SEISMIC SLOPE STABILITY ASSESSMENT IN A MODERATE SEISMICITY REGION, HONG KONG

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ABSTRACT :

The current code of practice for building design in Hong Kong does not require any seismic considerations and generally there is no requirement to consider seismic ground motion in the design of slopes. However, the Chinese Code for seismic design of buildings, GB 50011 – 2001, categorises Hong Kong as being in Zone VII+ with a 10% in 50 year peak ground acceleration of 15%g. Conventional earthquake design for a slope is usually based on a pseudo static slope stability calculation. To limit the slope movement in earthquake, it is recommended that the critical acceleration of slope (A_c) shall be no less than half of design peak ground acceleration. The critical acceleration of slope is the ground acceleration that gives a FoS against failure of unity. This paper presents an estimation of the earthquake induced displacement of typical slopes subjected to various levels of seismic ground motions using the finite difference package FLAC with the dynamic option. The input earthquake time histories are based on the scenario events obtained from the de-aggregation of recent seismic hazard study in Hong Kong. These scenario events, in terms of earthquake magnitude and distance, are those that contribute the most to the seismic ground motion at each seismic hazard level. The current design practice for new slopes in Hong Kong requires a minimum FoS against failure of 1.4 for slopes with a high consequence to life. This study shows that for such a slope subjected to a rare earthquake event (2,475 year return period), the earthquake-induced resultant displacement is less than 30mm. For an existing slope with a minimum FoS of 1.2, the induced displacement could exceed 100mm under such an earthquake. The movement is concentrated on the shallow slope surface. However, this may still threaten the integrity of a particular hazardous installation. In such circumstances, it is recommended to consider seismic loading specifically for essential and hazardous facilities above or below the existing slopes with a FoS against failure of less than 1.2.

KEYWORDS: earthquake, seismic, slope stability, FLAC, Hong Kong

1. INTRODUCTION

The Hong Kong Special Administrative Region is located in an area of moderate seismicity. The current codes of practice for building design do not require any seismic considerations. However, the Chinese Code for seismic design of buildings, GB 50011 – 2001, categorises Hong Kong as being in Zone VII+ with a 10% in 50 year peak ground acceleration of 15%g.

In the study by Pappin and Bowden (1998), a range of typical slopes had been considered and the probability of seismically induced down slope movement is quantified. The results show that, for a slope to be at a meaningful risk from seismic activity, it would need to have a static FoS of less than about 1.1 for typical structures and less than about 1.2 for essential facilities. This is based on the conventional practice that for down slope movements of less than 20mm the risk to cause damage is low whereas a displacement of 100mm is associated to a high risk of failure in most slopes. It then follows on to conclude that current design methods in Hong Kong of ensuring safety are sufficiently conservative. The only case where seismicity may need to be considered is where a slope failure could threaten the integrity of a particularly hazardous installation.

A preliminary quantitative risk assessment (QRA) study of earthquake-induced landslides at man-made slopes in Hong Kong (GEO Report No. 98) had been carried out by the Geotechnical Engineering Office of the Hong Kong Government (Geotechnical Engineering Office 1998). The assessment systematically considered the seismicity in Hong Kong, the effects of earthquake on slope stability and the likely consequences with respect to loss of lives in the event of slope failures. It is concluded that the risk of earthquake-induced landslides at slopes designed or upgraded to current geotechnical standards is much smaller than the risk of rain-induced landslides for pre-1978 man-made slopes that have not been upgraded to current standards. The current geotechnical standards appear to be adequate in maintaining the overall risk of earthquake-induced failures on new slopes at a relatively low level.

However, no detailed studies have been carried out to investigate the slope movement subjected to earthquake ground motions of different hazard levels. This paper determines the earthquake-induced displacement using the finite difference package FLAC. Slope models with typical geometry and soil strength parameters have been modelled with earthquake time histories of different hazard levels. The input time histories for the finite difference model are based on the scenario earthquake events obtained from the de-aggregation of a recent seismic hazard study. These scenario events, in terms of earthquake magnitude and source distance, are those that contribute the most to the seismic ground motion at each seismic hazard level. A summary of the probabilistic seismic hazard assessment studies undertaken in recent years is presented to estimate the potential seismic ground motion levels in Hong Kong.

2. REVIEW OF SEISMIC SLOPE STABILITY ANALYSIS

The simplest method of seismic slope stability analysis is to compute the FoS using a pseudo-static approach. Newmark (1965) proposed that the induced permanent displacement using a sliding block method being a more appropriate measure of slope performance in earthquake. This has since become widely accepted. Further changes in the computation have been made with the rise of numerical methods in geotechnical engineering.

2.1. Pseudo-static Analysis

Pseudo-static analysis simply extends the static analysis and determines the FoS of slope subjected to a static horizontal acceleration. In the analysis the horizontal inertia force induced by an earthquake is represented by a static horizontal force as a product of a seismic coefficient k and the weight of the potential sliding mass. Based on the principal of the limit equilibrium method, the critical acceleration A_c is derived as that which produces a FoS of unity. The main advantages of this approach are that it makes use of the well-established limit equilibrium method and it is easy to use. However, the transient nature of earthquake motion cannot be considered using the pseudo-static approach.

2.2. Newmark's Sliding Block Model

Newmark (1965) showed that the earthquake induced displacement in slope can be explored by considering the equilibrium of a rigid block on a slope subjected to horizontal accelerations. The acceleration of the block is limited by the available shear resistance between the block and a pre-determined sliding plane. When the acceleration imposed on the soil mass exceeds its critical acceleration (A_c), the net disturbing force on the soil mass will be larger than the net resisting force and slope displacement will result. Newmark (1965) presented the results that little displacement occurs unless the A_c/A_m ratio is less than about 0.5, where A_m is the peak earthquake ground acceleration.

Sarma (1975) used similar approach but incorporated the dominant period of the earthquake motion (T), which is defined as the period corresponding to the peak on the acceleration spectrum of the input motion. Sarma's data can be expressed by equation 2.1.

$$X_m = \frac{CA_m T^2}{4} 10^{(1.07-3.83 A_c / A_m)} \quad (2.1)$$

where X_m is the maximum displacement, T is the dominant period of earthquake, C = cos(θ + β - ϕ') / cosϕ', θ is the angle of the earthquake acceleration to horizontal, β is the slope angle and ϕ' is the angle of internal friction of the soil. C generally has a value near to one.

Ambraseys & Menu (1988) also used the sliding block assumptions to assess statistically the displacements of slopes with different ratios of A_c/A_m based on 48 near-field earthquake records with a magnitude of between 6.6 and 7.3 and recommended another correlation. Ambraseys & Srbulov (1994) further expanded the work and incorporated the function of source-site distance.

2.3. Numerical Modelling of Earthquake-induced Permanent Displacement

As mentioned above a pre-determined sliding plane is required in Newmark's method. This involves a search for critical failure, depending on the assumption of failure mode. However, if numerical modelling is used, this assumption is no longer required and the displacement can be computed based on the distortion in each element according to the stress-strain relationship. In this paper, numerical calculations are performed using FLAC with the dynamic option. FLAC is a finite difference package and has been extensively used to analyse dams and slopes, e.g. Chugh & Stark (2005), Marcuson et al (2007), Cetin & Isik (2005) and Kong (2003).

3. ANALYSIS METHODOLOGY OF THIS STUDY

Numerical analysis has been carried out on a typical cut slope (45 degrees) in Hong Kong with two different weathering profiles comprises completely decomposed granite (CDG) underlain by moderately decomposed granite (MDG) (Figure 1). The slope is assumed to be dry in this study. The material properties are determined from the range of parameters recommended in Geotechnical Engineering Office (1993) and are listed in Tables 1 and 2.

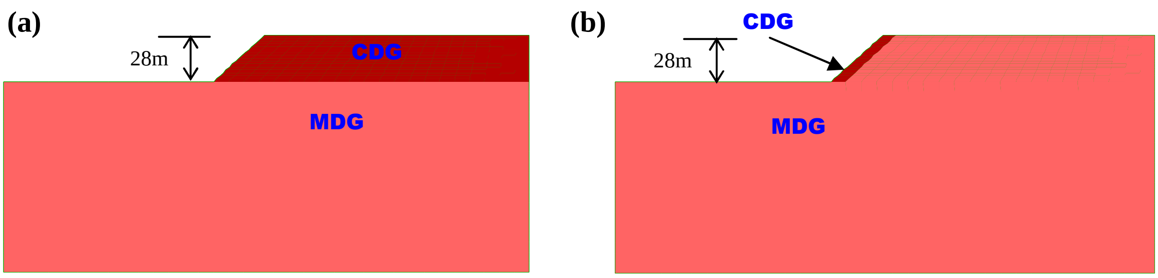

Figure 1: Weathering profiles: (a) deep weathering profile with horizontal bedrock; (b) shallow bedrock (10m thick CDG)

Table 1: Material properties of CDG

Soil Model	Mohr-Coulomb
Cohesion (c') and friction angle (phi')	c'=5 kPa, phi'=39^0 (Soil 1) c'=10 kPa, phi'=40^0 (Soil 2)
Density ρ	1900 kg/m^3
Poisson's Ratio ν	0.3
Shear Wave Velocity Vs	200m/s
Shear Modulus G ($G = \rho Vs^2$)	76 MPa
Young's Modulus E ($E = 2G/(1+\nu)$)	198 MPa
Bulk Modulus K ($K = E/3(1-2\nu)$)	97 MPa
Tensile Strength	6 kPa (Soil 1) 11 kPa (Soil 2)

Table 2: Material properties of MDG

Soil Model	Elastic
Density ρ	2400 kg/m^3
Poisson's Ratio ν	0.25
Shear Wave Velocity Vs	1000m/s
Shear Modulus G ($G = \rho\ Vs^2$)	2400 MPa
Young's Modulus E ($E = 2G(1+\nu)$)	6000 MPa
Bulk Modulus K ($K = E/3(1-2\nu)$)	4000 MPa

3.1. Static and Pseudo-static Analysis

Limit equilibrium method has been adopted to determine the static and the pseudo-static FoS of slope in the two soil types listed in Table 1. This was done using *Oasys* Slope programme and a constant horizontal acceleration is applied to the slopes until the FoS become unity. This force is regarded as the critical acceleration, A_c of the slope (Table 3).

Table 3. Static FoS and Critical Acceleration of Slopes

	Static FoS	**Critical Acceleration, A_c**
Slope in Soil 1 (c'=5 kPa, phi'=39^0)	1.2	0.11g
Slope in Soil 2 (c'=10 kPa, phi'=40^0)	1.4	0.23g

3.2. Numerical Analysis using FLAC

FLAC (for Fast Lagrangian Analysis of Continua) uses explicit finite difference scheme to solve the full equation of motion using lumped grid point masses derived from the surrounding zone. It uses an updated Lagrangian procedure for coping with large deformations. For this study 2-dimensional (2-D) plane strain analyses have been carried out using FLAC version 5.0 with the dynamic option. More details regarding the program can be found in the User's Manuals (Itasca Consulting Group, 1993).

3.3. Methodology

The models with the boundary condition are shown in Figure 2. The boundary at the base of the model is fixed in both x- and y-direction. The vertical boundaries are fixed in x-direction. For dynamic boundary conditions, free-field boundaries and quiet boundaries are coupled to simulate an infinite domain and ensure that dynamic waves are not reflected at the boundaries.

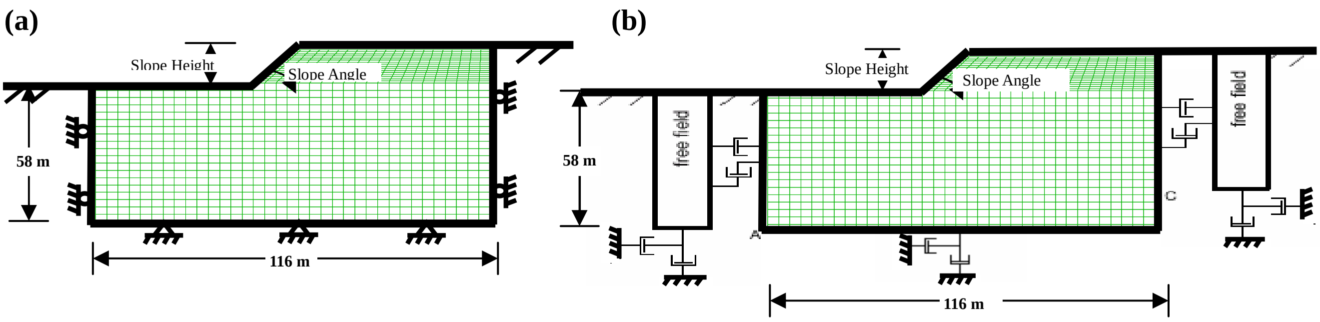

Figure 2: Boundary conditions for slope model: (a) static; (b) dynamic.

The gravity acceleration of 9.81m/s^2 is applied to the model and run until an equilibrium state is obtained. The equilibrium state of the geometry can be assured with the horizontal and vertical displacement histories and the unbalanced force become constant. Once static equilibrium is reached, the displacements are redefined as zero. Earthquake record is inputted along the base of the slope in terms of velocity time history. Detailed discussion on the derivation of the input time history record is provided in section 4. Soil damping is critical to the displacement and a sensitivity analysis has been carried out considering soil damping ratio between 5% and 15%. It was found that the magnitude of displacement varies within 50%. Similar results have been obtained by other researchers (Kong 2003, Rathje and Bray 1999). The average value, soil damping of 10% is adopted in the analysis which corresponds to the range of the induced strain level subject to the input earthquake motions. The time histories of the displacement, velocity, and acceleration at various locations of the slope face have been recorded.

4. SEISMIC HAZARD OF HONG KONG

In recent years, a probabilistic seismic hazard assessment studies have been undertaken by the Ove Arup and Partners Hong Kong Ltd to estimate the potential seismic ground motion levels on bedrock in Hong Kong. A detailed catalogue of historical and recent earthquake events occurred within the South China region has been compiled. A suite of recent published empirical and stochastic attenuation relationships has been used (Pappin et al, 2008) with published source models and source parameters in a logic tree analysis. Uniform hazard bedrock ground-motion spectra having various probabilities of being exceeded in 50 years have been calculated. The results have been de-aggregated to investigate what earthquake magnitude and distance combinations have contributed most to the hazard levels for the different probabilities of earthquakes.

4.1. Peak Horizontal Ground Acceleration on Rock

The calculated hazard levels, in terms of peak horizontal ground acceleration (for 5% damping) on rock, at the three probabilities of being exceeded, are summarised in Table 4. The assessment has been undertaken for peak ground acceleration and periods of 0.1, 0.2, 0.5, 1.0, 2.0 and 5.0 seconds. The uniform hazard response spectra at each probability of being exceeded are shown in Figure 3. It is considered that the 2% in 50 years can represent the design earthquake event for slopes associated with typical structures and the 1% in 50 years can represent the rare earthquake of extreme magnitude for hazardous facilities in Hong Kong, such as LNG tank.

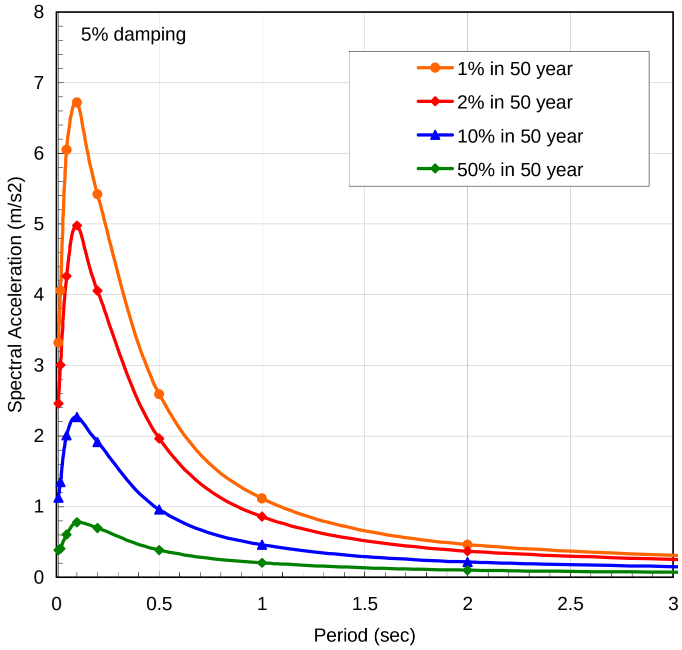

Figure 3: Horizontal acceleration UHRS on rock sites

Table 4: Seismic hazard assessment results

Probability of Being Exceeded	Peak Acceleration (m/s^2)	Spectral Acceleration (m/s^2)					
		Period (s)					
		0.1	0.2	0.5	1.0	2.0	5.0
50% in 50 years	0.39	0.78	0.70	0.39	0.21	0.10	0.03
10% in 50 years	1.13	2.27	1.92	0.96	0.46	0.22	0.06
2% in 50 years	2.46	4.98	4.06	1.96	0.86	0.37	0.10
1% in 50 years	3.32	6.72	5.42	2.59	1.12	0.46	0.12

4.2. De-aggregation of Hazard

The hazard results have been de-aggregated, in terms of magnitude and distance, to investigate earthquake occurrences that have contributed the most to the resulting ground-motion hazard. The de-aggregation was undertaken in accordance with the procedure recommended by McGuire (1995). De-aggregation has been carried out for peak horizontal acceleration, and the 0.2 and 2.0-second response spectral ordinates at the three probabilities of being exceeded (10%, 2% and 1%). The results of the de-aggregation represented the near-field and far-field scenario earthquake events at the 0.2 and 2 second respectively and are summarised in Table 5. The near-field earthquake magnitude in seismic sources around Hong Kong have maximum of M = 5.5 to 6.5 and the Dangan Island source zone 30km south of Hong Kong has a maximum magnitude of M = 7. The far-field large earthquake is dominated by the Shantao (Nan'ao) earthquakes with distance of 300km or the Taiwan earthquakes with distance of 600km.

Table 5: De-aggregated earthquake scenarios for Hong Kong

Probability of being Exceeded	Return Period (years)	Short / Long Period (s)	M-d pair	Scaling Factor
10% in 50 years	475	0.2s	M = 5.8, d = 40km	1.5
		2.0s	M = 8.3, d = 600km	0.6
2% in 50 years	2,475	0.2s	M = 6.0, d = 30km	1.5
		2.0s	M = 7.5, d = 300km	1.9
1% in 50 years	4,975	0.2s	M = 6.0, d = 30km	2.0
		2.0s	M = 7.5, d = 300km	2.4

4.3. Input Ground Motions

In the absence of appropriate measured strong-motion records in the South China region, time histories from stable continental regions have been modified by adjusting them to match the target spectrum in the frequency domain. Table 6 shows the selected earthquake record with similar de-aggregated magnitude and distance pair for short period motion as presented in Table 6. The input time histories were selected in order to minimise the degree of adjustment needed, alternatively stochastic simulations of the seismological model, using computer program GENQKE, developed in the University of Hong Kong and the University of Melbourne (Lam et al, 2000) were also used. The analyses of the earthquake induced displacements in slopes are the average of the results using the scaled real time histories and a number of random artificial simulated records.

Table 6: Selected real time history for near-field earthquake

Name of Earthquake	Moment Magnitude	Distance	Input Short Period Motion
North Palm Springs, USA, 07/08/1986, Silent Valley	6.2	26 km	2,475 years and 4,975 years

5. FINITE DIFFERENCE ANALYSIS

The finite difference analysis results are presented in Table 7 and examples of the output displacement contour plots are presented in Figure 4. It was found the earthquake induced movements are generally shallow and the maximum residual displacements occurred near the slope crest. The displacement at the slope toe is generally negligible. It was found that the maximum resultant displacements for 4,975 years return period are about 45mm for slopes in flat bedrock and 20mm for slopes in shallow bedrock with a static FoS of 1.4. However, the maximum displacements increase to 200mm when the static FoS reduces to 1.2 (see Table 7). This magnitude of displacement is sufficient to expect slope failure. It is found that there is a log-linear relationship between the displacement and Ac/Am and return periods (see Figure 5).

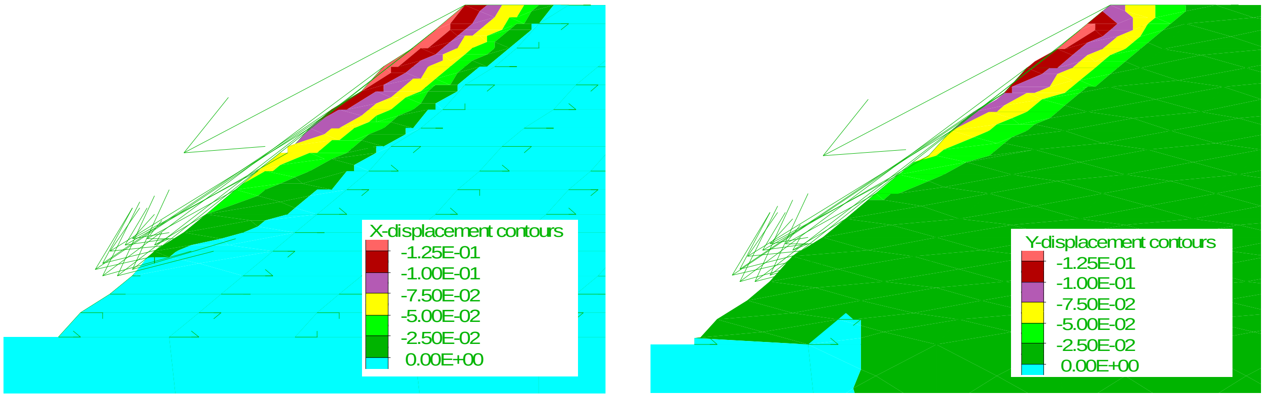

Figure 4: Example of FLAC analysis output: Weathering Profile 2 – Shallow Bedrock, Static FoS 1.2 subject to earthquake motion of 4975 year return period – x-displacement in metre (LHS) and y-displacement in metre (RHS)

Table 7: Maximum Resultant Horizontal Displacement in Slopes

Return Period	Flat Bedrock		Shallow Bedrock	
	FoS=1.2	FoS=1.4	FoS=1.2	FoS=1.4
475 yrs	11mm	2mm	12mm	0.1mm
2,475 yrs	***124mm***	24mm	93mm	4mm
4,975 yrs	***208mm***	44mm	***156mm***	20mm

(a) (b)

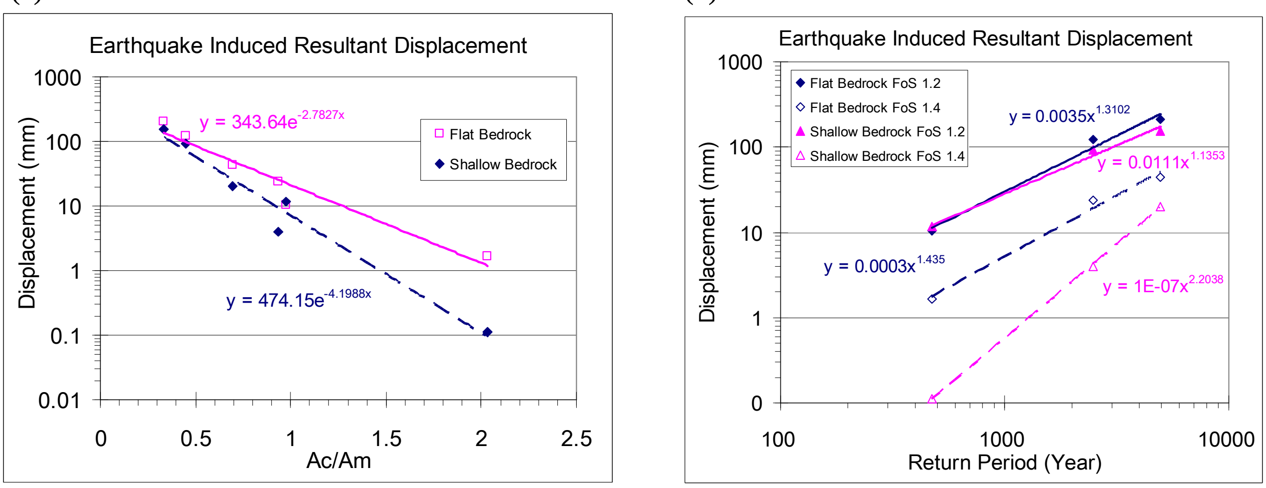

Figure 5: (a) Resultant displacement in slope vs. Ac/Am ; (b) Resultant displacement in slope vs. return period

In order to compare the results with the published data based on Newmark's sliding block method, the lateral slope displacement is represented by an "equivalent slope displacement". The equivalent slope displacement is determined by averaging the resultant displacement of the sliding mass, which was approximately 40% of the maximum displacement. In order to adopt Ambraseys & Srbulov (1995) for comparison, an earthquake scenario with magnitude of 6.0 has been assumed. For Ambraseys & Menu (1988), a dominant period of 0.6 second in slope is used.

As shown in Figure 6, the results in this study generally agreed with the data from Ambraseys & Menu (1988). However, it shows that the results from Sarma (1975) and Ambraseys & Srbulov (1995) are lower than the predicted values in this study.

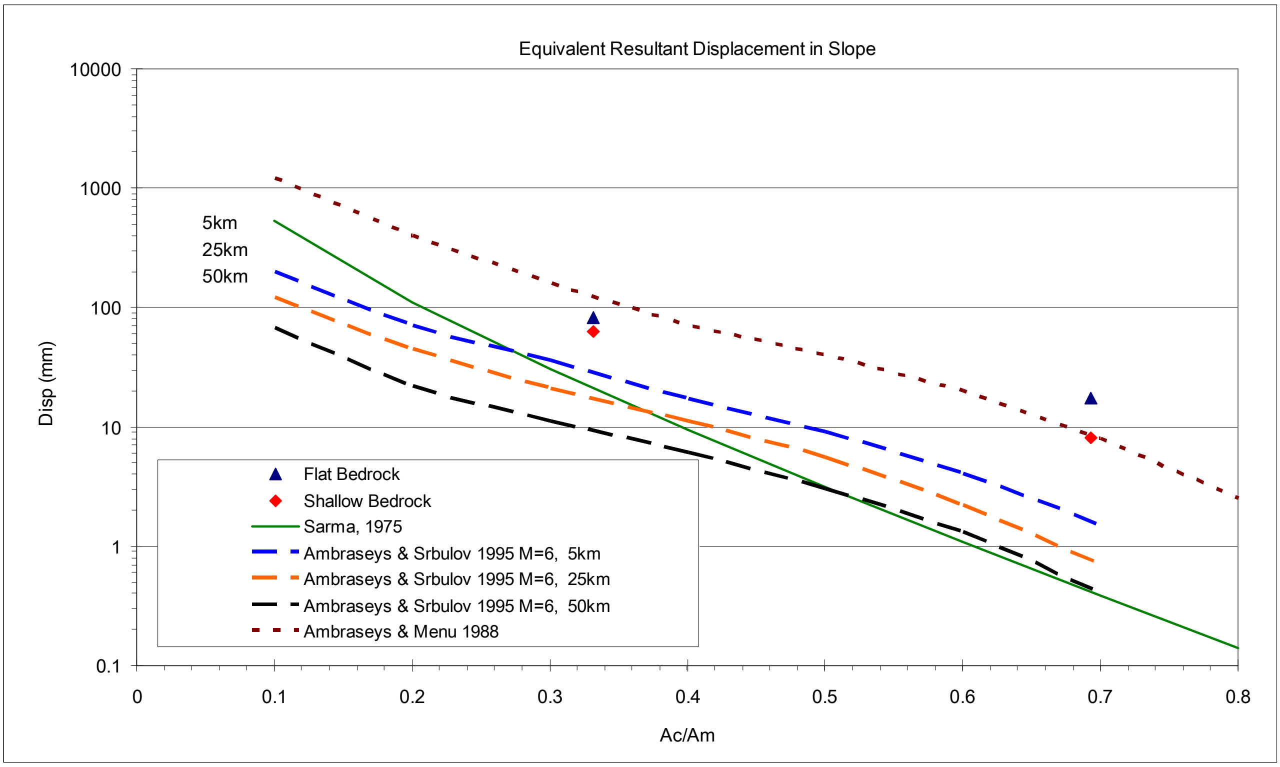

Figure 6: Comparison between the numerical analysis results from this paper (equivalent displacement) and published results from sliding block method.

6. RESPONSE SPECTRUM ON SLOPE

In addition to the earthquake induced displacement in the slopes, the response spectra have also been computed to further investigate the dynamic response of the slopes. The acceleration response spectrum and spectral ratio of slope with static FoS of 1.2 are presented in Figures 7 and 8. The maximum soil amplifications at the natural period ranged from 3 to 5.

7. CONCLUSIONS AND RECOMMENDATIONS

This study shows that the rare earthquake event (2,475-year return period) for Hong Kong, only induces a maximum displacement of less than 30mm in slopes with a static FoS of 1.4. However, for an existing slope with a FoS of 1.2, earthquake induced displacement could exceed 100mm under earthquake in 2,475-year return period. This magnitude of displacement may threaten the integrity of an adjacent installation.

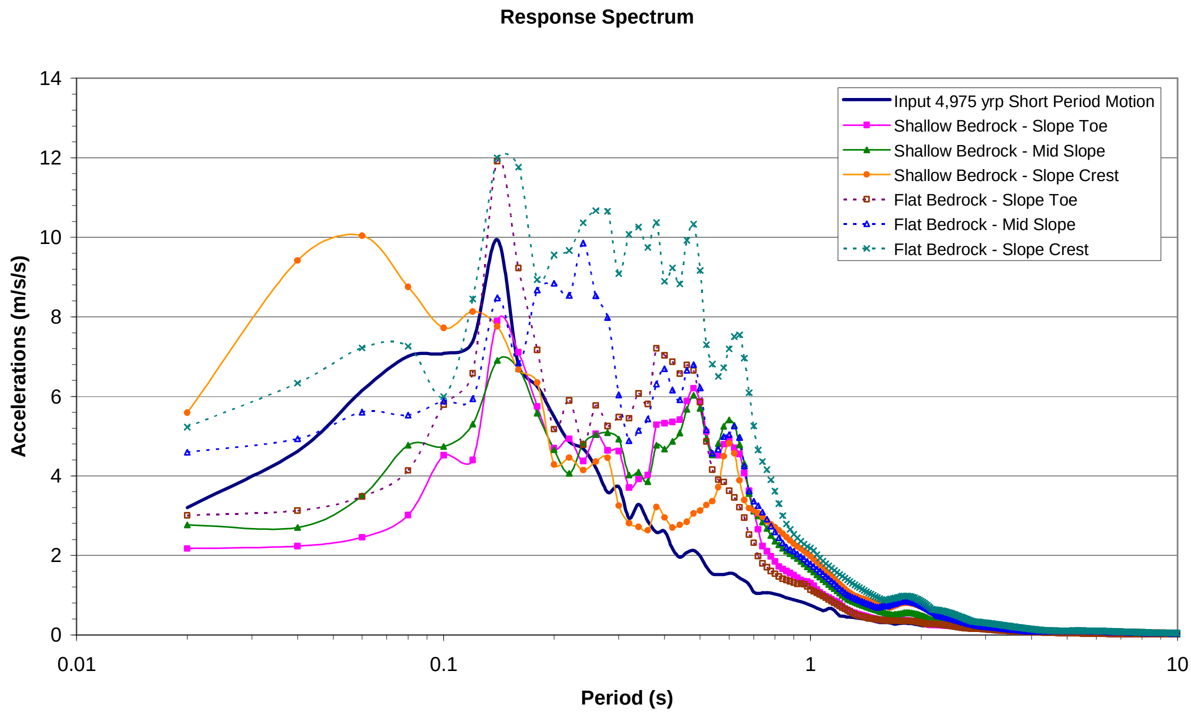

Figure 7: Acceleration response spectrum for 4,975 years return period ground motion (Static FoS of 1.2)

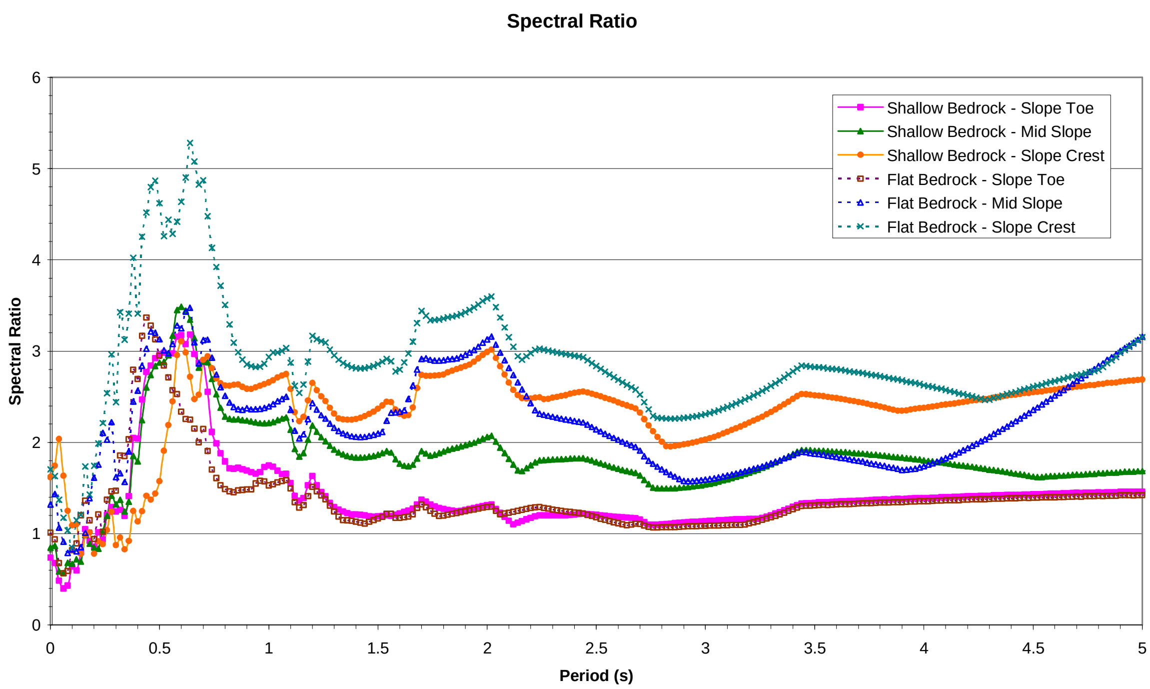

Figure 8: Spectral ratio for 4,975 years return period ground motion (Static FoS of 1.2)

It is noted that the displacement computed based on the distortion in each element according to the stress-strain relationship in the numerical modelling can be quite different to the sliding block analysis. The definition of slope displacement for both methods of analyse can cause different criteria of failure for a slope design.

The earthquake induced displacement in the slope with flat bedrock is generally larger and movements are deeper than in the slope with shallow bedrock. The soil amplification factors are also estimated from the analytical results and they are within the range of 3 and 5.

The results indicated that the current geotechnical standards for slopes with FoS of 1.4 are generally adequate for extreme earthquake scenario events of 2,475-year return period. However, for slopes with FoS of 1.2, the induced slope displacement with similar events may threaten the integrity of essential facilities located above or below the slopes.

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