff layer were obtained from the DH-1 and loose-medium sand layer obtained from DH-23. Correlation with average SPT data are performed to compare empirical values, especially ø values (internal friction) for sand layer. The shear strength value of the Sand dense layer is taken from the empirical value obtained from the SPT results.

Table 1. Input data of soil parameter

Layer	γ_{sat} (kN/m^3)	γ_n (kN/m^3)	ϕ' (deg)	c' (kN/m^2)	N SPT (average)	ϕ_{emp} (deg)	c (kN/m^2)
1. Clay, soft-stiff	15.12	14.97	31.62	43.12	9.80	N/A	N/A
2. Sand, loose-medium	15.73	14.95	33.60	0.00	17.40	38.00	0.98
3.Sand, dense	18.27	16.12	-	-	43.70	35.00	0.98
4.Sandy claystone		Bedrock			42.50		
5Clayey sandstone		Bedrock			50.00		

Layer	Volume Weight (kN/m^3)	*Poisson's Ratio*	*Damping Ratio*
Clay	15.03		
Sand Loose-Medium	15.32		
Sand, Dense	19.72	0.334	0.2
Sand Claystone 3	12.14		
Sand Claystone 2	11.76		
Clayey Sandystone	12.81		

3.2. Static slope stability analysis

Analysis using the Morgenstern-Price method with software SLOPE/W. Morgenstern and Price (1965) developed a method similar to the Spencer method, they developed two factor of safety equations; one with respect to moment equilibrium and another with respect to horizontal force equilibrium, but they allowed for various user-specified interslice force functions.

The interslice functions available in SLOPE/W for use with the Morgenstern-Price (M-P) method are:

- Constant
- Half-sine
- Clipped-sine
- Trapezoidal
- Data-point specified

Selecting the Constant function makes the M-P method.

For illustrative purposes, let us look at a M-P analysis with a half-sine function with the result as presented in Figure 4 while Figure 5 shows how the moment and force factors of safety vary with lambda. The M-P Factor of safety occurs where the two curves across.

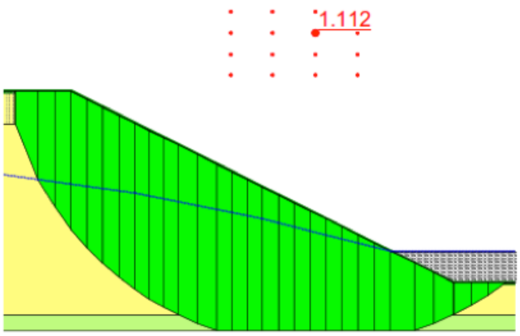


Figure 4. Results of Morgenstern price analysis

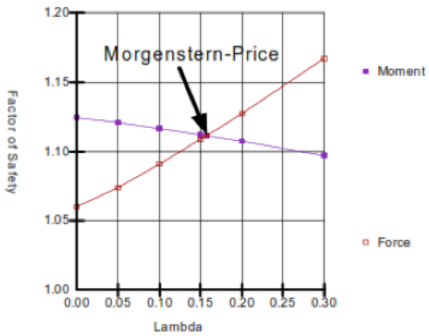


Figure 5. Morgenstern Price SF with half-sine function

The specified and applied interslice force functions are shown in Figure 6. The specified function has the shape of a half-sine curve. The applied function has the same shape, but is scaled down by a value equal to lambda which is 0.145. Consider the forces on Slice 10 (Figure 7). The specified function at Slice 10 is 0.86 and lambda is 0.146. The normal force on the right side of Slice 10 is 316.62. The corresponding interslice shear then is,

$$X = E\lambda f(x)$$

$$X = 316.62\ x\ 0.146\ x\ 0.86$$

$$X = 39.7$$

This matches the interslice shear value on the free body diagram in Figure 7.

A significant observation in Figure 7 is that the M-P Factor of Safety (cross over point) is lower than the Bishop's Simplified Factor of Safety (moment equilibrium ay lambda zero).

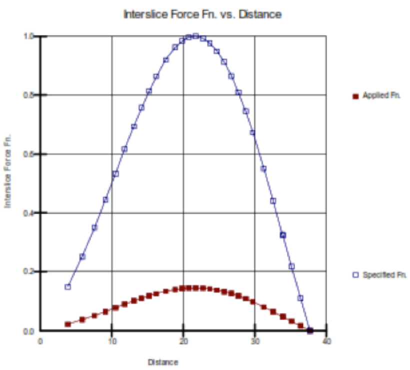


Figure 6. Interslice half sine-function

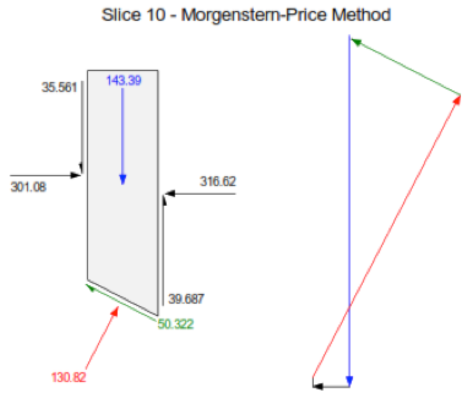


Figure 7. Free body and force polygon

This is because the moment equilibrium curve has a negative slope. This example shows that a simpler method like Bishop's Simplified method that ignores interslice shear forces does not always err on the save side. A more rigorous method like the M-P method that considers both interslice shear and normal forces results in a lower factor of safety in this case.

In summary, the Morgenstern-Price method:

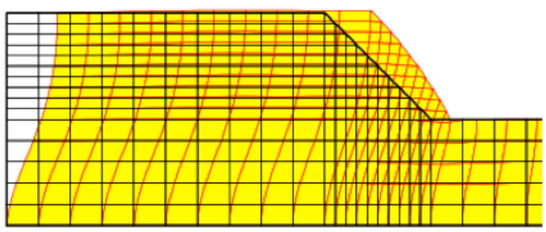
- Considers both shear and normal interslice forces,
- Satisfies both moment and force equilibrium, and
- Allows for a variety of user-selected interslice force function.

3.3. Dynamic slope stability

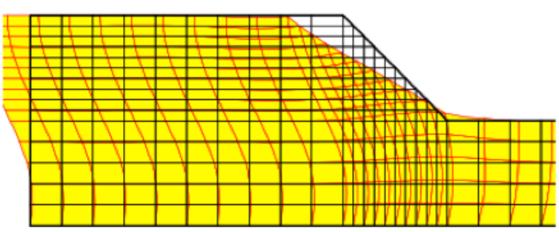
In SLOPE/W, dynamic effects can be considered in several ways. The simplest is a pseudostatic type of analysis. A more complex way is to use QUAKE/W finite element dynamic stresses and pore-water pressures together with SLOPE/W.

QUAKE/W can animate the motion of the slope during the entire 10 seconds. The diagrams in Figure 8 are two snapshots during the shaking and as is readily evident, the dynamic stresses oscillate dramatically.

The condition in Figure 8(a) may cause the factor of safety to decrease while the situation Figure 8(b) may cause the factor of safety to increase. This type of information is available for each time step the results are saved to a file during analysis. In this example, the integration along the earthquake record occurred at an interval of 0.02 seconds. The total of 500 integration steps is consequently required for the 10 seconds of shaking. The results were saved for every 10th time step resulting in 50 sets of output files.



(a)



(b)

Figure 8. A snapshot of deformation during an earthquake

SLOPE/W computes a factor of safety for each time step the data is saved to a file. For this example, SLOPE/W computes 50 safety factors. These safety factors can then be plotted versus time as shown in Figure 9. The graph vividly illustrates the oscillation in the factor of safety as noted earlier. Note that the factor of safety momentarily falls below 1.0 several times during the shaking.

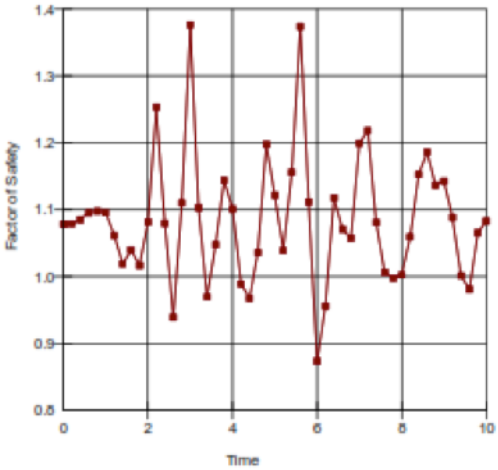


Figure 9. Factor of safety Vs time

Soil dynamic parameters can be determined based on the results of measurements in situ in the field such as seismic cross hole tests, seismic down-holes (up-hole tests), Multichannel Analysis of Surface Wave (MASW), microtremor array or test results laboratories such as the resonant column test, cyclic triaxial test, and cyclic direct simple shear test. Soil dynamic parameters needed for propagation analysis. Shear waves are dynamic shear modulus, G_{max}, or shear wave velocity, Vs, dynamic damping material, ξ, and the relationship between shear modulus and damping ratio with shear strain. The maximum dynamic shear modulus (G_{max}) is usually correlated with the shear wave velocity (v_s) at a small strain (+ 10-4%) as:

$$G_{max} = vs^2\gamma/g \tag{3}$$

where : γ = unit weight, and g = gravity velocity

In this study the shear wave velocity profile (V_s 30) uses cross-hole data up to a depth of 100 meters and data from the study of microtremor arrays to bedrock to correlate it with G_{ma}x values as discussed above. From the results of the study of speed profiles shear waves using the microtremor array method obtained a value of vs 750 m/s at a depth of approximately 390 meters. Velocity v_s value of 750 m/s is considered as v_s value of bedrock.

4. Results

4.1.Static slope stability analysis

Groundwater level data is obtained from direct measurement results inside drill holes using a dipmeter. Based on the results of permeability tests, the ground water system at the site is a free ground water system and there is no depressed ground water so that groundwater data is entered as phreatic not as a piesometric level.

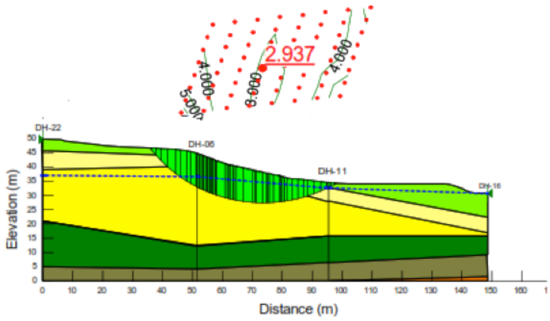


Figure 10. Slope stability analysis normal condition

Analysis of slope stability under normal conditions results in a value minimum security 2,937 as shown in Figure 10. Analysis of slope stability with a water level rise scheme the soil is done by considering the groundwater level observation data, and the maximum possible groundwater level rise. Based on scheme for maximum groundwater level rise, models are set for calculation with an increase in ground water level of 2 m obtained the safety factor of 2.282 as shown in Figure 11.

Simulation calculations with the peak acceleration scheme on the surface of 0.406 produce a safety factor of 0.914 (Figure 12).

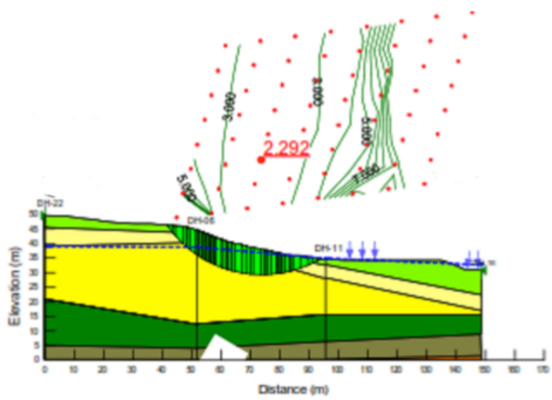


Figure 11. Slope Stability Analysis increase in ground water level

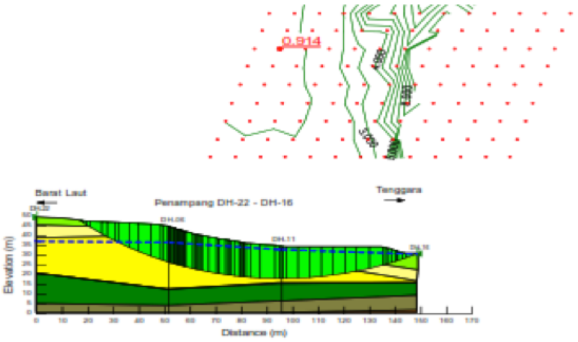


Figure 12. Slope Stability Analysis with peak acceleration on the surface

4.2.Dynamic slope stability analysis

Physical and mechanical parameters for input in the analysis are shown in Table 1. Pore-Water Pressure (PWP) Function in the form of Spline Data Point Function type with estimated parameter N exponent = 0.7. Cyclic Number Function is a type of Spline Data Function with Estimated material samples are Loose Sand, Medium Loose Sand, Medium Dense Sand, and Dense Sand (adjusting to the material). Mesh distribution using 5 m (Approx. Global Element Size = 5 m) as shown in Figure 13. Boundary conditions made with the left and right "Fixed X" and the bottom "Fixed XY".

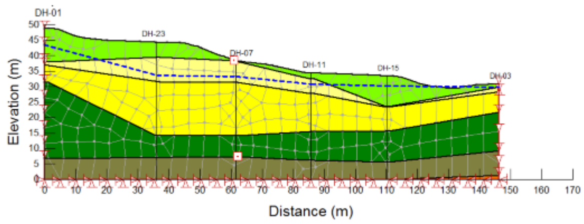
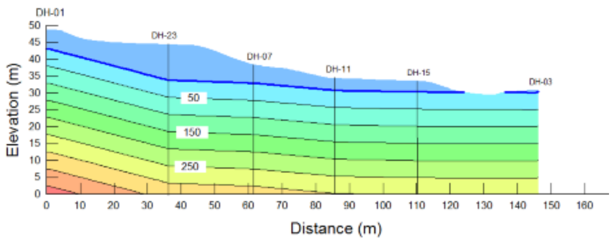
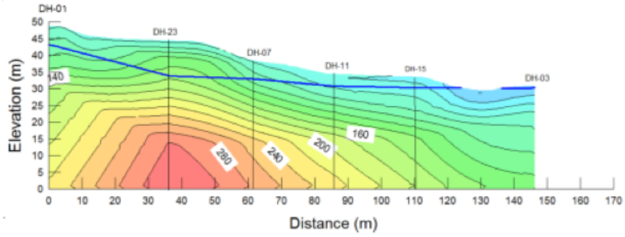


Figure 13. Cross section analysis and mesh properties

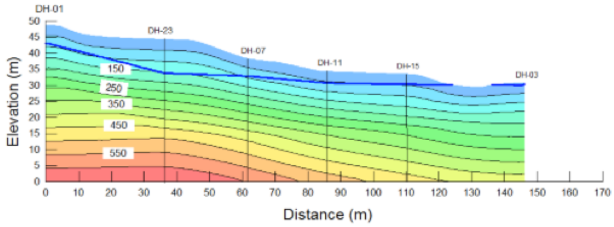
Initial pore water pressure ranges from 0 kPa at ground water level position and reaches 200 kPa at a depth of 30-40 m. The results of the initial condition analysis for pore water pressure, total stress, and effective vertical stress are shown in Figure 14.



(a)



(b)



(c)

Figure 14. Analysis results of initial condition. (a) pore water pressure; (b) total stress and; (c) effective vertical stress

The graph of acceleration vs time in a 1000 year return period earthquake can be seen in Figure 15. In the boundary condition section, the left and right sides of the fixed Y, and the bottom fixed X and Y. History points are set at the bottom and at the top of the cross section to show the ground's response to the earthquake in a position on the surface and far from the surface.

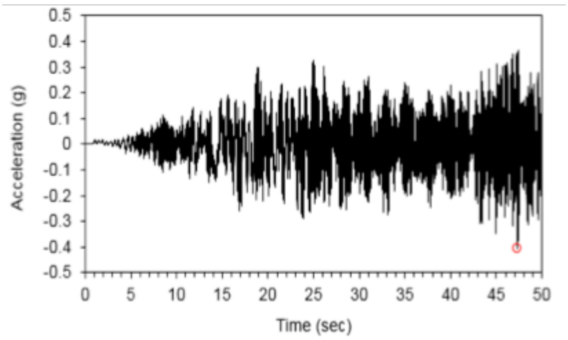


Figure 15. Acceleration Vs time

Based on the analysis results obtained graphs of ground response to earthquakes are depicted on the horizontal acceleration graph each time unit based on the history point position Figure 16 and 17. Horizontal earthquake acceleration graph shows the earthquake acceleration on the surface is greater than the history point position in the depth.

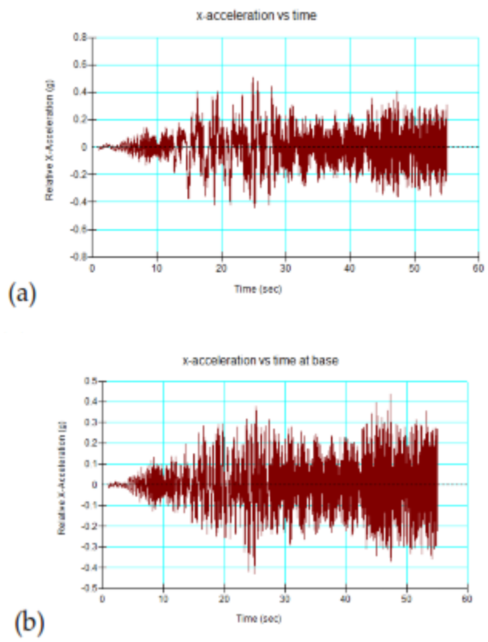


Figure 16. Graph of earthquake acceleration on (a) ground level, and; (b) a depth of 32 m from ground level

Graph relative lateral displacement at the history point position on the surface and below the surface shows changes in the position of soil material unity of time when experiencing earthquake acceleration. In the position at the bottom, displacement between 0 - 2 cm, while on the intermediate surface 0 - 5.5 cm. Graph of the relationship between relative displacement and position soil depth on the line that connects the point history at the top and below are shown in Figure 18. The lines show displacement pattern at a time unit that varies between 25 – 50 seconds.

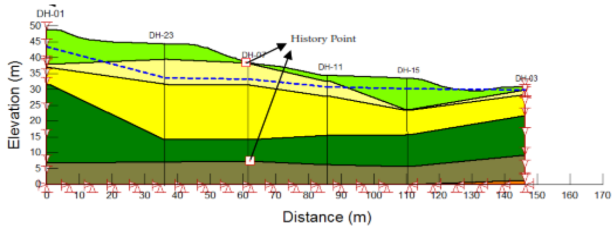


Figure 17. History point position

Pore water pressure pattern at the 25th earthquake acceleration seconds shows a different pattern compared to the initial conditions at 0 seconds.

The total stress pattern does not change, while the vertical effective stress pattern changes very significantly. In the 46th second ground vibrations reach the top with a shift of 7 cm so that stress patterns in the soil are relatively far changed from the initial conditions (Figure 19).

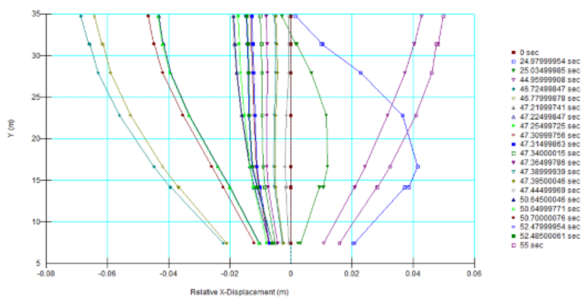
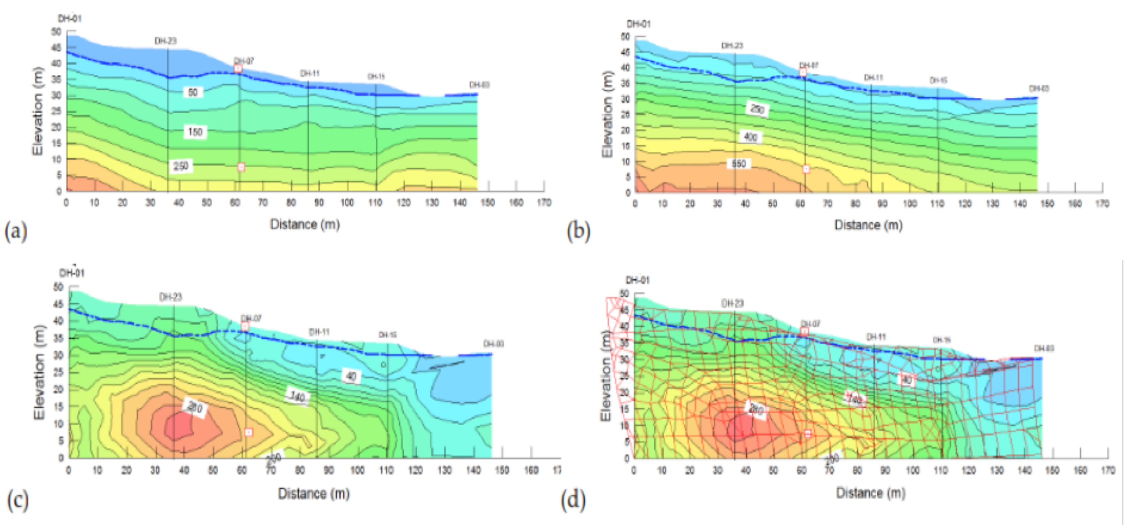


Figure 18. Horizontal displacement vs. depth (Y) graph in units of time



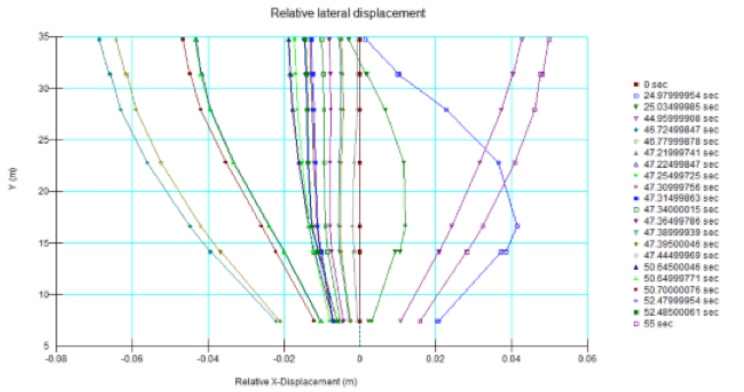


Figure 19. Cross section (a) pore water pressure, (b) total stress, (c) vertical effective stress, and (d) displacement

5. Conclusion

Slope stability analysis results in static modeling conditions relatively safe with the number of safety factors are 2.937 for normal condition and 2.292 when ground water table increase. The safety factor value analysis decreased to 0.914 under the condition of earthquake loading of the 1000-year re-period with a ground level peak acceleration value of 0.406 g. Dynamic Slope stability analysis results pore water pressure shows a different pattern compared to the initial conditions at 0 seconds, total stress pattern does not change, while the vertical effective stress and displacement pattern changes very significantly.

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