Rong, X. Xu, XZ. Li, YY. (2012). "Experimental research on aseismic behavior of PHC pipe piles." *Industrial Construction*, Vol. 43 (7): 72-75.
Shi, F. (2004). "Experimental research on load transfer mechanism of pretensioned high strength spun concrete piles." *Chinese Journal of Geotechnical Engineering*, Vol. 26 (1): 95-99.
Sun, Ye. and Liu, Zuhua. (2012). "Strain distributing disciplinarian of phc pipe-piles under seismic action." *Low Temperature Architecture Technology*, Vol. 165: 24-27.
Tang, L. and Ling, XZ. (2014). "Response of a RC pile group in liquefiable soil: a shake-table investigation." *Soil Dynamics and Earthquake Engineering*, Vol. 67: 301-315.

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Influence of Shallow Foundation Characteristics on the Seismic Response of Mid-Rise Buildings Subjected to Strong Earthquakes

Quoc Van Nguyen[1]; Behzad Fatahi[2]; and Aslan S. Hokmabadi[3]

[1]Ph.D. Candidate, School of Civil and Environmental Engineering, Univ. of Technology Sydney (UTS), Sydney, Australia. E-mail: Quoc.V.Nguyen-1@student.uts.edu.au
[2]Senior Lecturer, Geotechnical Engineering (Ph.D., CP.Eng.), School of Civil and Environmental Engineering, Univ. of Technology Sydney (UTS), Sydney, Australia. E-mail: Behzad.fatahi@uts.edu.au
[3]Geotechnical Engineer (Ph.D., CP.Eng.), Ove Arup & Partners, Hong Kong. E-mail: aslan.s-hokmabadi@arup.com

Abstract: Performance based seismic design is a modern approach to earthquake-resistant design shifting emphasis from "strength" to "performance". In this study, the influence of the shallow foundation (footing) size on the seismic performance of the buildings subjected to strong earthquakes is investigated considering Soil-Structure Interaction (SSI). A fifteen storey moment resisting frame sitting on shallow foundation over soft soil with different foundation size is simulated numerically using ABAQUS software. The developed three dimensional numerical simulation accounts for nonlinear behaviour of the soil medium by considering the variation of soil stiffness and damping as a function of developed shear strain in the soil elements during earthquake. Elastic-perfectly plastic model is adopted to simulate foundations and structural elements. Four strong earthquake records, including El Centro 1940, Hachinohe 1968, Northridge 1994, and Kobe 1995 have been taken as input accelerations for time history analysis in time domain. Due to natural period lengthening, there was a significant reduction in the base shears when the size of the foundation was reduced. It can be concluded that the foundation size can influence the dynamic characteristics and seismic response of the building due to SSI and should therefore be given careful consideration in order to ensure a safe and cost effective seismic design.

INTRODUCTION

The influence of the underlying soil on the seismic response of a structure can be disregarded when the ground is stiff enough, and consequently, the structure can be analysed considering the fixed-base conditions. However, the same structure will behave differently when it is constructed on a soft soil deposit. Earthquake characteristics, the travel path, the local soil properties, and the soil–structure interaction are the factors affecting the seismic excitation experienced by structures.

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The results of the first three factors can be summarised as free-field ground motion. However, the foundation of a structure does not follow the deformation of the free-field motion due to its stiffness, and the dynamic response of the structure itself induces the deformation of the supporting soil (Kramer, 1996). Two key mechanisms are generally involved during a seismic soil-foundation-structure interaction: kinematic interaction and inertial interaction. Kinematic interaction occurs because stiff foundation elements in the soil cause the foundation motion to deviate from the free field ground motion. Kinematic interaction could also be due to ground motion incoherence, foundation embedment effects, and wave scattering or inclination (Stewart et al., 1999). Inertial interaction results from the inertia developed in the structure as its own vibration produces base shear, moment, and torsional excitation. These loads cause displacements and the foundation to rotate relative to the free field condition (Kramer and Stewart, 2004). Fundamentally, the size of a foundation can influence the kinematic and inertial interactions mainly by altering the mass and stiffness of the soil foundation system which in turn influences the seismic response of the superstructure.

Several researchers (e.g. Sbartai, 2015; Sameti and Ghannad, 2014; Chen, 2015; Hokmabadi et al., 2014) studied the seismic soil-foundation-structure interaction (SFSI) phenomena and its influence on the seismic response of buildings by adopting the Winkler (substructure) methods and the numerical methods. Adopting advanced numerical models has a number of advantages over the Winkler methods, especially their ability to conduct time history analyses while considering effects such as the nonlinear stress–strain behaviour of the soil and the superstructure, material and radiation damping, advance boundary conditions, and interface elements. Another advantage of using numerical methods is their ability to perform the analysis in a fully-coupled manner without resorting to independent calculations of site or superstructure response (Meymand, 1998). Consequently, numerical modelling predictions can capture the different parameters involved in soil-foundation-structure interaction (SFSI) that are closer to reality.

The aim of this study is to numerically investigate the influence of shallow foundation size on the seismic response of a regular mid-rise moment resisting building frame during earthquake excitations using ABAQUS software (version 6.12) as a fully coupled nonlinear time history analysis.

NUMERICAL MODEL

Case study description

In this study, a fifteen storey concrete moment resisting building frame, 45 m high and 12 m wide with 16 columns consisting of three spans in each direction, and 15 slabs and a foundation, is selected (FIG. 1). This building frame represents conventional mid-rise moment resisting buildings. The structural sections were specified after conducting a routine design procedure regulated in the relevant building codes (AS3600, 2009, AS1170.4, 2007). SAP2000 V 14 (CSI, 2010) software was utilised for the structural analysis and design of the cross sections of beams and columns. Then, a nonlinear time-history dynamic analysis under the influence of the four earthquake ground motions shown in FIG. 1 was carried out. In this dynamic analysis the geometric nonlinearity and P-Delta effects were considered according to AS3600 (2009). The fundamental frequency of the adopted building was 0.830 Hz and its total mass was 1683 tonnes.

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The adopted superstructure sits on 30m deep soft soil that is categorised as Class E_e according to the Australian standard (AS1170.4, 2007). The sub-soil is a soft clayey soil with a density of 1470 kg/m^3, a shear wave velocity of 150 m/s, and an-undrained shear strength of 50 kPa. The properties of this subsoil were extracted from actual in-situ and laboratory tests (Rahvar, 2006), so these parameters have merit over the assumed parameters which may not be completely conforming to reality. It was assumed that the water table was below the level of the bedrock.

The shallow square foundations (footings) were designed to support the structure against static and dynamic loads to satisfy the requirement for bearing capacity and maximum settlement. All the shallow foundations were 1 m thick and were made from reinforced concrete. The shallow foundations had different size widths to facilitate an investigation into how shallow foundation sizes influence the seismic response of building due to the soil-foundation-structure interaction. These foundations had five different sizes, including: 1.1B, 1.3B, 1.5B, 1.7B and 2.0B, where B is the width of the building (=12 m). All these foundation sizes were acceptable from an engineer's perspective and satisfied the requirements for bearing capacity and maximum settlement, although the safety factor of the smaller foundations was less than the large ones. Moreover, although the 1.7B and 2.0B foundations are not common in practice, a wider range of foundation sizes was considered in this study to better understand how foundation size affects the seismic response of a building during strong earthquakes. The seismic response of these foundation sizes are compared and discussed in the following sections via a 3D finite element numerical simulation.

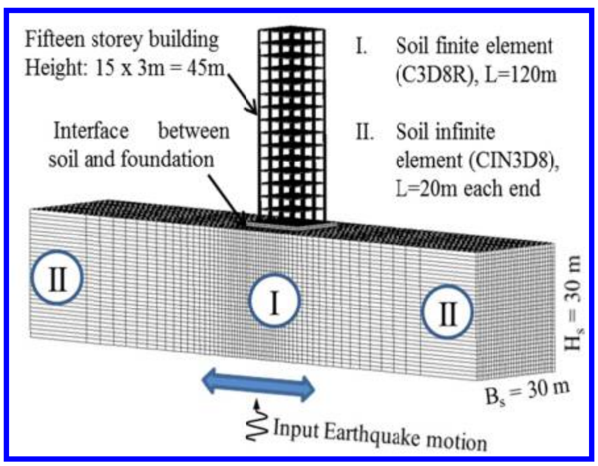

FIG. 1. Problem definition and modelling element details of the developed soil-foundation-structure system

Numerical Modelling Details

ABAQUS v 6.14 finite element analysis software was used in this study for the numerical simulation of the soil-foundation-structure systems. This software package can simulate complex problems that require large computational memories using a direct method of analysis. Beam and shell elements were used to simulate the columns and floor slabs of the superstructure in this numerical model. The characteristics of the

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columns are presented in Table 1. The structural elements were modelled using an elastic-viscoelastic constitutive model while considering the Rayleigh damping according to Ryan and Polanco (2008) (Equation (1)).

$$[C] = \alpha\,[M] + \beta\,[K] \tag{1}$$

where *[C]*, *[M]*, and *[K]* are the damping, mass, and stiffness matrices, respectively, α and β are the model coefficients used to specify the model damping ratio in two modes. By assuming the same damping ratio (ξ) for two modes with frequencies f_i *and* f_j, the model coefficients α and β can be obtained from equations for Rayleigh damping in Chopra (2007). In this study, a structural damping ratio (ξ) of 5% together with model coefficients of α= 0.3996 and β= 0.0049, calculated based on the first and second mode frequencies of the structure (see Table 2), was used to simulate structural damping in the dynamic analysis.

Table 1. Adopted characteristics of designed reinforced concrete column sections

Section Type	$I_x\,(m^4)$	$I_y\,(m^4)$	$Area\,(m^2)$	*E (kPa)*	*v*
Type *I (Levels 1 – 3)*	5.33E-3	10.87E-3	0.302	2.86E7	0.2
Type *II (Levels 4 – 7)*	3.64E-3	7.45E-3	0.250	2.86E7	0.2
Type *III (Levels 8 – 11)*	2.40E-3	4.89E-3	0.203	2.86E7	0.2
Type *IV (Levels 12 – 15)*	1.50E-3	3.05E-3	0.160	2.86E7	0.2

Table 2. Natural frequencies of the adopt 15 storey fixed base structure

Motion mode	Mode 1 (f_1)	Mode 2 (f_2)	Mode 3 (f_3)	Mode 4 (f_4)
Frequency (Hz)	0.830	2.341	4.018	5.781

The nonlinearity of soil during an earthquake plays an important role in the dynamic response of soil-structure systems. In this study, an equivalent linear method has been adopted, as described by Seed and Idriss (1969). In this method, a try and error process utilising soil nonlinear backbone curves to find the "strain compatible" values of damping and modulus is used to capture the soil non-linearity during shaking excitations. The adopted equivalent soil stiffness value for each earthquake record was different depending on the maximum shear strain generated in the soil deposit, while Rayleigh damping was adopted to capture variations of soil damping during each earthquake. Table 3 presents the adopted soil properties. Table 3 presents the adopted soil properties.

Table 3. Adopted soil parameters in numerical models

Soil Properties	Denote	Unit	Value
Mass density	ρ	kg/m^3	1470
Shear Wave Velocity	V_s	*m/s*	150
Poisson's ratio	*v*	-	0.4
Plasticity Index	*PI*	-	15%

For the soil-foundation-structure interaction analysis in this study, surface-based contacts were defined such that the master surface is the top surface of the soil and the

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slave surface is the bottom surface of the foundation. Moreover, finite sliding formulation and the surface-to-surface discretisation method were utilised for the contacts. The mechanical properties of the contact surfaces defining the tangential and normal behaviour of the contact surfaces can influence the results of the numerical modelling and should be chosen with great rigor. Normal behaviour adopts 'hard' contact in a pressure-over closure relationship. A FORTRAN subroutine, FRIC_COEF, is embedded into ABAQUS to simulate the tangential behaviour of the contacts based on Mohr-Coulomb failure model.

Four strong earthquake input motions, including the 1994 Northridge, the 1995 Kobe, the 1940 El Centro, and the 1968 Hachinohe earthquakes (referring to FIG. 2), were imposed onto the finite element numerical model while conducting a time-history analysis. Due to the large size of the model (around 70 Giga-bytes for a single case), the fast computation facilities were used to conduct this time-history analysis, and even then it took around 50 hours to run a single case under the applied earthquake excitation. The results of the 3D finite element numerical simulation are presented and discussed in the following section.

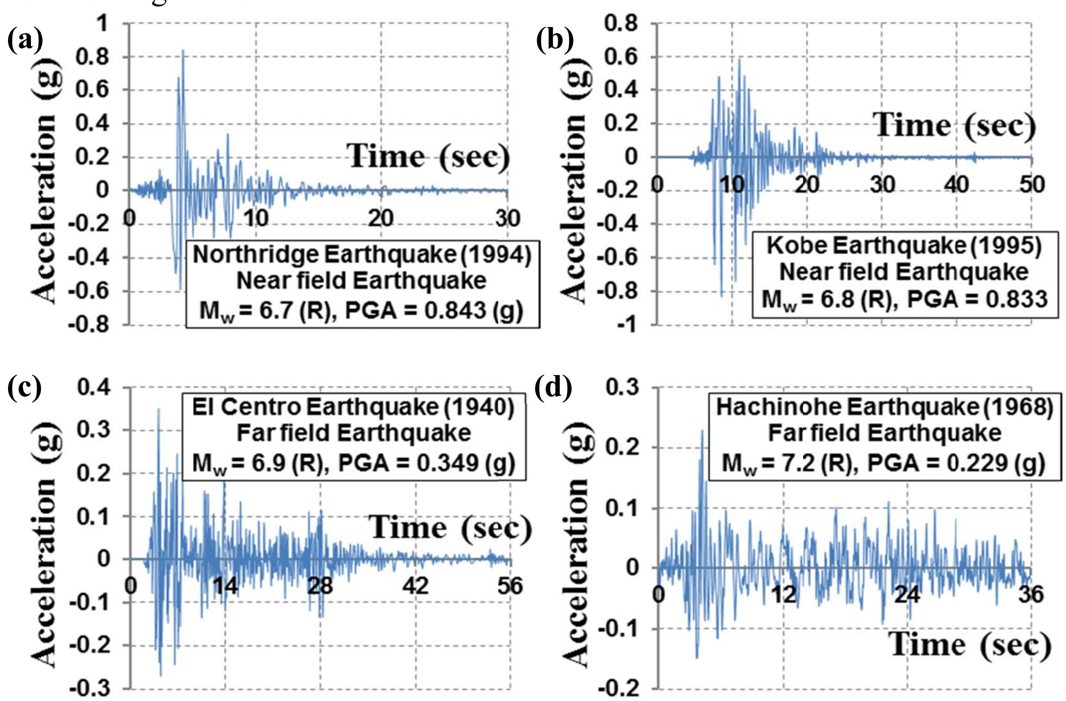

FIG. 2. Adopted earthquake records: : (a) 1994 Northridge; (b) 1995 Kobe; (c) 1940 El Centro; and (d) 1968 Hachinohe earthquake

RESULTS AND DISCUSSION

The results of the 3D numerical model developed for the fifteen-storey building supported by shallow foundations of different sizes and the fixed-base building subjected to the 1994 Northridge, 1995 Kobe, 1940 El Centro, and 1968 Hachinohe earthquakes are summarised and compared in FIG. 3 and FIG.4. Referring to FIG. 3, SFSI amplified the maximum lateral deflection of the superstructure during shaking excitations. For instance, the maximum lateral deformation of the fixed-base building

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(excluding SFSI) under the 1994 Northridge earthquake was 395mm, while the same building experienced a lateral deformation of up to 590 mm (49% more) when it was supported by a 1.1B shallow foundation that accounts for SFSI. Moreover, as a general trend, by increasing the size of the shallow foundation from 1.1B to 2.0B the structure experiences less lateral deformation. For instance, an increase in the size of the foundation from 1.1B to 1.5B resulted in up to 25% less lateral deformation under 1940 El Centro earthquake (FIG. 13a). This is a considerable reduction in the lateral deformation of a structure subjected to strong earthquakes.

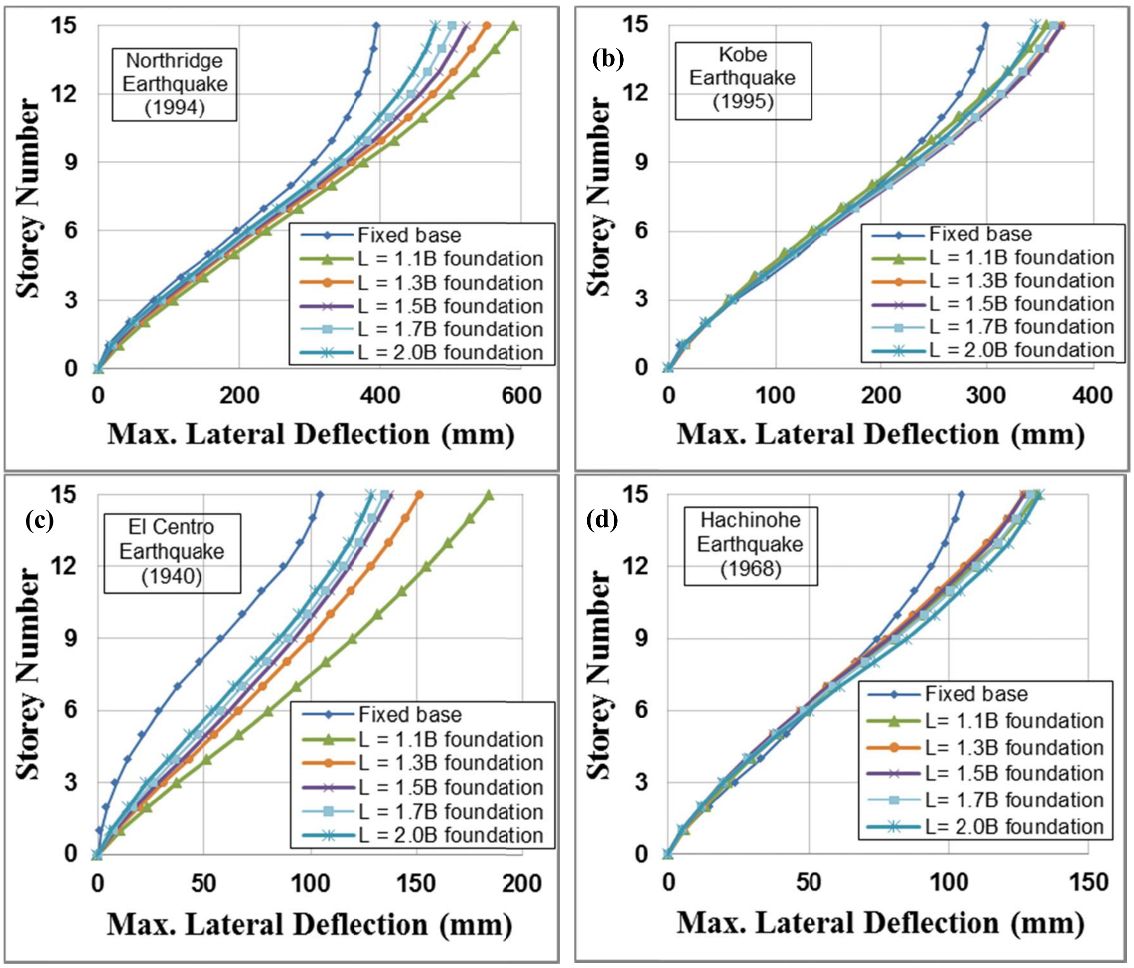

FIG. 3. Maximum lateral deflection of the fifteen-storey structure supported by shallow foundations with varies sizes under the influence of: (a) 1994 Northridge; (b) 1995 Kobe; (c) 1940 El Centro; (d) 1968 Hachinohe earthquakes

In order to investigate the influence foundation size on the energy absorbed by the structure during earthquakes, the results of the developed 3D numerical model in terms of shear forces were compared for different cases. To determine the maximum shear force at each level, the shear forces generated in every column at that level were summed up in every time increment during the time-history analysis, and the absolute maximum shear force experienced at that level during the earthquake is reported as presented in FIG. 4. In general, considering SFSI contributed to the reduction in the

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shear forces in the structure, whereas larger shallow foundations attracted more inertial forces from the earthquake excitations than the smaller sized foundations. For instance, the maximum base shear of the structure supported by the 1.5B foundation under the 1940 El Centro earthquake was 4.1 MN, while the corresponding value for the structure supported by 1.1B foundation was 3.6 MN (13% less energy absorption).

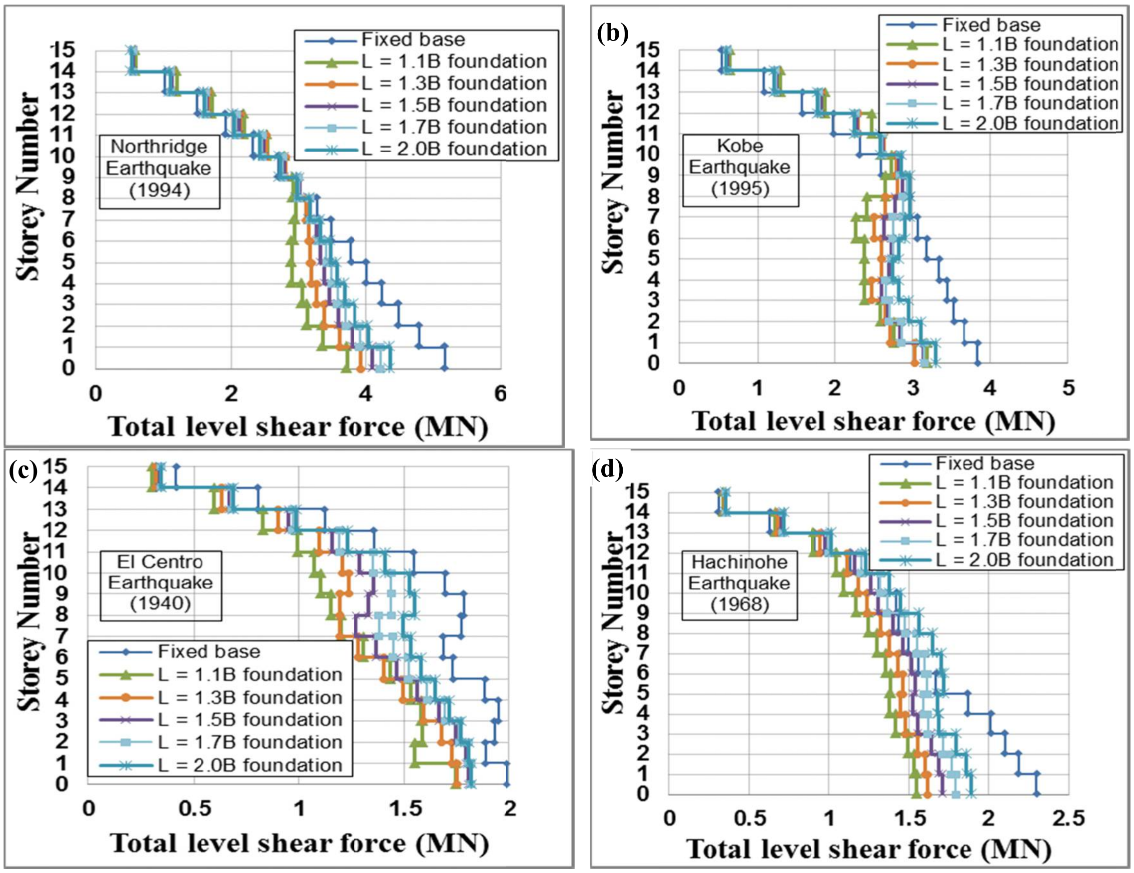

FIG. 4. Maximum shear force distribution of the fifteen-storey structure supported by shallow foundations with varies sizes under the influence of: (a) 1994 Northridge; (b) 1995 Kobe; (c) 1940 El Centro; (d) 1968 Hachinohe earthquakes

Decreasing the size of a foundation caused the spectral acceleration to decrease considerably as the natural period lengthened. As a result, such an increase in the natural period substantially changed the response spectral acceleration (S_a). In the case where the mid-rise moment resisting building frames with a shallow foundation rests on soft soil deposits, the natural period lay in the long period region of the acceleration response spectrum curve. Due to the natural period lengthening induced by a reduction in the size of a foundation, the spectral acceleration (S_a) tended to decrease, which then reduced the base shear of the structure.

CONCLUSIONS

This study investigated the influence of shallow foundation size on the seismic response of a regular mid-rise moment resisting building frame during earthquake

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excitations. ABAQUS was used to numerically simulate the soil-foundation-structure system by conducting a fully coupled nonlinear time history analysis.

According to the results obtained, the size of a shallow foundation can influence the structural design of the building under seismic loads considering the seismic soil-foundation-structure interaction. Larger shallow foundations can moderate the amplifications of lateral deflection and in turn inter-storey drifts of the structure caused by SFSI. This can be a cost effective alternative to control the performance level of buildings. Moreover, changes in the size of shallow foundations resulted in absorbing an amount of energy from the imposed earthquake that corresponded to the natural frequency of a particular system. It was observed that buildings with larger shallow foundations attracted more inertial forces from earthquake excitations than smaller foundations.

REFERENCES

AS1170.4 2007. Structural design actions—Earthquake actions in Australia. NSW, Australia: Standards Australia.

AS3600 2009. Concrete Structures. NSW, Australia: Standards Australia.

Chen, L. 2015. Dynamic Interaction Between Rigid Surface Foundations on Multi-Layered Half Space. *Int. J. of Structural Stability and Dynamics*, 1550004.

CSI 2010. SAP2000 v14 Analysis Reference Manual. California: CSI (Computers and Structures Inc.), Berkley.

Kramer, S. L. 1996. *Geotechnical earthquake engineering*, Prentice Hall.

Kramer, S. L. & Stewart, J. P. 2004. Geotechnical Aspects of Seismic Hazards. *In:* Bozorgnia, Y. & Bertero, V. V. (eds.) *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering.* LLC: CRC Press.

Hokmabadi, A., Fatahi, B., and Samali, B. (2014). "Physical Modeling of Seismic Soil-Pile-Structure Interaction for Buildings on Soft Soils." *Int. J. Geomech.*, 10.1061/(ASCE)GM.1943-5622.0000396, 04014046.

Hokmabadi, A.S., Fatahi, B. & Samali, B. 2014, 'Assessment of soil-pile-structure interaction influencing seismic response of mid-rise buildings sitting on floating pile foundations', *Computers and Geotechnics*, vol. 55, pp. 172-186.

Meymand, P. J. 1998. *Shaking table scale model tests of nonlinear soil-pile-superstructure in soft clay.* PhD thesis in Civil Engineering, University of California, Berkley.

Rahvar 2006. Geotechnical investogation and foundation design report of Mahshahr train station. Mahshar, Iran: P. O. Rahvar Pty Ltd, Iran Railway Authority.

Ryan, K. L. & Polanco, J. 2008. Problems with Rayleigh Damping in Base-Isolated Buildings. *Journal Of Structural Engineering,* 134**,** 1780-1784.

Sameti, A. R. & Ghannad, M. A. 2014. Equivalent Linear Model for Existing Soil-Structure Systems. *Inter. Jour. of Structural Stability and Dynamics***,** 1450099.

Sbartai, B. 2015. Dynamic Interaction of Two Adjacent Foundations Embedded in a Viscoelastic Soil. *Inter. Journal of Structural Stability and Dynamics***,** 1450110.

Seed, H. B. & Idriss, I. 1969. Influence of Soil Conditions on Ground Motion during Earthquakes. *Journal of Soil Mechanics & Found., Division, ASCE,* 95**,** 99-137.

Stewart, J., Fenves, G. & Seed, R. 1999. Seismic soil-structure interaction in buildings. I: Analytical aspects. *J. Geotech. & Geoenv. Engrg.,* 125**,** 26-37.

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Characterization of Freezing Fresh Concrete by Multiple Non-Destructive Methods

Yan Liu[1]; Junliang Tao[2]; Xinbao Yu[3]; Zhen Liu[4]; and Xiong (Bill) Yu[5]
[1]Assistant Professor, Dept. of Engineering, Univ. of Mount Union,
1972 Clark Ave., EBB 123, Alliance, OH 44601 (corresponding author). E-mail: liuyan@mountunion.edu
[2]Assistant Professor, Dept. of Civil Engineering, The Univ. of Akron,
244 Sumner St., Akron, OH 44321-3905. E-mail: jtao2@uakron.edu
[3]Assistant Professor, Dept. of Civil Engineering, Univ. of Texas, Arlington
Box 19308, 248C Nedderman Hall, Arlington, TX 76019. E-mail: xinbao@uta.edu
[4]Assistant Professor, Dept. of Civil and Environmental Engineering, Michigan Technological Univ.
Dillman 201F, 1400 Townsend Dr., Houghton, MI 49931. E-mail: zhenl@mtu.edu
[5]Professor, Dept. of Civil Engineering, Case Western Reserve Univ.,
2104 Adelbert Rd., Bingham Building-Room 206, Cleveland, OH 44106 -7201. E-mail: xiong.yu@case.edu

Abstract: Seismic methods are useful tools to non-destructively assess the behaviors of fresh concrete. They have also been applied to characterize the properties of curing concrete to provide information for construction decision. This paper shows that freezing of concrete significantly affects the engineering properties of concrete. In the experimental program, ultrasonic tests were conducted on curing concrete subjected to different freezing process. The results indicate while there exists linear correlation between low strain seismic wave velocity and concrete strength under normal curing conditions, such relationships do not hold if the concrete is subjected to freezing process. A correction accounting for the effects of ice on the bulk strength needs to be applied. This correction was found to have linear relationship with water content. Procedures to correct the effects of freezing are proposed, which include the use of Time Domain Reflectometry to measure the water content. Finally the strength of concrete in frozen status can be estimated. This information could be incorporated to determine the magnitude of Winter Load Increase in cold regions for government agencies.

INTRODUCTION

The evaluation of mechanical properties of concrete by nondestructive techniques is gaining popularity. Several techniques are currently in use, such as impact echo, ultrasonic test, spectra analyses of surface wave. They are based on the information contained in the propagation of ultrasonic waves. Different wave modes and transceiving methods are explored. For example, Boutin[1] and Arnaud used the speed of longitudinal waves (L-waves, also known as compression waves) of low frequencies from measuring the time of transition between fluid and solid state of cellular cement paste. A new device for monitoring the hydration of cement mortar that measures the transit time and the energy of an L-wave pulse propagating through a mortar sample has been introduced by Reinhardt[2] et al. With this device the setting and hardening process of mortar can be evaluated. Other investigators have applied both, longitudinal and transverse waves (T-waves, also known as shear waves) to examine the hydration of cementitious materials. Sayers[3] and Grenfell found a linear relationship between the effective bulk and shear moduli determined by pulse

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