Analytical study of seismic slope behavior in a large-scale shaking table model test using FEM and MPM

Étude analytique du comportement des pentes sismiques dans les essais de modèles de grandes dimensions sur table à secousses conformément aux méthodes FEM et MPM

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ABSTRACT: Seismic safety of slopes is generally estimated through stability analysis using a simplified conservative approach or Finite Element Method (FEM) analysis approach, focusing on the conditions of slopes before slope failure. However, it is also important to understand the conditions of slopes after slope failure. Accordingly, the authors carried out a series of shaking table tests with large-scale slope models. The models consist of a model with weak layer and a model which has high response acceleration at top of the slope. Results from the tests indicated that it is important to consider large deformation along slip lines in the weak layer and amplification and phase lag of response acceleration at the top. The one layered slope model was analyzed by FEM with a nonlinear model as a constitutive law focusing on the amplification and phase lag of response acceleration at top of model. Both slope models were analyzed by Material Point Method (MPM). Consequently, the same trend of the amplification and phase lag of response acceleration and failure patterns as that seen at the shaking table test was obtained by the FEM or MPM.

RÉSUMÉ : La sécurité sismique des pentes est en général calculée par une analyse de stabilité selon une approche conservative simplifiée du type méthode de Fellenius ou Méthode d'analyse par éléments finis (FEM), l'accent étant mis sur l'état des pentes avant leur défaillance. Il est toutefois important, en termes de stabilité sismique des pentes, de connaître l'état des pentes après leur défaillance. À cet effet, les auteurs ont procédé à une série d'essais de modèle de pentes de grandes dimensions sur table à secousses. Les modèles consistaient en un modèle à couche faible (modèles à trois couches) et un modèle à accélération de réponse élevée au sommet de la pente (modèle à une couche). Le résultat des essais montre que, dans l'estimation de la sécurité des pentes, il est important de prendre en compte des déformations importantes le long des lignes de glissement dans la couche faible et l'amplification et le déphasage de l'accélération de la réponse en sommet de pente. Les deux modèles de pente ont été analysés par la Méthode aux Points Matériels (MPM). De fait, les mêmes tendances d'amplification et de déphasage de l'accélération de réponse et les mêmes schémas de défaillance observés pour les essais sur la table à secousses ont été obtenus par la méthode FEM ou MPM.

KEYWORDS: slope model, shaking table test, FEM, MPM

1 INTRODUCTION.

In terms of seismic safety of nuclear power plants in Japan, it is emphasized that we carefully have to consider the safety of the nuclear power plants against slope failure as well as tsunamis which are related incidents during earthquake. Seismic safety of slopes is generally analyzed through stability analysis using a simplified conservative approach such as the Fellenius method, or the Finite Element Method (FEM) analysis approach, focusing on the conditions of slopes before slope failure. However, it is also important to understand the conditions of slopes during earthquake and after slope failure. Accordingly, a series of shaking table tests with large-scale slope models was carried out by the authors at the world's largest shaking table, nicknamed "E-Defense" of NIED in Hyogo, Japan. This paper presents results from analytical study of seismic slope behaviour in the shaking table model test by FEM and Material Point Method (MPM). Also, it is stated that the validity of these methods on seismic behaviour of slopes and several issues to be solved in future work toward developing analytical tools for assessing the seismic safety of slopes.

2 OUTLINE OF THE SHAKING TABLE TEST

Details of the shaking table test are shown in Shinoda et al. (2013). In this chapter, outline of the test is stated. Figure 1 shows the initial states of the test models. The test models consisted of a slope model which had high amplitude of response acceleration at the top of slope and a slope model with a lower-strength cohesive sand layer. The former was called one layered model because the model mostly consisted of one kind of layer (general part). The model also had reinforced part at left hand side slope consisting of geotextile, cohesive sandy soil and sandbags in order to produce slope failure at only right hand side slope. The latter was called three layered model because the model consisted of three different layers: surface layer, weak layer, which represents the lower-strength cohesive sand layer, and base layer. The gradients and widths of the weak layer were 45 degrees and 400 mm, respectively. The both models were made with heights of approximately 3.0 m.

Table 1 shows the slope model soil properties as determined from tri-axial compression tests. The base layer was made of dense crushed stone stabilized with cement. The general part and weak layer were made of siliceous sand mixed with bentonite. The surface layer for three layered model was reinforced by geotextile. To prevent sliding at the divisions between layers of three layered model, the boundaries were bench-cut as shown in Figure 1. Teflon-lined sheet were also left between the slope models and the acrylic sidewalls of the shaking table container to ensure that there were no frictional forces between the models and the walls. The response of the models was measured using accelerometers and laser displacement transducers installed on the slope models.

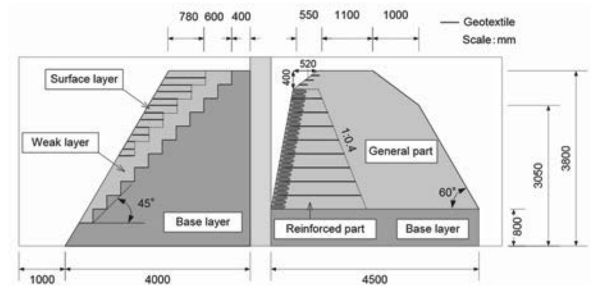
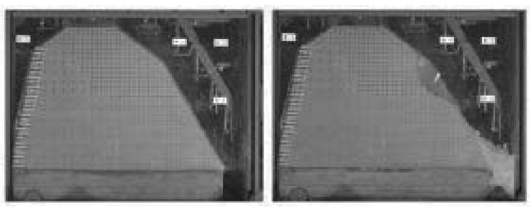


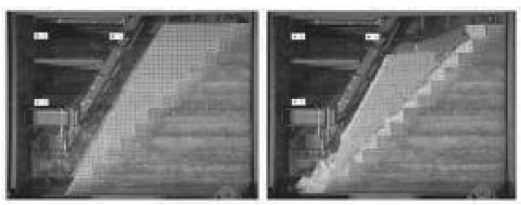
Figure 1. Initial state of test models (left figure: three layered model, right figure: one layered model)

Table 1. Slope model soil properties as determined from tri-axial compression tests with the materials in the layers

	Young's modulus (kN/m^2)	Initial shear modulus (kN/m^2)	Poisson's ratio	Unit weight (kN/m^3)	Cohesion (kN/m^2)	Internal frictional angle (deg)
General part Weak layer	7.7×10^4	2.9×10^4	0.264	16.2	12.9	24.6
Reinforced part	9.4×10^4	3.5×10^4	0.383	16.2	17.6	19.4
Base layer	2.5×10^6	9.4×10^5	0.267	18.5	280.5	57.3



(a) One layered model

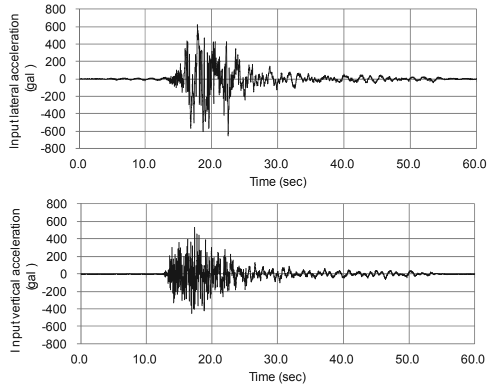


(b) Three layered model

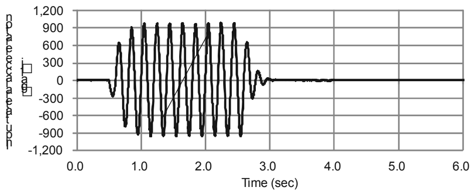
Figure 2. Initial and final photos of test models (above figure: one layered model, below figure: three layered model)

The input waves in the shaking table tests were a 5 Hz sine wave with a wave number of 10 and an observed seismic wave in Niigata Chuetsu earthquake in 2007 (dominant frequency: 0.5 Hz). The amplitude of the waves was increased in stepwise changes with 50 to 100 gal pace. The waves were input along lateral and vertical directions on the condition that amplitude of vertical wave was two thirds of that of lateral one.

Figure 2 shows the initial and final photos of test models. The one layered model exhibited partial catastrophic failure at right hand side slope when the input wave amplitude reached 654 gal for lateral wave and 537 gal for vertical wave of the observed seismic wave shown in Figure 3 (a). The three layered model exhibited slide down along the slip surface generated in the weak layer when the input wave amplitude reached 984 gal for lateral wave of the sine wave shown in Figure 3 (b). These waves are used as input waves in below-mentioned analyses.



(a) Input waves for one layered model



(b) Input wave for three layered model

Figure 3. Input waves used in FEM and MPM anaysis

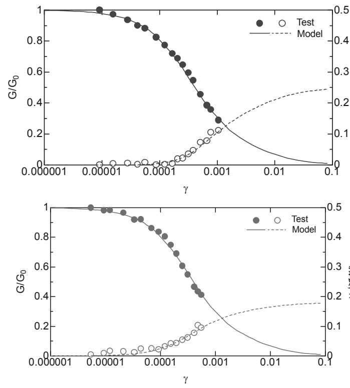
3 ANALYTICAL METHOD

3.1 *FEM*

FEM analysis was carried out focusing on the investigation of possibility of analyzing the amplification and phase lag of response acceleration at the top of slope of the one layered model. The GHE-S model (Murono and Nogami, 2006) together with the multiple nonlinear spring model (Towhata and Ishihara, 1985) was used as a constitutive law of the general and reinforced part. Considering confining pressure dependency of initial shear modulus G_0, relationship between G/G_0 (G: shear modulus) and damping ratio h and shear strain γ are modeled by the GHE-S model as shown in Figure 4. Elasticity model was used as a constitutive law of the base layer. Wave attenuation was considered by Rayleigh damping (damping constants α = 0.0 and β = 0.001).

3.2 *MPM*

The MPM (Sulsky et al, 1994 and 1995), which is one of the mesh-free methods, was used as the analytical method. Figure 5 explains analysis flow of the MPM, which is similar to that of FLAC (Cundall and Board, 1988). But, the MPM can deal with larger deformation through particle discretization. The MPM also avoids tensile instability that is annoying in the Smoothed Particle Hydrodynamics (SPH) (Lucy, 1977; Gingold and Monaghan, 1977). Hence, the MPM does not need an artificial damping. The super/subloading yield surface (SYS) Cam-clay model (Asaoka et al, 2000) was used as an elasto-plastic constitutive law for general part and weak layer in the MPM model. The model can describe degradation processes from both an overconsolidated state to a normally consolidated state and from a structured state to a destructured state. Figure 6 shows the results of investigation to determine the stress-strain characteristics of a material specimen in the general part and weak layer under tri-axial compression tests and cyclic tri-axial tests using the model with the parameters shown in Table 2. On the other hand, the perfect elasto-plastic Drucker-Prager model and the elasticity model were used for the surface layer of three layered model and base layers as a constitutive law, respectively.



(a) General part (b) Reinforced part

Figure 4. Results of investigation to determine the stress-strain characteristics of a material specimen under cyclic tri-axial tests using the GHE-S model

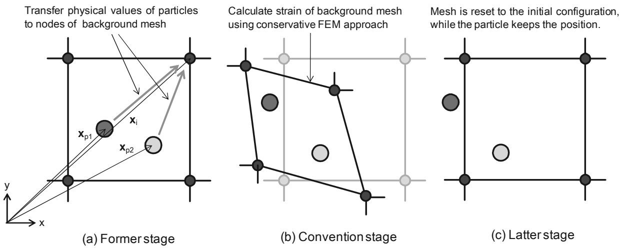


Figure 5. Analysis flow of the MPM

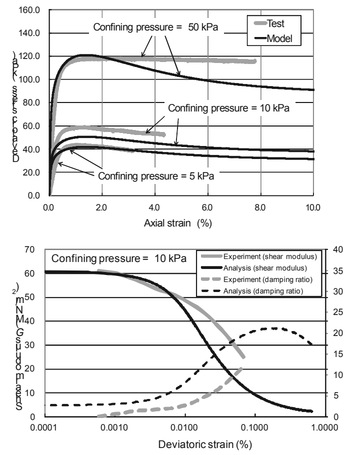


Figure 6. Results of investigation to determine the stress-strain characteristics of a material specimen under tri-axial compression tests and cyclic tri-axial tests using the SYS Cam-clay model

Table 2. Modelling parameters of the SYS Cam-clay model

Elasto-plastic parameters		
Compression index λ	Minimum value	0.0025
	Maximum value	0.05
Reference value of γ_p for λ γ_λ		0.0001
Swelling index κ	Minimum value	0.0015
	Maximum value	0.049
Reference value of γ_p for κ γ_κ		0.01
Critical state constant M		0.90
Specific volume at q = 0 and p '= 98.1 kPa on NCL N		1.785
Poisson's ratio		0.264
Cohesion (kPa)		8.0

4 ANALYTICAL RESULT

4.1 *FEM*

Figure 7 shows analytical and test results of lateral response acceleration and displacement at observation points shown in Figure 8 (a). The analytical results are largely consistent with the test results. Figure 8 (b) to (d) shows distributions of amplitude of lateral response acceleration and maximum shear strain when the amplitude of lateral response acceleration is the minimum. In test results, the lateral response acceleration is amplified at the top and right hand side slope as shown in Figure 8 (b). Large amplification of the lateral response acceleration is produced at middle part of the right hand side slope, where partial catastrophic failure occurred (see Figure 2 (a)). On the other hand, although the analysis can describe overall behavior of amplification and phase lag of lateral response acceleration as shown in Figure 8 (c), that cannot describe localized amplification of lateral response acceleration at right hand side slope shown in Figure 8 (b) seen in test. Also, shear strain growth is prominent at the toe of right hand side slope as shown in Figure 8 (d), which is inconsistent with a middle part of the slope where partial catastrophic failure occurred. This indicates that the used FEM model is applicable to describe overall behavior of amplification and phase lag of lateral response acceleration, but the model has problems to solve to deal with shear strain growth due to localized amplification of lateral response acceleration.

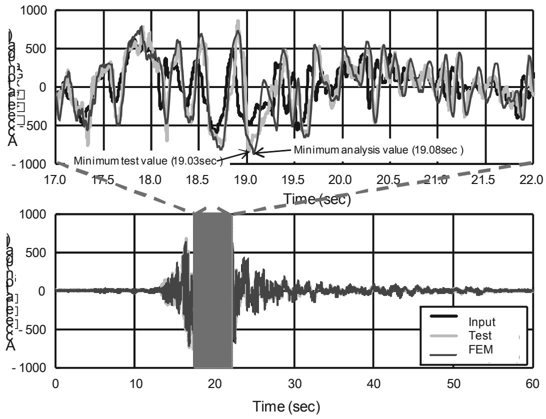
4.2 *MPM*

Figure 9 and Figure 10 show processes of distributions of maximum shear strain and lateral response acceleration derived from MPM analysis. In one layered model, analytical results show catastrophic failure at right hand side slope, but the amount of deformation is overestimated comparing to test results. In three layered model, final configuration derived from the analysis is largely consistent with that of the test. Figure 11 shows time histories of lateral and vertical response displacement at observation points displayed in Figure 10 (a) introduced from test and analysis. Start time and rate of change of displacement derived from the analysis is largely consistent with that in the test. These indicate that the MPM analysis can deal with the large deformation such as slide down although a constitutive law was modeled up to residual state as shown in Figure 6.

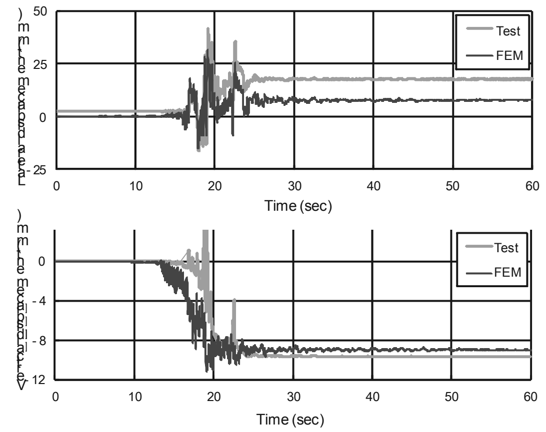
5 CONCLUSION

Seismic behavior of large-scale slope model on the world's largest shaking table test was analyzed by FEM and MPM. The outcomes can be summarized as follows:

1) The same trend of the amplification and phase lag of response acceleration at the top of slope of one layered slope model as that seen at the shaking table test could be obtained by the FEM with GHE-S model together with the multiple nonlinear spring models. However, the FEM model could not describe the localized amplification of response acceleration and shear strain growth at the middle part of the slope where partial catastrophic failure occurred.
2) The similar failure patterns of one and three layered slope models to that seen at the shaking table test could be obtained by the MPM with the SYS Cam-clay model. However, the MPM analysis could not produce good agreements in the one layered slope model regarding the amount of deformation, which should be improved in the future work.
3) Consequently, it is considered that the FEM analysis is appreciate for a slope with large amplification of response acceleration and the MPM analysis is appreciate for a slope with a weak layer as analytical tools for assessing seismic safety of slopes. However, both models should be improved to evaluate seismic behavior of slopes more accurately.

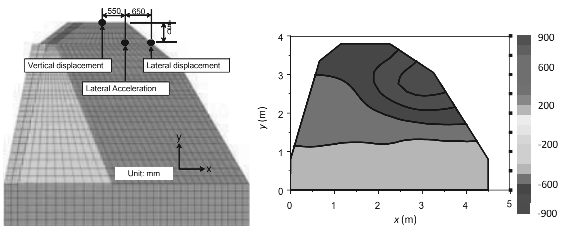


(a) Lateral response acceleration

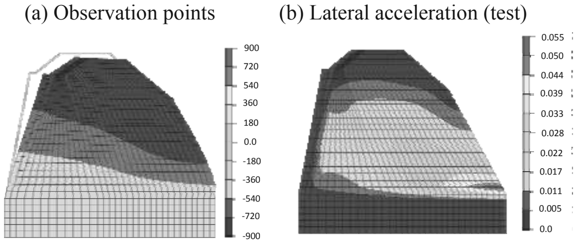


(b) Lateral and vertical response displacement

Figure 7. Analytical results and test results of lateral response acceleration and response displacement at the observation points



(a) Observation points (b) Lateral acceleration (test)



(c) Lateral acceleration (FEM) (d) Maximum shear strain (FEM)

Figure 8. Positions of observation points, distributions of lateral acceleration (unit: gal) and maximum shear strain when the amplitude of lateral response acceleration is the minimum

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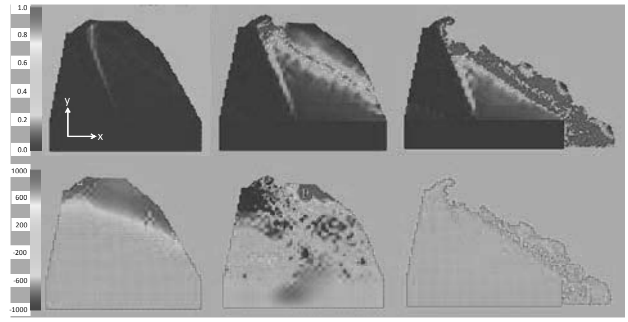
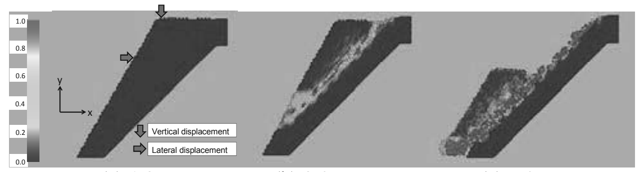


(a) 16.3 sec (b) 19.0 sec (c) 40.0 sec

Figure 9. Processes of distributions of maximum shear strain (upper figure) and lateral response acceleration (below figure, unit: gal) of one layered model



(a) 1.2 sec (b) 2.0 sec (c) 7.0 sec

Figure 10. Processes of distributions of maximum shear strain of three layered model

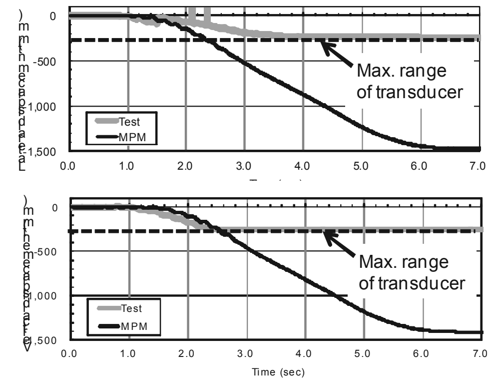


Figure 11. Time histories of lateral response displacement (upper figure) and vertical response displacement (below figure) of the three layered model at the observation points

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