6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Effect of different far-field ground motions on the seismic response of soft clay – centrifuge and numerical studies

L. Zhang[1], S. H. Goh[2]

ABSTRACT

This paper presents results from a series of centrifuge and numerical studies on kaolin clay beds subjected to two types of far-field ground motions. The first was a long-duration ground motion of about 300s representative of that which may be experienced in Singapore due to an earthquake event generated along the Sunda Subduction Trench about 600 km away. The second was a short-duration ground motion of about 25s that represents the type of shaking that may be experienced in Singapore due to a typical far-field earthquake arising from the strike-slip Great Sumatran Fault about 350 km away. To study the effect of different earthquake intensity, each ground motion was further scaled up and down to obtain a set of three motions with identical frequency spectra but different peak accelerations. The acceleration responses at the clay surface were measured in the centrifuge tests and compared with the input base accelerations for both types of ground motions. The measured accelerations at the clay surface generally had much larger magnitudes and dominant periods compared to the base motion, due mainly to ground motion amplification and period lengthening effects caused by the soft kaolin clay. It was also found that the measured acceleration responses at the clay surface triggered by both the long- and short-duration ground motions yielded generally similar amplification factors and resonance periods. These experimental data agree favorably with the numerical results obtained from finite element analysis using a non-linear hyperbolic-hysteretic soil model.

Introduction

In many cities such as Singapore, Mumbai and Shanghai, large portions of the land are underlain by soft soil deposits (such as the Kallang formation for Singapore), and pile foundationsare commonly employed to support buildings and infrastructure. The performance of pile foundations installed in soft soils against natural hazards such as earthquakes is an important area of study. A major problem associated with earthquakes in soft grounds is the amplification of seismic-induced ground motion by the soft soil layer(s) (Tinawi et al. 1993; Pan 1997; Mayoral et al. 2009; Banerjee 2009), such thatthe installed piles may be subjected to amplified loading even under small or moderate earthquakes. Many studies have shown that soil-structure-interaction (SSI) effects on the seismic response of foundationsare quite significant for stiff structures founded on soft soils rather than flexible structures on stiff soils (Aviles and Perez-Rocha 1998; Kim and Roesset 2004; Rayhani and El Naggar 2008; Rayhani and El Naggar 2012). Furthermore, the stiffness degradation of soft clay during seismic loading can influence the natural frequency of the overall pile-soil-superstructure system (Burr et al. 1994, 1997; El

[1]Dr. L. Zhang, Department of Civil and Environmental Engineering, National University of Singapore, Singapore, ceezl@nus.edu.sg
[2]Asst. Prof. S. H. Goh, Department of Civil and Environmental Engineering, National University of Singapore, Singapore, gohsianghuat@nus.edu.sg

Naggar et al. 1995, 2004; Boominathan et al. 2006), which makes the dynamic response of the entire system more complex.

This paper presents results from a series of centrifuge and numerical studies on kaolin clay beds subjected to two classes of far-field ground motions, in the absence of any pile foundations. The first was a long-duration eventcomprising about 300s of strong shaking, which may represent the possible bedrock motion experienced in Singapore due to an earthquake generated along the Sunda Subduction Trench about 600 km away. The second was a short-duration ground motion of about 25s which may be experienced in Singapore due to a typical far-field earthquake arising from the strike-slip Great Sumatran Fault about 350 km away. To study the effect of different earthquake intensity, each ground motion was further scaled up and down to obtain a set of three motions with identical frequency spectra but different peak accelerations. The results of the soft clay response (without pile foundations) presented in this paper providea useful reference dataset for comparison withsubsequent studies involving foundation piles embedded in such soils.

Centrifuge test results and discussions

Experimental procedure

The centrifuge tests in this study were carried out using the centrifuge facility at the National University of Singapore.The elevation layout of the laminar boxtest model is shown in Figure 1.The clay beds used in the centrifuge model tests were prepared using kaolin powder, the general properties of which are shown in Table 1. The test sample was subjected to both 1-g and 50-g stress loadings and consolidation processes to mobilize the desired strength profile. The 1-g consolidation under a uniform pressure loading of 5 kPa typically lasts about 2 weeks, following which the applied pressure was removed and the sample mounted on the centrifuge, together with the shaker and other accessories. The clay sample was then subjected to in-flight centrifuge consolidation under 50g until the degree of consolidation along the entire depth of the clay layer was 90% or more, which required about 18 hours of continuous spinning. Upon completion of the consolidation process, the soil sample was subsequently subjected to in-flight earthquake shaking via the centrifuge shaker attached to the base of the laminar box.

The input base motions adopted in this study were synthetically generated using ‘averaged’ response spectra that are representative of past earthquakes measured in Singapore. While actual measurements from previous events were available, it was found that, in some cases, such as the 2004 Aceh earthquake, the far field motions measured in Singapore were quite insignificant and do not reflect the severity of the earthquake magnitude and intensity. This is likely due to directivity effects associated with the location, depth and orientation of the source rupture. For this reason, synthetic ground motions that are more consistent with the averaged trends of the historical measurements are adopted in this study.

Figure 2 shows the two baseline input ground motions adopted in this study, corresponding to long duration (~800s) and short duration (~25s) far-field events triggered by the Sunda Subduction Trench and the Great Sumatran Fault respectively. Their response spectra yield dominant periods of about 1.2s and 0.9s for the long and short duration motions respectively, which agree well with the values reported by Balendra et al. (2002) and Balendra and Li (2008).

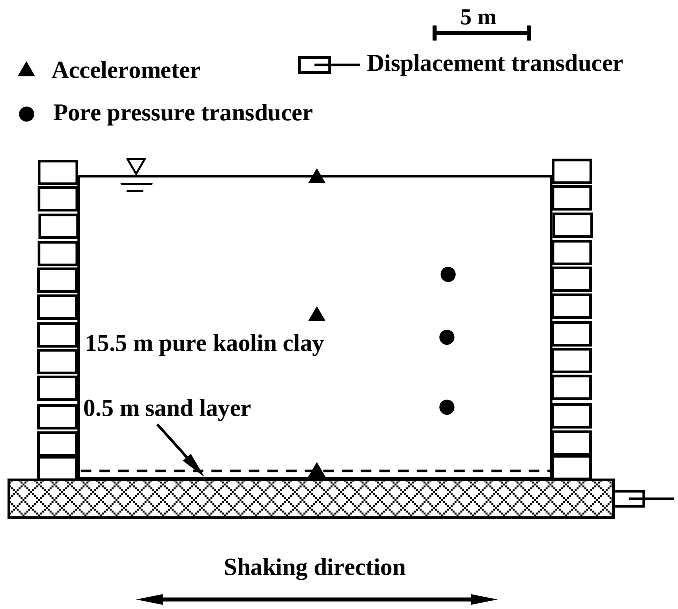


Figure 1. Schematic layout of centrifuge model (prototype scale, gravity level: 50g)

Table 1. Basic properties of kaolin clay

Property	Average value/Range
Bulk unit weight (kN/m^3)	16.1
Water content	60.2%
Liquid limit	75.6%
Plastic limit	42.1%
Compression indexC_c	0.546
Recompression indexC_s	0.12
Coefficient of permeability (m/s)	3×10^{-9}~5×10^{-8}

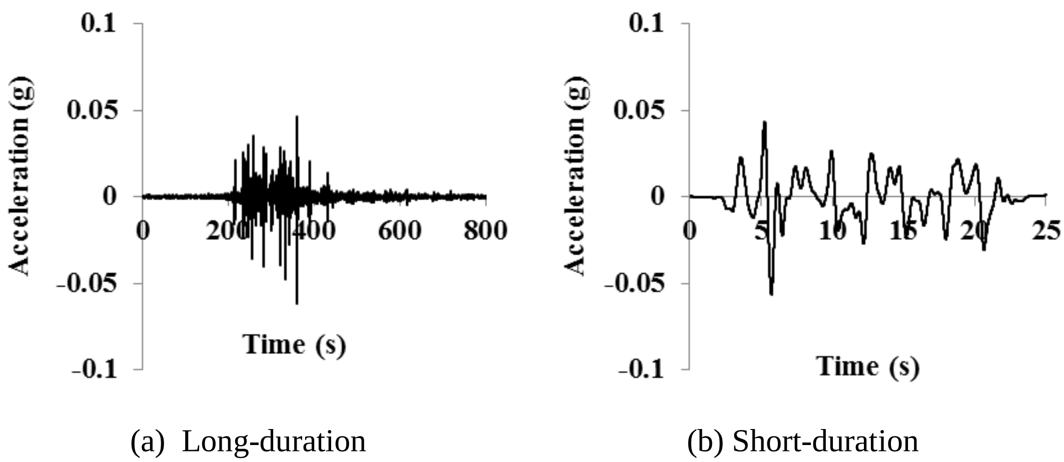


Figure 2. Baseline ground motions used in the centrifuge tests (peak acceleration = 0.06g)

Table 2. Peak accelerations of the scaled ground motions

Ground motion intensity	Peak acceleration (g)	
	Long-duration ground motion	Short-duration ground motion
Small	0.01	0.01
Medium (baseline)	0.06	0.06
Large	0.16	0.13

As shown in Table 2, each baseline motion was further scaled up and down to obtain three ground motions of different intensities, hereafter termed as small, medium and large ground motions respectively. It is noted that all three scaledfar-field motions are relatively small in absolute terms, and that the designations of small, medium and large are adopted simply as a convenience for investigating the effect of varying ground motion intensity on the free-field acceleration response, with the frequency content and duration unchanged.

Free-field acceleration response of pure kaolin clay beds

For the kaolin clay beds subjected to the medium-intensity (baseline) long and short duration input base motions (Figure 2), Figure 3 plots the response spectra of the measured accelerations at both the base and surface of the clay samples. For both the long and short duration shakings, the surface response shows significant amplification of the ground motion relative to the base. At the same time, there is also an increase in the dominant period of the surface motion to a value closer to 2s, as can be seen by the rightward shift of the peak surface response relative to the peak base response. Such an amplification of the base motion and a lengthening of the dominant period are consistent with the findings of many previous studies performed on soft soils (Tinawi et al., 1993; Pan, 1997; Mayoral et al., 2009; Banerjee, 2009; Ma, 2010).

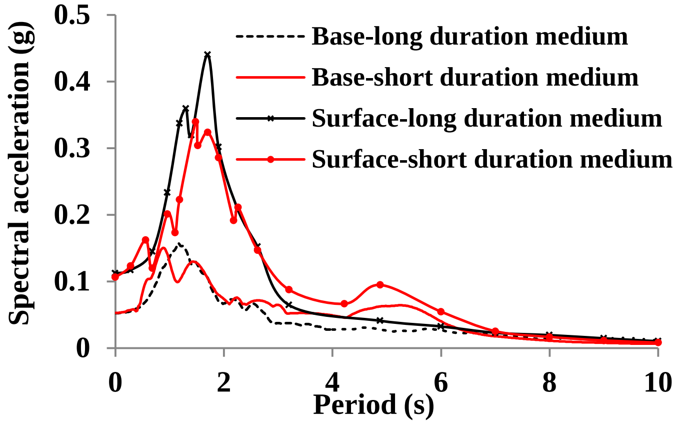


Figure 3. Response spectra of measured accelerations at clay surface and base (5% damping)

The spectral amplification curve shown on Figure 4 for the long-duration earthquake is obtained by dividing the surface response spectrum of Figure 3 byits corresponding base motion spectrum. The peak value on the curve corresponds to the resonance amplification factor and resonance period.

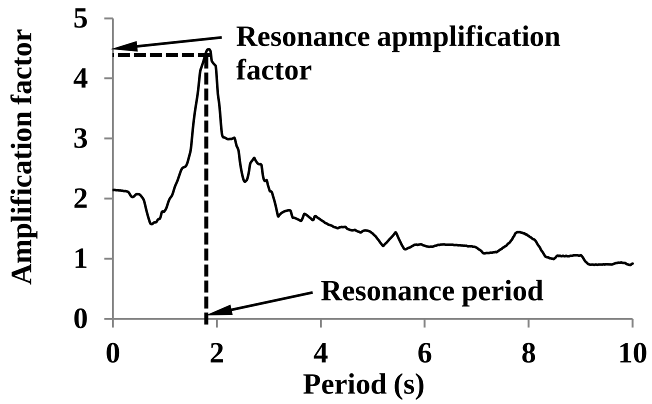


Figure 4. Free-field spectral acceleration amplification curve for the kaolin clay sample

An alternative, more straightforward interpretation of the amplification factor, hereafter termed the direct amplification factor, is also considered. This is obtained directly from the time history records by dividing the peak raft acceleration by the corresponding peak base acceleration (PBA). Figure 5 plots both the resonance and direct amplification factors against the PBA. Although there is some variation of the resonance amplification factor with PBA for both the long- and short-duration ground motions, the resonance amplification factors generally lie within a relatively narrow range of between 3 and 5. Such a range of the resonance amplification factors is consistent with those reported byPan (1997), Megawati and Pan (2009), Banerjee (2009) and Ma (2010).

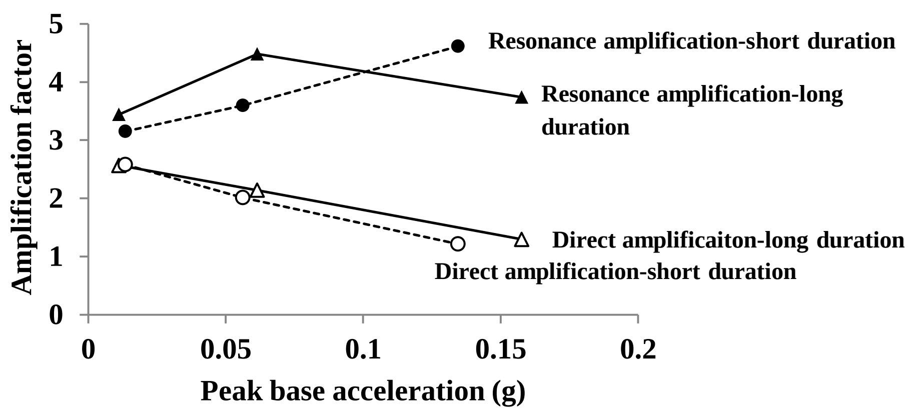


Figure 5. Comparison of resonance and direct amplification responses at the clay surface for scaled motions with different peak base accelerations

As the resonance amplification is dependent on the damping characteristics of the clay bed, the relatively narrow range of the resonance amplification factors suggests that the damping ratio of the clay bed is not significantly affected by the range of ground motion intensities adopted in this study. On the other hand, the direct amplification factor appears to monotonically decrease with the peak base acceleration as shown on Figure 5. Besides the damping ratio, the direct amplification factor is also dependent on the proximity between the dominant period of the input motion and the resonance period of the clay bed. The smaller the difference between the dominant period of the input motion and the resonance period of the clay layer, the larger is the direct amplification response. As can be seen from Figure 6, the resonance periodsat the clay surface increase with the peak base accelerationfor both the long- and short-duration motions. This leads to an increasing difference between the resonance period of the clay layer and the unchanged dominant period of the input base motion as the peak base acceleration increases. It also explains why the direct amplification factors decrease with increasing ground motion intensity.

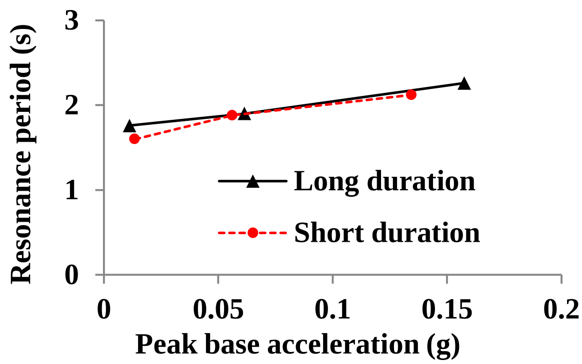
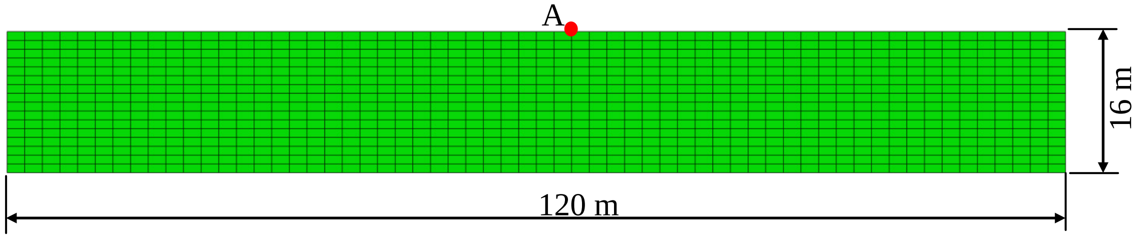


Figure 6. Resonance period of surface accelerations versus peak base accelerations, for a kaolin clay bed subjected to both long- and short-duration scaled ground motions

Finite element analyses and discussions

Two-dimensional finite element model

Using ABAQUS/Explicit Version 6.11, a 2-D finite element model was set up to simulate the centrifuge experiments discussed in the previous section. Figure 7 shows the plane strain model, which contains 960 4-node bilinear elements with reduced integration and hourglass control. The vertically collocated nodes on the two lateral boundaries were connected using rigid tie-rods so that the corresponding nodes on these two faces are constrained to undergo the same motion in the direction of shaking. This approach was adopted inmany studies (e.g. Lu 2006; Ma et al. 2012; Banerjee et al. 2014) to replicate the boundary conditions in a laminar box, wherein the presence of rigid laminar rings ensures that points at the same depth have the same displacements at any point of time. The behavior of the kaolin clay was simulated using a hyperbolic-hysteretic soil model, which was proposed by Banerjee (2009) and calibrated using laboratory test data from cyclic triaxial and resonant column tests on kaolin clay. In this study, the hyperbolic-hysteretic model was coded as a user-defined VUMAT subroutine in ABAQUS.

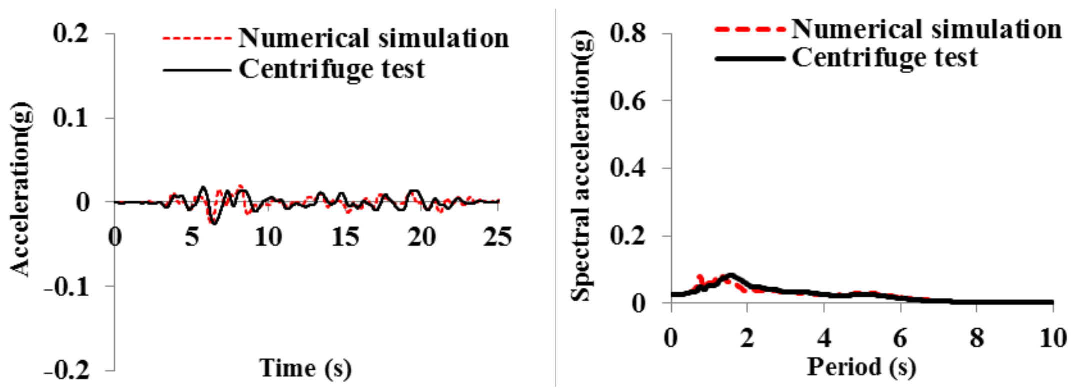


* Point A denotes the node used to compare the computed acceleration response with the corresponding centrifuge data

Figure 7 Finite element mesh for the 2-D numerical simulation

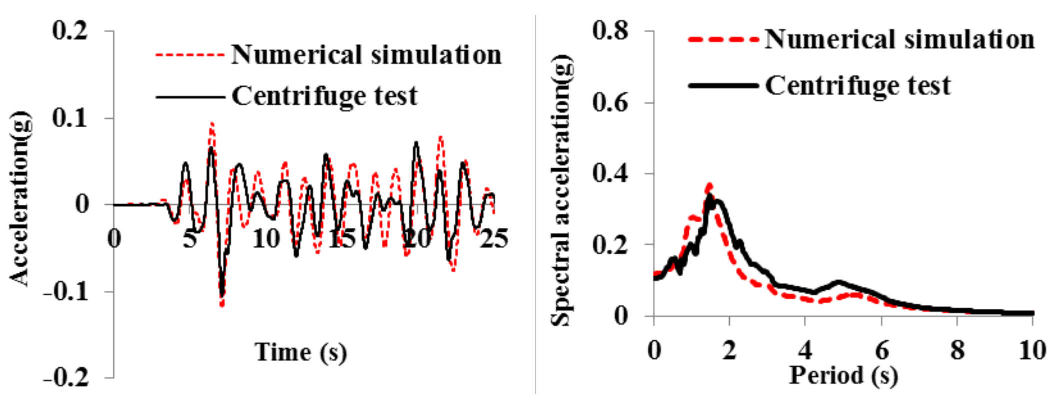
Comparison between measured and computed free-field acceleration response

Due to length constraints, only the numerical results for the short-duration ground motions are presented and compared with the centrifuge test results in this paper. Figures 8, 9 and 10 plot the computed and measured centrifuge acceleration time histories at Point A on the clay surface, as well as the corresponding response spectra, for the kaolin clay bed subjected to the scaled short-duration small, medium and large ground motions, respectively. Overall, the numerical simulations provide reasonably good predictions of the clay surface acceleration time histories as well as the corresponding response spectra. The differences between the numerical predictions and centrifuge measurements for the peak clay surface accelerations are about 1%, 10% and 14% for the small, medium and large ground motions, respectively. The corresponding differences for the peak spectral accelerations are about 1%, 8% and 7% for the small, medium and large ground motions, respectively.



(a) Time history (b) Response spectrum (5% damping)

Figure 8. Computed and measured acceleration (a) time histories and (b) response spectra at the clay surface for the short-duration, small-intensity ground motion

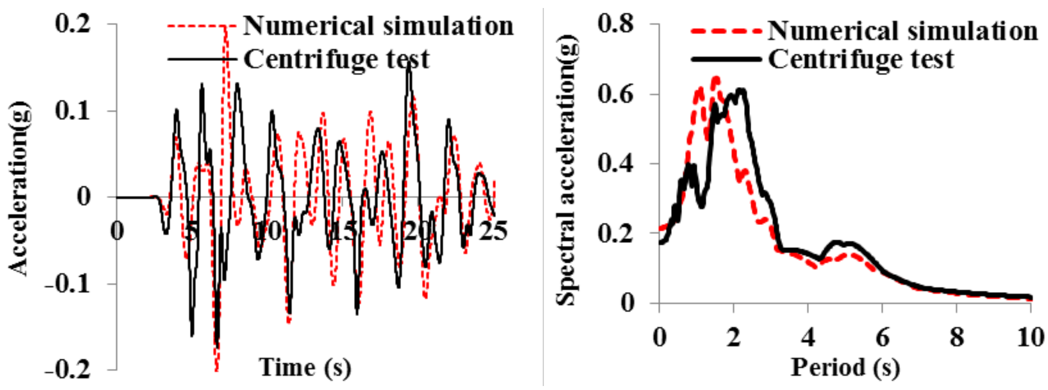


(a) Time history (b) Response spectrum (5% damping)

Figure 9. Computed and measured acceleration (a) time histories and (b) response spectra at the clay surface for the short-duration, medium-intensity ground motion

Besides, as shown in Figures 8(b) and 9(b) for the short-duration ground motions with small and medium intensities, the computed and measured dominant periods of the free-field acceleration responses agree well with each other. However, as Figure 10(b) shows, the numerical simulation tends to underestimate the dominant period of the measured free-field acceleration response for the large intensity motion. This discrepancy may be due to the performance limitation of the hyperbolic-hysteretic constitutive soil model under high strain conditions, in which it under-predicts the strain-softening effects compared to those exhibited by the actual clay.

For the pure kaolin clay bed subjected to small, medium and large short-duration ground motions, the computed ground accelerations from ABAQUS explicit finite element analysis with the VUMAT subroutine show favorable agreement with the centrifuge test results, After the validation study presented in this section, the seismic finite element analysis with the hyperbolic-hysteretic soil model can be extended to simulate more complex problems involving pile-raft systems embedded in a uniform kaolin clay sample.



(a) Time history

(b) Response spectrum (5% damping)

Figure 10. Computed and measured acceleration (a) time histories and (b) response spectra at the clay surface for the short-duration, large-intensity ground motion

Conclusions

This paper presents the centrifuge test results showing the surface acceleration response for pure kaolin clay beds subjected to long- and short-duration small, medium and large ground motions. In addition, a series of 2-D finite element analyses were performed using ABAQUS/Explicit Version 6.11, incorporating a VUMAT user-defined subroutine to account for the hyperbolic-hysteretic soil behavior. The numerical results were presented and compared with the corresponding centrifuge tests. Some conclusions can be made as follows.

(1) The phenomena of ground motion amplification and lengthening of the dominant period were observed for the free-field clay surface acceleration response, regardless of the intensity and duration of the ground motions.
(2) The damping characteristics of the clay bed are not significantly affected by the range of ground motion intensities adopted in this study.
(3) For the kaolin clay beds considered in this study, both the free-field surface response spectra

and amplification factors are not significantly influenced by the duration of the input base motion.

(4) For kaolin clay beds subjected to short-duration ground motions, the numerical simulations can generally provide good predictions of the measured free-field acceleration responses.

The results and findings presented in this paper do not involve the presence of any pile-raft foundations. Nevertheless, they can serve as a useful reference or baseline for further studies involving pile-raft foundations in soft clay stratum subjected to seismic excitation.

Acknowledgments

The authors gratefully acknowledge the financial support and research scholarships provided by the National University of Singapore. The centrifuge tests were carried out with the support and assistance of the technical staff at the Centre for Soft Ground Engineering, NUS.

References

Aviles J. and Perez-Rocha L. E. (1998). "Site effects and soil-structure interaction in the Valley of Mexico." *Soil Dynamics and Earthquake Engineering*, **17**(1), 29-39.

Balendra T., Lam N. T. K., Wilson J. L. and Kong K. H. (2002). "Analysis of long-distance earthquake tremors and base shear demand for buildings in Singapore." *Engineering Structures*, **24**(1), 99-108.

Balendra T. and Li Z. (2008). "Seismic hazard of Singapore and Malaysia." *Electronic Journal of Structural Engineering(Special Issue*), 57-63.

Banerjee S. (2009). "*Centrifuge and Numerical modeling of soft clay-pile-raft foundations subjected to seismic shaking*" Ph.D. thesis, National University of Singapore.

Banerjee S., Goh S. H. and Lee F. H. (2014). "Earthquake-induced bending moment in fixed-head piles in soft clay." *Géotechnique*, **64**(6), 431-446.

Boominathan A. and Ayothiraman R. (2006). "Dynamic response of laterally loaded piles in clay." Proceedings of the Institution of Civil Engineers: *Geotechnical Engineering*, **159**(3), 233-241.

Burr J. P. (1994). "*The dynamic lateral response of pile groups*" Ph.D. thesis, University of Auckland.

Burr J. P., Pender M. J. and Larkin T. J. (1997). "Dynamic response of laterally excited pile groups." *Journal of Geotechnical and Geoenvironmental Engineering*, **123**(1), 1-8.

El Naggar M. H. and Novak M. (1995). "Effect of foundation nonlinearity on modal properties of offshore towers." *Journal of geotechnical engineering*, **121**(9), 660-668.

Kim Y. S. and Roesset J. M. (2004). "Effect of nonlinear soil behavior on inelastic seismic response of a structure." *International Journal of Geomechanics*, **4**(2), 104-114.

Lu J. C. (2006). "*Parallel finite element modeling of earthquake ground response and liquefaction*" Ph.D. thesis, University of California, San Diego.

Ma K., Banerjee S., Lee F. H. and Xie H. P. (2012). "Dynamic soil-pile-raft interaction in normally consolidated soft clay during earthquakes." *Journal of earthquake and tsunami*, **06**(03), 1250031-1~1250031-12.

Mayoral J. M., Alberto Y., Mendoza M. J. and Romo M. P. (2009). "Seismic response of an urban bridge-support system in soft clay." *Soil Dynamics and Earthquake Engineering*, **29**(5), 925-938.

Megawati K. and Pan T.-C. (2009). "Regional seismic hazard posed by the Mentawai segment of the Sumatran megathrust." *Bulletin of the Seismological Society of America*, **99**(2 A), 566-584.

Mostafa Y. E. and El Naggar M. H. (2004). "Response of fixed offshore platforms to wave and current loading including soil-structure interaction." *Soil Dynamics and Earthquake Engineering*, **24**(4), 357-368.

Pan T. C. (1997). "Site-dependent building response in Singapore to long-distance Sumatra earthquakes." *Earthquake spectra*, **13**(3), 475-488.

Rayhani M. H. T. and El Naggar M. H. (2008). "Numerical modeling of seismic response of rigid Foundation on soft soil." *International Journal of Geomechanics*, **8**(6), 336-346.

Rayhani M. T. and El Naggar M. H. (2012). "Physical and Numerical Modeling of Seismic Soil-Structure Interaction in Layered Soils." *Geotechnical and Geological Engineering*, **30**(2), 331-342.

Tinawi R., Sarrazin M. and Filiatrault A. (1993). "Influence of soft clays on the response spectra for structures in eastern Canada." *Soil Dynamics and Earthquake Engineering*, **12**(8), 469-477.