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Numerical analysis of gradient-changing slope under earthquakes

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Abstract: A two-dimensional finite element numerical model was proposed to analyze earthquake responses of gradient-changing slope based on a shaking table test. In order to study dynamic characteristics of the gradient-changing slope, seismic waves with different peak accelerations, sorts and frequencies were input at bottom boundary of the numerical model. Simulation results show that dynamic performance of the numerical model is similar to practical homogeneous soil slope. Then, numerical model was verified by comparing simulation results with test data. The results are helpful to further study on mechanism of slope stability under earthquake and the guidance for practical engineering.

Introduction

Performance of soil slopes subjected to seismic loadings is an important issue to be considered in slope design. For engineering practice, it is of particular interest to predict the dynamic responses of natural and man-made slopes under seismic loadings. In order to study dynamic behaviour of slope associated with earthquake, physical model tests such as centrifuge model tests and shaking table tests are desirable. The centrifuge model test uses centrifuge acceleration to simulate prototype model behaviour. Kutter (1983) conducted centrifuge test with clay soil and found that the displacement predicted with strain softening would better coincide with the test results. Through a series of dynamic centrifuge tests, Brennan et al. (2005) evaluated shear modulus and damping ratio of soil. The major problem of centrifuge model test is the scaling effect due to the difficulty of scaling the instrumentation properly.

Shaking table test is another important approach to study seismic response of soil slope. Lo Grasso et al. (2004) investigated the performance of reinforced slope through a number of shaking table tests. It was concluded from the study that reducing the spacing of reinforcement near the top of the model is beneficial for the stability of the slope. Surcharge has a great effect on altering the failure surface mechanism. Failure surface is circular for slopes with surcharge, while without surcharge it is a typical two-wedge failure surface. Lin and Wang (2006) conducted shaking table test to identify the initiate status of landslide movement from the acceleration time-history curves based on nonlinear behaviour of slope soil. In order to understand the influences of peak horizontal ground accelerations and wave frequencies on seismic displacement of slope, Huang et al. (2011) carried out a shaking table test on reinforced model slope. The test results indicated that the relationship between amplification responses and the plastic displacement of the slope were obtained.

The analytical methods were considered as the seismic stability of slopes in terms of a pseudo static factor of safety in the past time. These simple analysis approaches later evolved into more elegant sliding block-type displacement-based procedures (e.g., Newmark 1965). The assumption of this sliding block procedure is that, permanent deformation occurs on a potential sliding mass, when earthquake-induced inertial forces exceed the yield resistance along the slip surface. Deformations continue until the inertial forces decrease and the velocities of the sliding mass and underlying ground coincide. Seismic responses of slope have also been investigated using advanced numerical technique, i.e. finite element method. Numerical models are capable to provide insight into the initiation and subsequent progressive movement of seismic slope deformations.

In this paper, a two-dimensional finite element numerical model was proposed to analyse earthquake responses of gradient-changing slope based on a shaking table test. In the consideration of input seismic waves with different peak accelerations, sorts and frequencies, slope dynamic response of several cases were obtained from the numerical simulation, and the numerical model was verified by test results. Some useful conclusions are presented for understanding slope characteristics under seismic loading conditions.

Finite Element Model

The shaking table test of gradient-changing slope has been completed at State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University. The prototype of test model is symmetrical trench slope of immersed tunnel, which is selected from man-made submarine tunnel trench of Hongkong-Zhuhai-Macau Link under construction. Take the test model as study object, a two-dimensional plane strain finite element model was established using ABAQUS procedure. Figure 1 shows the numerical model of three-stage slope with homogeneous soil based on time-history analysis. The total nodes number is 1370, and the corresponding elements number is 1264.

The mechanical parameters of slope soil for the numerical model are shown in Table 1, and the material properties are the same as model soil in the shaking table test. Mohr-Coulomb criterion is used for the material of soil. Rayleigh damping is applied to this soil material model, and the damping coefficients α and β could be calculated as

$$\alpha = \zeta \frac{2\omega_1 \omega_2}{\omega_1 + \omega_2} \tag{1}$$

$$\beta = \zeta \frac{2}{\omega_1 + \omega_2} \tag{2}$$

where ζ is damping ratio, and ω_1 and ω_2 stand for the first and second order frequency of the numerical model.

The bottom boundary is fixed in vertical direction, but infinite elements were set on both lateral boundaries to reduce the reflection of seismic waves. In the numerical simulation process of slope dynamic response under seismic loadings, several sorts of earthquake acceleration waves are chosen as input seismic waves from the bottom boundary of the numerical model (see Figure 2).

To validate material model, two free field numerical models were conducted by ABAQUS software and SHAKE91 procedure respectively. Transfer functions in frequency domain obtained by both numerical tools were compared in Figure 3. The numerical results show that the first order frequency is nearly the same of both numerical models, and the corresponding peak amplitudes are also coincident. But the shapes of transfer function curves are different in the second order mode. However, seismic characteristics of structures are mainly controlled by the first order mode in general. Thus, parameters of the material model are proved to be reasonable.

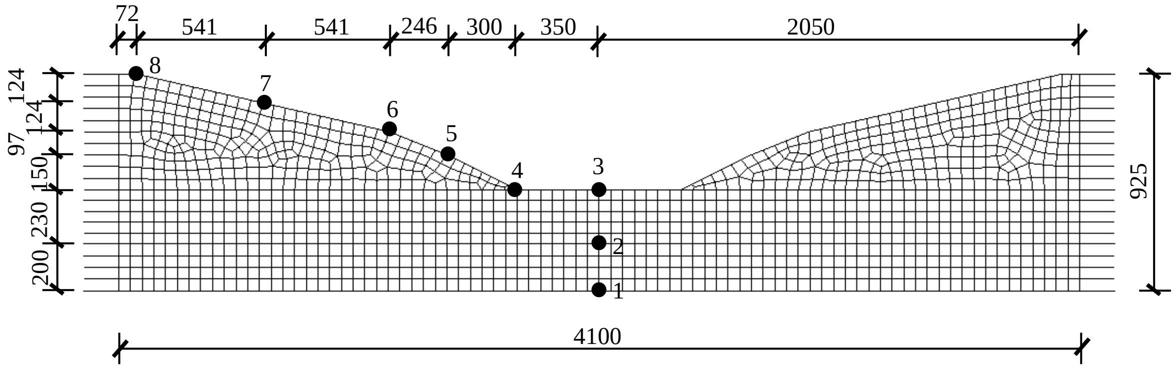
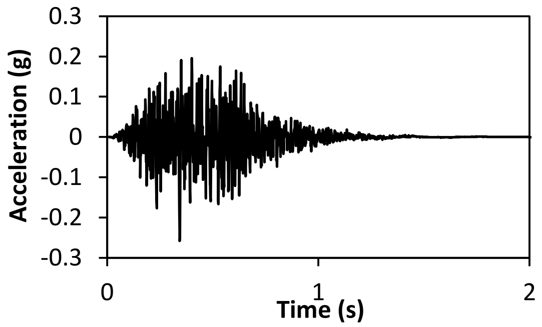


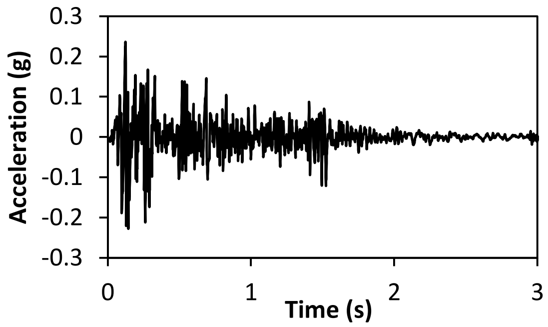
Fig.1 Finite Element Model of slope (Unit: mm)

Table 1 Mechanical parameters

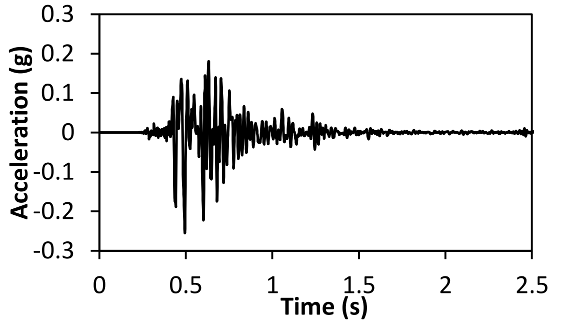
Layer	Density (kN/m^3)	Elastic modulus (kPa)	Poisson's ratio	Cohesion (kPa)	Friction angle (°)	Damping ratio
Model soil	0.694	7.952	0.35	0.0105	17.3	0.02



(a) Artificial wave



(b) El Centro wave



(c)Kobe wave

Fig.2 Seismic waves

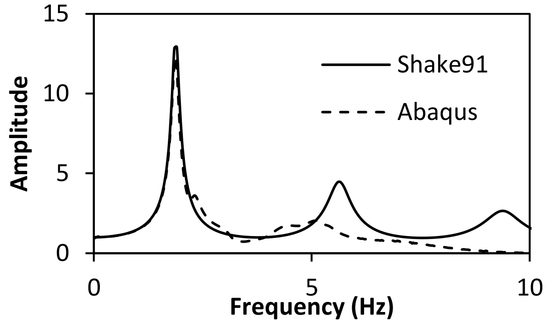


Fig.3 Transfer Function in Frequency Domain

Results and discussion

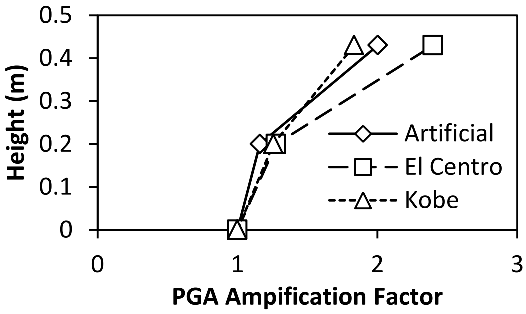
9 Cases were simulated to study seismic response of the slope, and different peak accelerations, sorts and frequencies of seismic waves were considered in these cases (see

Table 2). 8 monitoring points were selected inside the slope and on the slope surface to track acceleration of the slope mass varying with time. Figure 1 shows the location of the monitoring points in the numerical simulation based on the dynamic time-history analysis.

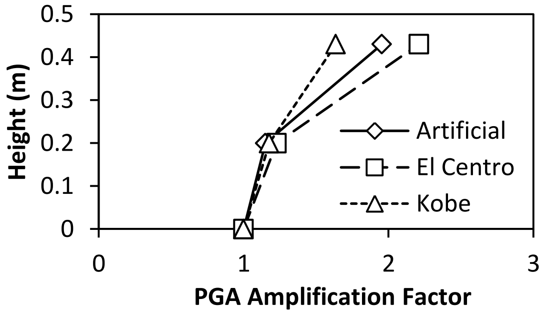
Table 2 Cases of numerical simulation

Case	Seismic wave	Peak acceleration	Frequency ratio
1	Artificial	0.25	17.32
2	El Centro	0.25	17.32
3	Kobe	0.25	17.32
4	Artificial	0.4	17.32
5	Artificial	0.6	17.32
6	Artificial	0.75	17.32
7	Artificial	0.25	11.55
8	Artificial	0.25	5.77
9	Artificial	0.25	1

Results from the Figure 4 indicate that, amplification factor of PGA (abbreviation of Peak Ground Acceleration) imply magnification trend from monitoring point 1 to point 3. Dynamic response excited by El Centro wave is a little stronger than the other two cases. Figure 5 shows that low frequency signals are amplified, while high frequency signals are filtered from bottom to top through soil. These numerical characteristics of seismic response are similar to practical soil. In addition, the simulation results of numerical model are coincident with the test data.

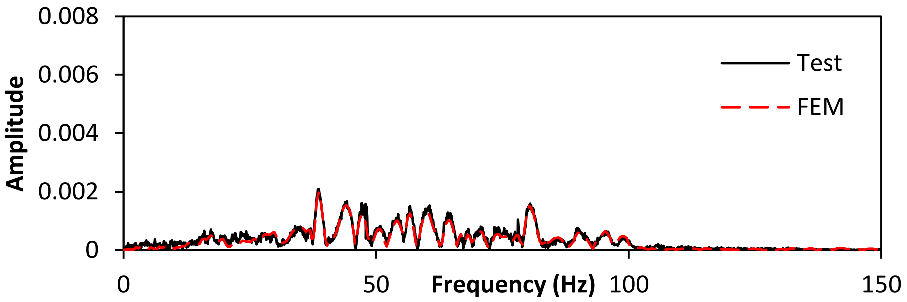


(a) numerical simulation

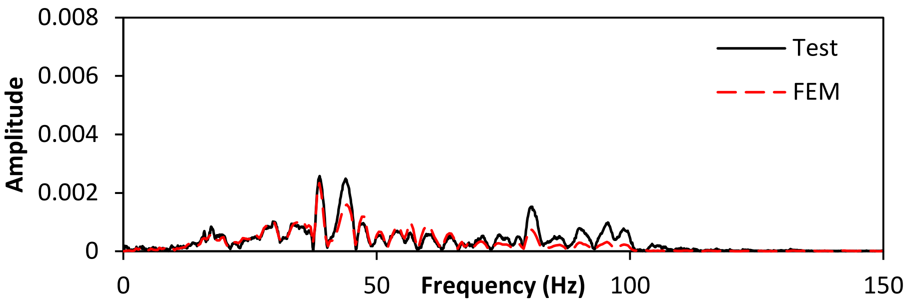


(b) test

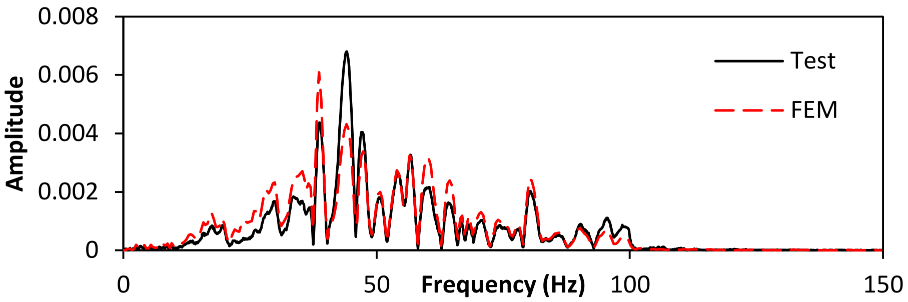
Fig.4 Vertical Amplification



(a) point 1

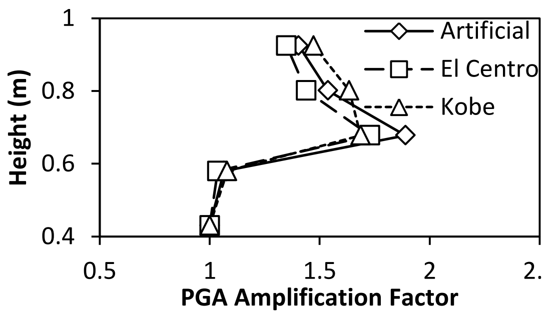


(b) point 2

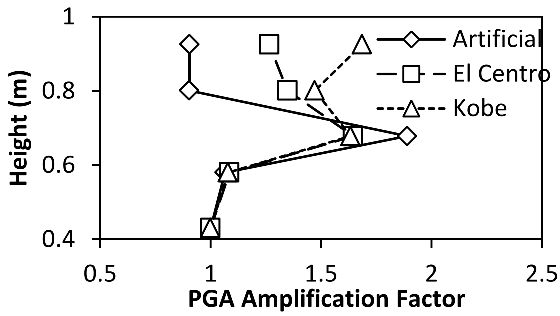


(c) point 3

Fig.5 Frequency Spectrum



(a) numerical simulation



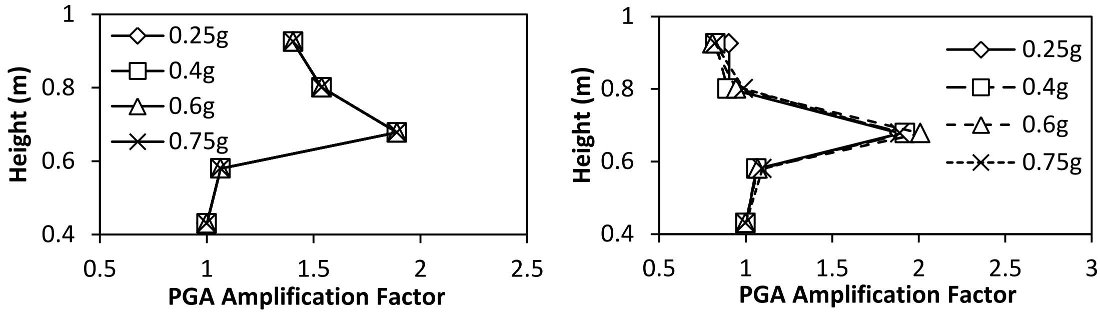
(b) test

Fig.6 Slope Surface Amplification

The distribution of PGA amplification factor along the slope surface is displayed in Figure 6. The amplification factor raise at first, then decrease, and the maximum PGA in any case of the three is observed at point 6 along the slope surface. The point location is where the slope gradient changing from 1:2.5 to 1:5 happens.

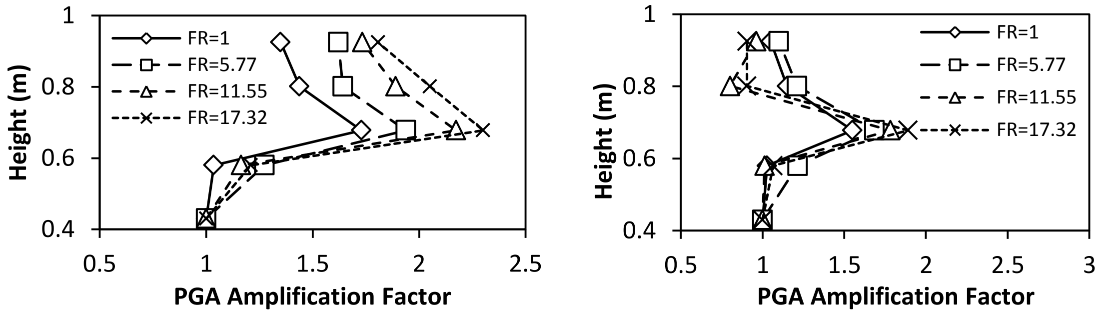
The effects of amplitudes of earthquake waves on dynamic responses of the slope are studied, as shown in Figure 7. The trends of PGA amplification factor distribution in the four cases are nearly the same in both numerical simulation and test conditions. The simulation results indicate that, the slope soil is still in linear elastic status after excitation by strong seismic waves.

Figure 8 shows that the amplification factors of PGA increase with the decreasing frequencies of input earthquake waves along the slope surface, and in all four cases distribution trends of PGA amplification factor appear raise at the first, then decrease.



(a) numerical simulation (b) test

Fig.7 Dynamic Response of Slope Surface in Cases of Different Peak Accelerations



(a) numerical simulation (b) test

Fig.8 Dynamic Response of Slope Surface in Cases of Different Frequencies

Conclusion

A two-dimensional finite element numerical model was established to study seismic responses of gradient-changing slope based on a shaking table test. In the numerical model, effects such as boundary condition, material parameters and different seismic waves were considered. Numerical results are coincident with test data in the same cases, therefore numerical and test model could be regarded as reasonable. Thus, the results are helpful to further study on mechanism of slope stability under earthquake and practical engineering.

Acknowledgements

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References

S.L. Kramer, *Geotechnical Earthquake Engineering*, 1st Edition, Elsevier, 1995.

G. Biondi, E. Cascone and M. Maugeri, Flow and deformation of sandy slopes. *Soil Dynamics and Earthquake Engineering*, 22(10), pp. 1103−1114, 2002.

K.L. Wang, M.L. Lin, Initiation and displacement of landslide induced by earthquake-a study of shaking table model slope test. *Engineering Geology*, 122, pp. 106-114, 2011.

N. Srilatha, G. Madhavi Latha and C. G. Puttappa, Effect of frequency on seismic response of reinforced soil slopes in shaking table tests. *Geotextiles and Geomembranes*, 36, pp. 27-32, 2013.

B.L. Kutter, Deformation of centrifuge models of clay embankments due to 'bumpy road' earthquakes. *Soil Dynamics and Earthquake Engineering*, 2(4), pp. 199-205, 1983.

A.J. Brennan, N.I. Thusyanthan and S.P.G. Madabhushi, Evaluation of shear modulus and damping in dynamic centrifuge tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(12), pp. 1488-1497, 2005.

A.S. Lo Grasso, M. Maugeri and P. Recalcati, Shaking table tests and analysis of reinforced slopes. *3rd Asian Regional Conference on Geosynthetics*, June 21-23, 2004, Seoul, Korea.

M.L. Lin, K.L. Wang, Seismic slope behavior in a large-scale shaking table model test. *Engineering Geology*, 86, pp. 118-133, 2006.

C.C. Huang, J.C. Horng and W.J. Chang, et al. Dynamic behavior of reinforced walls-horizontal displacement response. *Geotextile and Geomembranes*, 29(3), pp. 257-267, 2011.

N.M. Newmark, Effects of earthquake on dams and embankments. *Geotechnique*, 15(2), pp. 139-160, 1965.

W. Chen, T. Qiu. Simulation of earthquake-induced slope deformation using SPH method. *International Journal for Numerical and Analytical Methods in Geomechanics*, 38, pp. 297-330, 2014.

J.W. Zhou, P. Cui and X.G. Yang, Dynamic process analysis for the initiation and movement of the Donghekou landslide-debris flow triggered by the Wenchuan earthquake. *Journal of Asian Earth Sciences*, 76, pp. 70-84, 2013.

H.I. Ling, D. Leshchinsky and Y. Mohri, Soil slopes under combined horizontal and vertical seismic accelerations. *Earthquake Engineering and Structural Dynamics*, 26, pp. 1231-1241, 1997.

T. Kokusho, T. Ishizawa and K. Koizumi, Energy approach to seismically induced slope failure and its application to case histories. *Engineering Geology*, 122, pp. 115-128, 2011.

V.D. Gaudio, J. Wasowski, Advances and problems in understanding the seismic response of potentially unstable slopes. *Engineering Geology*, 122, pp. 73-83, 2011.

D. Assimaki, E. Kausel and A. Whittle, Model for dynamic shear modulus and damping for granular soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 126(10), pp. 859-869, 2000.

G. Gazetas, Seismic response of earth dams: some recent develops. *Soil Dynamics and Earthquake Engineering*, 6(1), pp. 2-47, 1987.

Y.S. Hong, R.H. Chen and C.S. Wu, Shaking table tests and stability analysis of steep nailed slopes. *Canadian Geotechnical Journal*, 42(5), pp. 1264-1279, 2005.

E.M. Rathje, J.D. Bray, Nonlinear coupled seismic sliding analysis of earth structures. *Journal of Geotechnical and Geoenvironmental Engineering*, 126(11), pp. 1002-1014, 2000.

M. Taiebat, A.M. Kaynia and Y.F. Dafalias, Application of an anisotropic constitutive model for structured clay to seismic slope stability. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(5), pp. 492-504, 2011.