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Prediction of seismically induced acceleration and settlement of slopes

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ABSTRACT: Prediction of seismic response of slopes is a numerical challenge because the static shear stresses induce large nonlinear deformation, far exceeding the levels encountered in a horizontal deposit. A series of two-dimensional (2D) nonlinear finite element analyses are performed to simulate the seismic response of slope. The numerical model is validated against centrifuge test measurements performed with an equivalent shear beam model container. We evaluate various parameters on the accuracy of the numerical model, including the soil layering, the nonlinear soil curve, and the selection of the input parameters for the nonlinear soil model. We show that the soil curve and the input parameters have a secondary influence on the calculated acceleration. However, they are revealed to have a primary impact on the calculated settlement. Through the application of the shear strength correction to the nonlinear model, the measured settlement is reliably predicted. The successful prediction of the vertical settlement demonstrates that it can potentially be used as a damage index by which to evaluate the slope stability.

RÉSUMÉ : La prédiction des réponses sismiques des pentes est un défi numérique car les contraintes de cisaillement statique induisent de grandes déformations non-linéaires, bien supérieures à celles rencontrées sur un plan horizontal. Afin de simuler la réponse sismique de ces pentes, l'analyse d'une série d'éléments finis non-linéaires en deux dimensions (2D) est réalisée. Le modèle numérique est validé par des mesures d'essais de centrifugation, effectuées à l'aide d'un conteneur équivalant au modèle de cisaillement d'une poutre. Divers paramètres sont évalués sur la précision du modèle, dont la stratification du sol, la courbe de sol non-linéaire et la sélection des paramètres d'entrée pour un modèle de sol non-linéaire. Nous montrons que la courbe du sol et les paramètres d'entrée n'ont une influence que secondaire sur l'accélération calculée. Cependant, il s'avère qu'ils impactent directement le tassement. Grâce à l'application de la correction de résistance au cisaillement du modèle non-linéaire, le tassement mesuré est prédit de manière fiable. La prédiction réussie du tassement vertical démontre qu'il peut potentiellement être utilisé comme un indice de dommage permettant d'évaluer la stabilité de la pente.

KEYWORDS: seismic slope stability, finite elements analysis, centrifuge test, displacement

1 INTRODUCTION

One of the primary interests in the field of geotechnical engineering is the prediction of slope stability under severe earthquake loading. It is especially important for slopes near nuclear power plants, where a slope failure can severely damage the facility. However, even for such critical situations, limit equilibrium procedure based pseudo-static analysis is the most widely used design method. Although the inherent limitations of this method are well understood and documented (Seed 1973, Bray and Travasarou 2009, Jibson 2011). Key limitations include the assumption that the soil has completely rigid plastic behavior and that the shear strength moves simultaneously along the sliding surface. Furthermore, it is assumed that the sliding surface is not dependent on the amplitude and frequency content of the earthquake. Due to the inherent limitations of the pseudo-static method, more sophisticated dynamic continuum models are required to evaluate the seismic stability of slopes.

To study the performance and estimate the permanent displacement of dams, Makdisi and Seed (1978) used the equivalent linear analysis to perform the dynamic finite element analysis. The method implies many approximate and simplified assumptions that may lead to conservative results. Bouckovalas and Papadimitriou (2005) studied the effect of vertically propagating seismic waves on the seismic response of slopes. In the finite element analysis, the soil was assumed as a linear viscoelastic material. To validate the numerical model, an analytical solution was used. However, to generalize the finding of this numerical study, there is a lack of calibration of results with experimental recordings. Rizzitano et al. (2014) explored the effect of soil topography on amplification of input motion, and soil was modeled through a linear and equivalent linear model in the 2D numerical analyses. The comparison of linear

and equivalent linear analysis results depicted that amplification behavior may be underestimated in the linear analysis. The accuracy of this numerical model was compared with the numerical analysis results provided in previous studies. Du et al. (2018) examined the effect of variability of soil properties on the slope displacement prediction and reported that variability in shear wave velocity and nonlinear soil properties cause a reduction in displacement. Song et al. (2020) investigated the seismic response of slope considering the interactions between topographic and soil layer amplification by including the 2D full-slope responses. To validate the numerical analysis and results of slope amplification, the slope surface response is compared with the results of previously performed numerical studies.

Because the soil is expected to undergo a high level of shear strains due to the static shear stress imposed in slopes, the use of the nonlinear soil model is needed. Such numerical models should be well-calibrated against recordings for possible use in practice. However, there is a serious lack of measurements of slope response subjected to earthquake loadings.

In this study, the numerical model was validated using centrifuge test data of a slope made up of granular soil. The spectral acceleration and the vertical settlement are outputs that are compared here. Furthermore, the effect of the parameters selected for the nonlinear model on the computed response is explored. The impact of the shear strength correction is specifically addressed, since its impact on the results of seismic slope stability analysis has not yet been explored.

2 CENTRIFUGE MODEL TEST

Korean Advanced Institute of Science and Technology (KAIST) centrifuge facility was used to perform the dynamic centrifuge

tests. The equivalent shear beam (ESB) box was utilized for the dynamic centrifuge test, which is reported to give a more realistic free-field boundary condition than a rigid box (Lee et al. 2013). The technical specifications and dimensions of the model container utilized in this study are reported in Lee et al. (2013). Figure 1 shows the centrifuge test model's layout, which includes the position of accelerometers and laser sensors. The centrifuge model was built to 1/55 scale, and the tests were carried out at a 55 g acceleration.

On the prototype scale, the height of the slope is 10 m, and the angle of inclination is 45°. It is underlain by flat ground with a thickness of 24.65 m. According to the Unified Soil Classification System, the soil is silty sand (SM). The shear wave velocity (Vs) was changed from 90 m/s around the surface of the soil profile to 287 m/s at the bottom. The Vs profile is depicted in Figure 2. The direct simple shear tests were performed to measure the shear strength parameters of soil. The measured friction angle of soil was 39°, and the cohesion value of 12 kPa. The unit weight of soil was 17.5 kN/m^3.
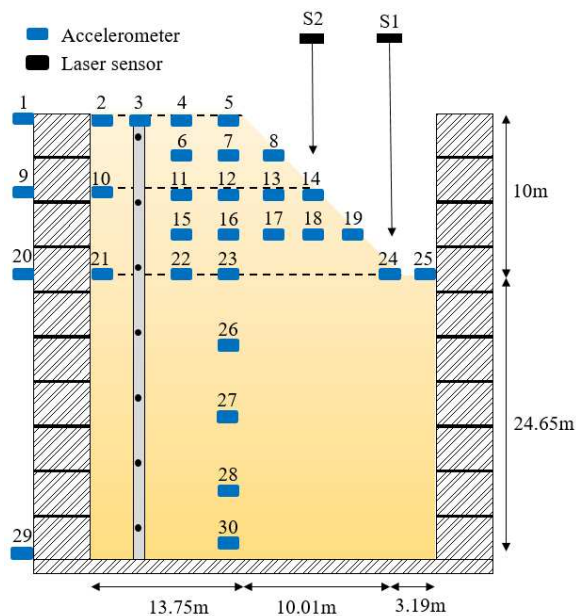

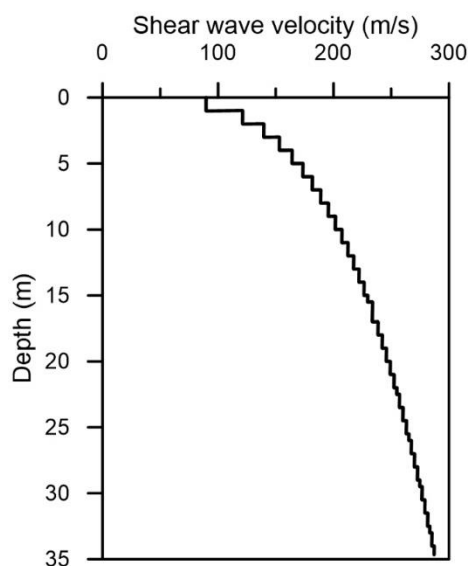Figure 1. Layout of centrifuge model test

Figure 2. Shear wave velocity profile

3 FINITE ELEMENT MODEL

In this study, finite element program LS-DYNA was utilized for the dynamic analysis, and validation of the numerical model was performed using centrifuge measurement described in the previous section. The finite element model of the slope is shown in Figure 3.

To avoid the effect of reflected waves from boundaries on slope response, the width was selected based on sensitivity study. The plain strain four-node elements were utilized in the numerical analysis for the soil domain. The layering of the model was done such as to account for the confining pressure dependency of shear wave velocity. The element size was 0.5 m and smaller than $\lambda/8$ recommended by Kuhlemeyer and Lysmer (1973).

The nonlinear soil properties were defined using the elasto-plastic hysteretic soil model (MAT-079) available in the LS-DYNA. The hysteretic soil model is a nested elastic-perfectly plastic yield surface model that utilizes a user-specified shear stress-strain relationship to simulate non-linear soil response (LSTC 2007). In addition, it incorporates the pressure-dependent shear strength of the soil. It has been widely used for seismic site response analyses (Bolisetti 2015, Bolisetti et al. 2018, Hashash et al. 2018). The pressure-dependent shear modulus reduction curves were developed for each layer using Darendeli (2001) formulation at the mid depth of each soil layer.
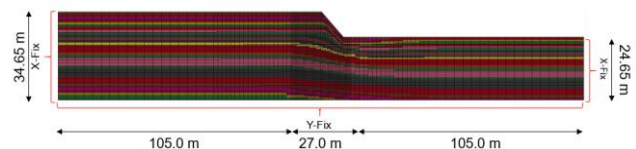

Figure 3. Finite element model of slope

The dynamic curves were fitted using three procedures to modulus reduction and damping curves of Darendeli (2001). The modulus reduction (MR) fit model matches the modulus reduction curves. The modulus reduction and damping (MRD) fit model; the second procedure matches both modulus reduction and damping curves. The shear strength (SF) fit model; the third procedure achieves the target shear strength at large strain along with the modulus reduction fit. The strength correction was applied through the generalized quadratic/hyperbolic (GQ/H) model (Groholski et al. 2016), and shear strength was calculated from Mohr-Coulomb criteria. Figure 4 compares the Darendeli and numerically derived curves calculated with four sets of parameters when subjected to effective vertical stress of 166 kPa. Figure 5 compares the shear stress plotted against shear strain for four levels of effective vertical stresses.
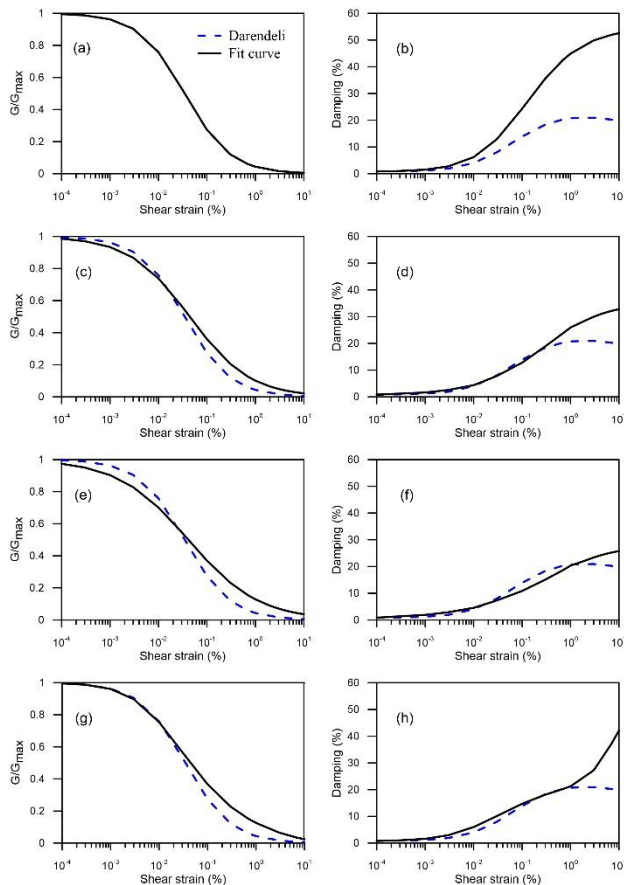
Figure 4. Comparison of the target nonlinear curves with the simulated curves using three procedures at an effective vertical stress of 166 kPa. (a), (b) MR model; (c), (d) MRD-1 model; (e), (f) MRD-2 model; (g), (h): SF model.
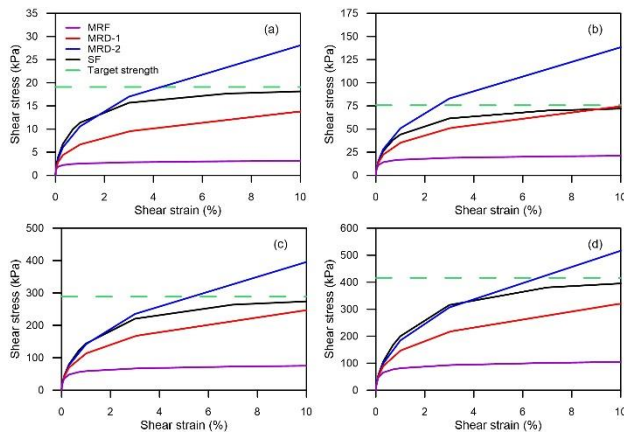

Figure 5. Comparison of the shear stress-strain curve of three soil models and the target shear strength at a vertical stress of (a) 10 kPa, (b) 80 kPa, (c) 340 kPa, and (d) 500 kPa.

4   RESULTS AND DISCUSSION

The measured motion during the Ofunato earthquake was used as input in the centrifuge. The motion was amplitude scaled to peak ground accelerations (PGAs) of 0.17g. Two earthquake motion are used to evaluate the effect of input motion, the motions were scaled to two peak ground accelerations (PGAs), which are 0.17g, 0.5g, for Ofunato motion and 0.2g, 0.5g for Whittier Narrows motion. The acceleration time history of the Ofunato and Whittier Narrows motion is shown in Figure 6.
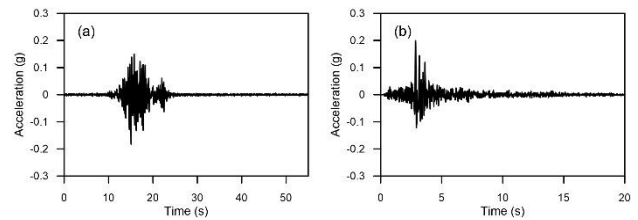

Figure 6. Acceleration time history (a) Ofunato (b) Whittier Narrows

The calculated responses are compared with the centrifuge model tests for Ofunato motion in Figure 7. The acceleration response spectra at the accelerometer 5 and 14 are compared in Figure 7. The output using the MRF model is not displayed because it failed to converge. Apparently, the low shear strength of the model induced unacceptable levels of shear strains, causing it to diverge. It is shown that the numerical model successfully predicts the acceleration response of the slope. The effect of the nonlinear soil model is revealed to have a marginal influence on the calculated acceleration.

Figure 8 compares the vertical settlement calculated at the center of slope (S2), normalized to the slope height. The measured response is shown in a grey line. Due to the large fluctuations observed in the recorded settlement, it is difficult to compare the peak settlements. Therefore, the measured settlement was smoothened to capture the median response, indicated by a green line. It is shown that the soil model has a pronounced influence on the settlement.
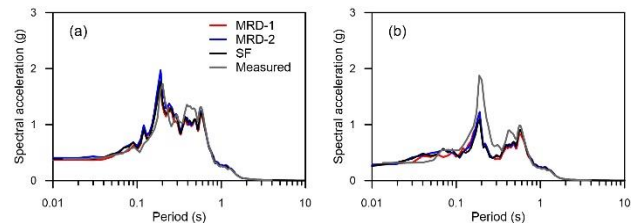

Figure 7. Comparison of the measured and calculated response spectra (a) A-5 (b) A-14
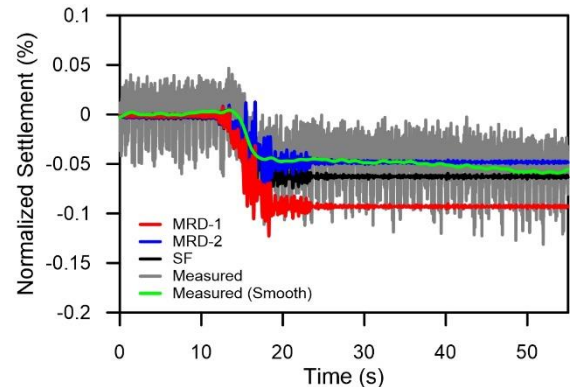

Figure 8. Comparison of the measured and calculated vertical settlement time histories at S2

To evaluate the effect of input motion on the response of the soil model, Ofunato and Whittier Narrows motion are applied with different amplitudes. The comparison of response spectra for three models is shown in Figure 9 at accelerometer A5 and A14.

The effect of nonlinear soil model can be estimated by comparing the vertical settlements at the crest of the slope. The differences in vertical settlement are summarized and shown in Figure 10. The normalized settlements of SF are greater than those of MRD-2 and lower than those of MD-1. This is because the stress-strain curve of SF was corrected with the target shear strength between that of MRD-1 and MRD-2. The differences of the normalized settlements are calculated relative to the

normalized settlement of SF to investigate the effect of nonlinear soil model as well as input motions. The differences of MRD-1 are increased up to 50% when Ofunato is applied. On the contrary, the normalized settlements of MRD-2 are decreased up to 25%.

An underprediction of the shear strength in the nonlinear model would result in the overestimation of the vertical settlement because the true strength of soil is not achieved. Similarly, the overprediction of shear strength will lead to the vertical settlement less than expected.
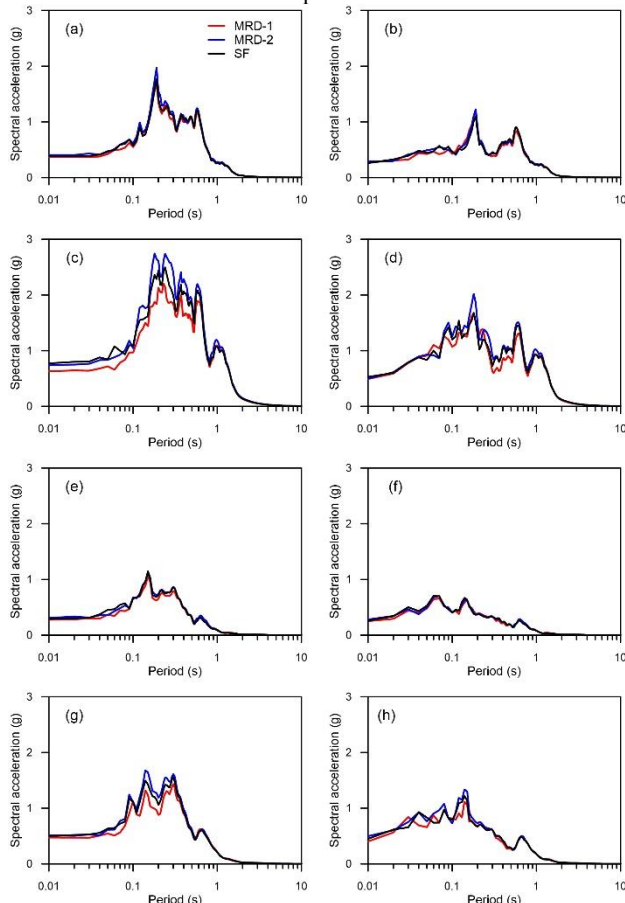

Figure 9. Effect of input ground motion on slope response at A5, A14 (a) – (b): Ofunato 0.17g, (c) – (d): Ofunato 0.5g, (e) – (f): Whittier Narrows 0.2g, (g) – (h): Whittier Narrows 0.5g
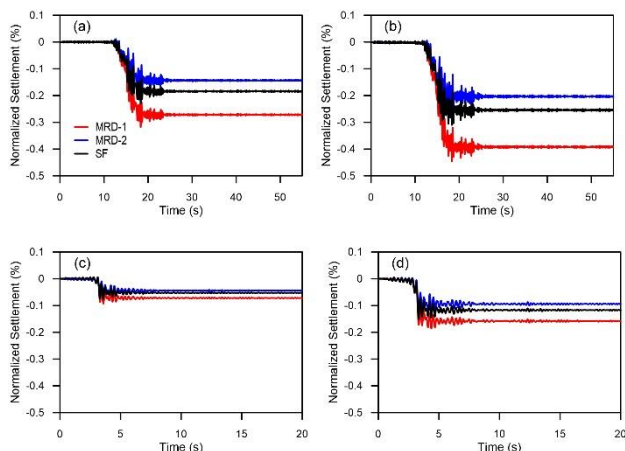

Figure 10. Effect of input ground motion on slope vertical settlement (a): Ofunato 0.17g, (b): Ofunato 0.5g, (c): Whittier Narrows 0.2g, (d): Whittier Narrows 0.5g

5 CONCLUSIONS

In this study, the influence of dynamic curve-fitting on the calculated response of slopes is explored through numerical analysis. To perform the dynamic analysis of slope, a 2D nonlinear finite element model is used. To probe the influence of the nonlinear soil model, four sets of input parameters were used for nonlinear soil model. When four nonlinear models are compared, the MR model achieves the lowest shear strength above 0.1% shear strain. MRD and SF models produce higher shear stresses than the MR model. MRD-2 model yield the highest shear stresses at shear strain exceeding 2%.

For validation of the numerical model, the calculated results are compared with centrifuge measurements for four nonlinear models. The MR model fails to converge because the significant underestimation of the shear strength produces unacceptably high levels of shear strain. The observation from the results shows that the MR model is not favorable for nonlinear model. The calculated spectral acceleration from MRD-1, MRD-2, and SF results in favorable agreement with the measured. Whereas the calculated settlement is much influenced by the nonlinear model.

6 ACKNOWLEDGEMENTS

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