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EFFECT OF SPACING ON THE INTERACTION OF ADJACENT STRUCTURES ON LIQUEFIABLE SOILS

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Abstract

Soil liquefaction is one of the most catastrophic consequences of earthquakes and has recently caused severe damage to structures in different countries. The damage primarily arises from the settlement and rotation of the buildings. Therefore, several numerical and experimental studies have focused on understanding the mechanisms governing the settlement and rotation of structures located on softened ground. These studies considered the structures isolated from other buildings. However, in real world cases (e.g. in cities), structures can be located close to one another and interact through the underlying soil. This interaction is called structure-soil-structure interaction (SSSI) and can modify the response of adjacent structures during earthquakes. There are a limited number of geotechnical centrifuge tests in the literature focusing on the governing mechanisms of this interaction as it is generally not practical to perform a large number of sensitivity analyses in centrifuge tests to better understand the problem., They can provide researchers with valuable data for validating liquefaction constitutive models, and once validated, numerical models can provide researchers with insight into the primary mechanisms of SSSI on liquefiable soils through extensive sensitivity analyses. Although a number of studies validate liquefaction models for SSI problems, almost no studies have included validation for cases involving SSSI, meaning it less understood. Due to this lack of understanding, current design codes neglect the effects of SSSI on structures located on softened ground, potentially leaving them more vulnerable to future earthquakes. This study includes fully coupled, effective stress dynamic finite difference analyses developed using PM4Sand constitutive model implemented in FLAC software to study the response of adjacent structures located on softened ground during earthquakes. The validity of the developed numerical model is first demonstrated by comparing the estimated responses of soil and structures (i.e. pore pressures, displacements and accelerations) to the experimental data from two well-documented centrifuge tests. These centrifuge tests consist of eight different adjacent structures (i.e. four different combinations of adjacent structures) each subjected to four different input motions (i.e. a total of 32 cases). Following validation of the numerical model, sensitivity analyses are performed to study the effect of spacing between the structures on the interaction of adjacent buildings for two cases: 1) two identical buildings; 2) two buildings with different bearing pressures and identical natural period and center of mass. The results show that when the buildings are identical, their behavior largely depends on the distance between their foundations as it controls the movement of the underlying soil. However, when considering one structure about three times heavier than the other, the response of the lighter building is mostly dependent on the settlement of the heavier structure, but the heavier structure is less affected by SSSI.
Keywords: Structure-soil-structure interaction; Liquefaction; Numerical Analysis; PM4Sand

1. Introduction

The current state of practice for designing the structures assumes buildings to be isolated. However, especially in large cities, structures can be quite close to adjacent structures and interact with one another through the underlying soil in a phenomenon called structure-soil-structure interaction (SSSI). Recent studies reported that SSSI can change the response of the buildings during earthquakes on stable ground. Whitman [1] first introduced the interaction of adjacent foundations through the soil as a problem that can modify their performance during earthquakes. Çelebi [2, 3] studied the recordings of two adjacent seven-story buildings during the Whittier-Narrows earthquake in the USA and reported that SSSI changes the response of both buildings, especially near their fundamental frequencies. Isbiliroglu et al. [4] performed a numerical study on the problem of SSSI and reported that in addition to the number of adjacent buildings around a structure, the distance between the buildings and their dynamic properties are important factors influencing SSSI. Knappett et al. [5] performed centrifuge tests to investigate the problem of SSSI on stable ground and stated that although SSSI decreased the settlement of buildings in some cases, it increased the foundation rotations in all cases compared to the isolated structures. Menglin et al. [6] performed a comprehensive literature review about the problem of SSSI on stable ground.

Most of the aforementioned studies suggest that SSSI can have both positive and negative effects on the performance of structures on stable ground. Soil liquefaction, which has led to structural damage during recent earthquakes [7-11], adds further complication to this interaction, making it less understood. The effect of liquefaction on the performance of buildings on loose soils has been investigated during various earthquakes. Several studies [12-15] have focused on the performance of structures during the Tohoku earthquake in Japan and identified the adjacency of the structures as a controlling factor determining their inclination. During this earthquake, adjacent structures tended to tilt towards each other when located close together and away from each other when located further away (e.g. across the street). Bray et al. [16] studied the performance of isolated and adjacent structures during the Kocaeli earthquake in Turkey and discussed a case of two adjacent buildings that tilted away from each other after the occurrence of liquefaction. Tokimatsu et al. [17] studied the settlement and rotation of buildings after the 1990 Luzon earthquake in the Philippines and concluded that SSSI can have a positive effect on the performance of adjacent structures as it reduced the foundation settlements in most cases. These studies reflect the importance of SSSI on modifying structural response on softened ground. However, the governing mechanisms and the parameters controlling the problem are still not well studied. Therefore, a limited number of centrifuge tests have been performed recently focusing on the problem of SSSI on liquefiable ground. Hayden et al. [18] performed two centrifuge tests to compare the performance of mat-supported isolated and adjacent structures located on liquefiable soil profiles. They concluded that although SSSI generally reduced the settlement and acceleration experienced by the foundations, it increased the tendency of the building to tilt away from each other during the shaking events. Kirkwood and Dashti [19] performed three centrifuge tests to investigate the mechanisms governing the performance of adjacent structures on softened ground. They concluded that the inclination of the adjacent buildings is a function of the effective and shear stresses in the soil under and between them, in addition to the accelerations experienced by their foundations. Although these experimental studies can help the researchers analyze some of the mechanisms of SSSI on liquefiable ground, further research is still necessary to understand the problem thoroughly. Numerical modelling is one of the most efficient means of studying the problem by performing extensive sensitivity analyses on different soil and structure parameters. However, the numerical models need robust validation against experimental data before being used for the parametric studies. Nevertheless, the authors are not aware of any numerical models validated against data from SSSI on liquefiable ground, likely due to limited experimental data in the past.

This paper presents fully coupled, dynamic, finite difference (FD) analyses using the PM4Sand constitutive model implemented in FLAC [20] software to study the interaction of adjacent structures located on softened ground. The developed numerical models are validated against two well-documented centrifuge tests performed by Hayden et al. [18]. After confirming the validity of the numerical modelling, sensitivity analyses are performed to study the effect of spacing between adjacent structures on their interaction. These preliminary parametric studies can help engineers understand when the interaction of nearby buildings becomes substantial and should be considered in structural design.

2. Methodology

2.1 Overview of the centrifuge tests

This study uses the results of two centrifuge tests performed by Hayden et al. [18] to validate the developed numerical models. The purpose of the tests, namely T4.5-50 and T4.6-40, was to study the performance of mat-supported isolated and adjacent structures located on liquefiable ground. The two numbers in the names of the tests indicate the thickness (in m) and relative density of the liquefiable layers, respectively. The tests were performed under centrifugal acceleration of 55 g, and all values in this paper are in prototype scale calculated using centrifuge scaling laws presented by Schofield [21]. Each test contained one layer of Loose Nevada sand as the main liquefiable layer underlain by a layer of Dense Nevada sand as shown in Fig. 1. Additionally, a thin layer of Dense Monterey 0/30 sand directly under the structures prevented liquefaction from occurring directly below the foundations. Three types of structures (Structure A, J and K) with the properties presented in Table 1 were used in these tests and were supported by mat foundations with an embedment depth of 0.7 m. The subscripts in the name of the adjacent structures indicate the name of their nearby building in addition to other information, if any. For instance, Structure $A_{A\text{-}S}$ is an A-type structure located next to another A-type structure and placed at the southern side of that structure pair. In addition to the soil and structures, about 140 sensors were included in each test to record the response of the soil and structures subjected to four input motions. These input motions included the small, moderate and large Port Island (PRI) motions (scaled versions of 1995 earthquake in Kobe, Japan) and the moderate TCU motion (a modified and scaled version of 1999 Chi-Chi earthquake, Taiwan) and were applied to the centrifuge container consecutively. The data reports of the tests [22, 23] contain a comprehensive explanation of the two experiments.

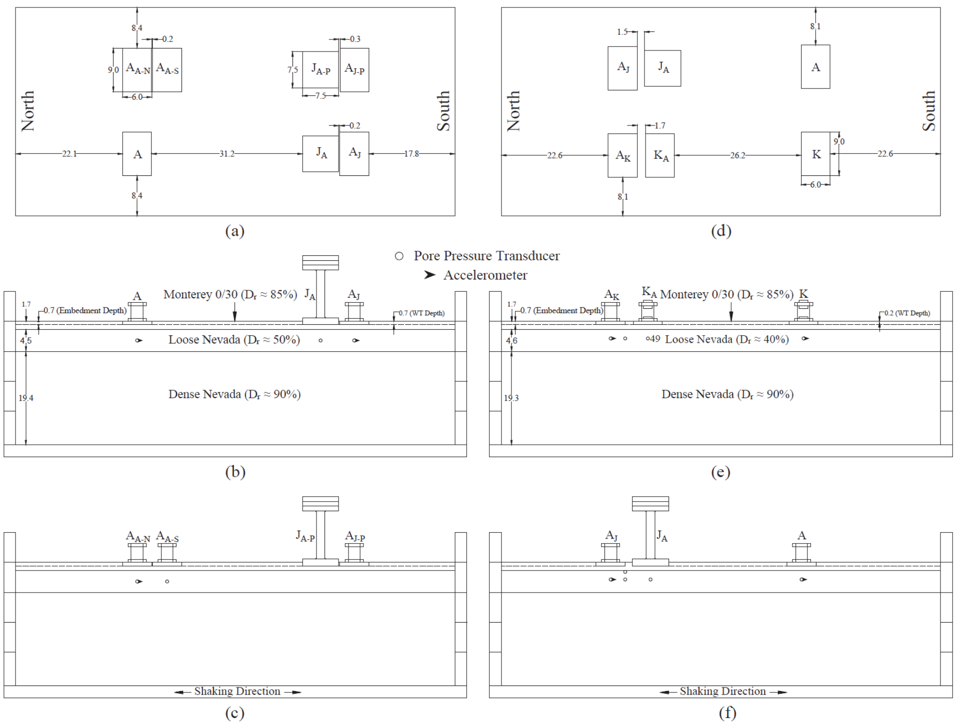


Fig. 1 – Layout of the two tests performed by Hayden et al. [18] (a) plan view of T4.5-50 (b) profile view of T4.5-50 for isolated “A” and structure pair “AJ” (c) Profile view of T4.5-50 for structure pair “AA” (d) plan view of T4.6-40 (e) profile view of T4.6-40 for isolated “K” and structure pair “AK” (f) profile view of T4.6-40 for isolated “A” and structure pair “AJ”

Table 1 – Properties of the structures used in the experiments

Structure	Bearing pressure (kPa)	Fixed-base period (s)	Deck center of mass (m)*
A	65	0.33	3.9
K	180	0.38	3.9
J	180	0.85	15

* Measured from bottom of the foundation

2.2 Numerical modelling

To study the problem of SSSI affected by liquefaction, fully coupled, plane-strain, dynamic models were developed in FLAC [20]. The PM4Sand constitutive model developed and implemented in FLAC by Boulanger and Ziotopoulou [24] was used to capture the response of the saturated soil to the shaking events. Mesh sensitivity analyses showed that a model with a maximum element size of 0.4 m near the foundations, reaching 0.6 m at the boundaries (Fig. 2) can minimize the computational burden of the problem without affecting the accuracy of the results. Additionally, model width sensitivity analyses showed that a minimum 20 m distance between foundation edges and the model boundaries can minimize the negative effects of wave reflection in the models. Additionally, boundary grid points that were at the same elevation in the models were attached together to achieve a periodic boundary condition as PM4Sand is not consistent with the "free-field boundaries" implemented in FLAC. Note that the sign of all accelerations recorded in the tests were reversed in the numerical modelling to maintain consistency with the sign convention of foundation rotations available on DesignSafe webpage (https://www.designsafe-ci.org).

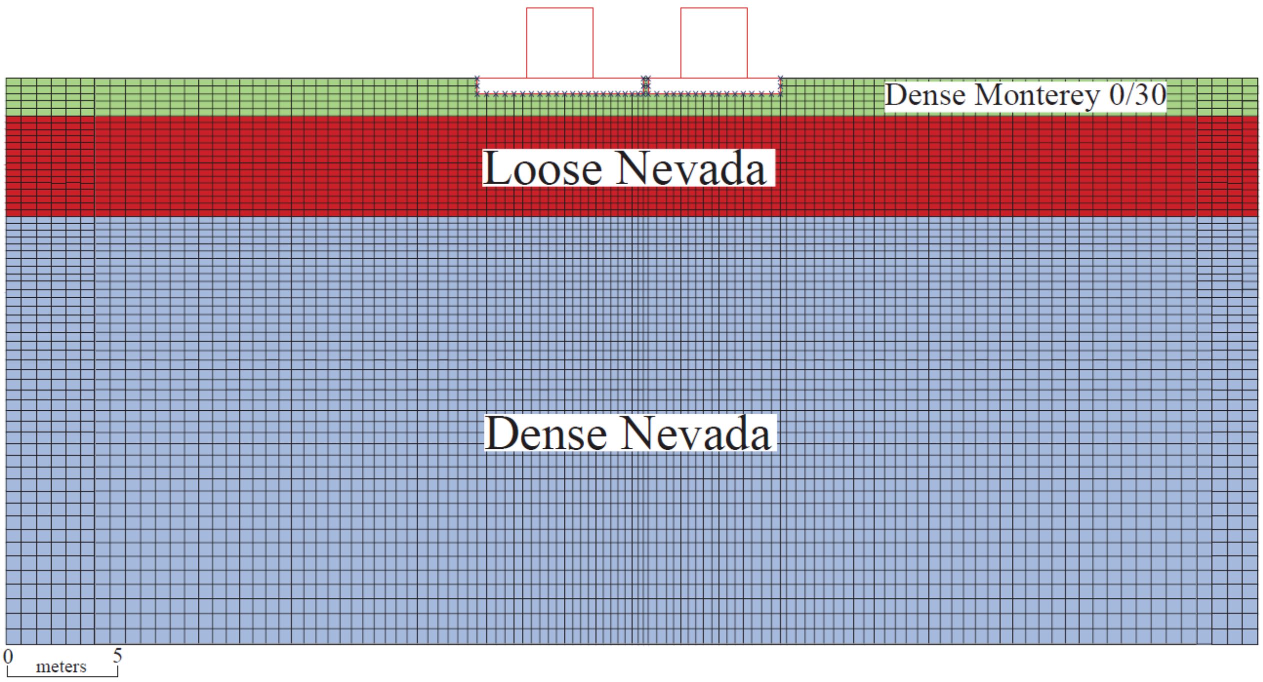


Fig. 2 – A developed model in FLAC software to study the problem of SSSI affected by liquefaction

The three primary parameters of PM4Sand (i.e. relative density, D_r, shear modulus coefficient, G_o and contraction rate parameter, h_{po}) presented in Table 2 for the soil layers in the centrifuge tests were calibrated based on the procedure explained by Balachandra [25], which is based on adjusting the values provided by Armstrong and Boulanger [26]. The values of the secondary parameters listed in Table 2 are from Armstrong and Boulanger [26]. For all other secondary parameters not listed in Table 2, the default values provided by Boulanger and Ziotopoulou [24] in the PM4Sand manual were used in this study. This approach is more consistent with likely applications in industry as it is often not practical to calibrate all soil parameters for a specific soil type in the field. Each analysis was initialized using an elastic material to calculate the initial stress conditions in soil layers before applying the PM4Sand parameters.In addition to damping due to hysteretic behavior in PM4Sand, 0.5% Rayleigh damping at a center frequency of 4.2 Hz was applied to the soil as recommended by Boulanger and Ziotopoulou [24] to eliminate the high-frequency noise in the models. The vertical hydraulic conductivities of the soil layers presented in Table 3 were chosen based on the values recommended by Karimi and Dashti [27] according to their relative densities. Additionally, the horizontal hydraulic conductivities of the soil layers are scaled versions of their vertical hydraulic conductivities based on the recommendations presented by Yarmohammadi et al. [28] to account for the effect of air pluviation on the anisotropy of the sand in addition to the lack of 3D drainage in a plane-strain model.

Table 2 – Calibrated parameters of PM4Sand for Nevada and Monterey sands

Soil type	D_r (%)	e_{min}	e_{max}	Density	φ'_{cv}	Q	R	G_o	h_{po}
Dense Nevada	90	0.485	0.793	1761.4	32°	9.5	0.7	902	0.0023
Loose Nevada	50	0.485	0.793	1629	32°	9.5	0.7	875.8	0.007
Loose Nevada	40	0.485	0.793	1599	32°	9.5	0.7	735	0.056
Dense Monterey	85	0.54	0.82	1687.7	33°	9.5	0.7	661.8	0.305

Table 3 – Soil hydraulic conductivities for Nevada and Monterey sands

Soil type	D_r (%)	k_v (m/s)	k_h (m/s)
Dense Nevada	90	5.63×10^{-5}	5.63×10^{-5}
Loose Nevada	50	1.50×10^{-4}	7.50×10^{-3}
Loose Nevada	40	1.63×10^{-4}	8.15×10^{-3}
Dense Monterey	85	1.32×10^{-3}	1.32×10^{-3}

The numerical models used the linear elastic beam elements implemented in FLAC to simulate the structural elements. The properties of these elements were chosen so that the structures in the models have the same fundamental period, bearing pressure and center of mass as the structures in the experiments. Additionally, a 2% Rayleigh damping at a center frequency of 2.8 Hz was applied to the structures in the numerical models. This damping was estimated based on the free vibration tests performed on the structures and had a negligible impact on the accelerations experienced by the structural elements in the numerical models. The steel or aluminum foundations in the experiments were coated with a layer of Monterey sand to simulate the interaction of a concrete foundation with the soil. Therefore, the soil-foundation interface in the numerical models had no cohesion ($c' = 0$) and a friction angle of $\varphi' = 43°$ [29] based on Monterey sand properties. Additionally, the interface had shear and normal stiffnesses equal to $k_s = k_n = 5.1$ GPa/m according to the equation suggested by FLAC [20]. Finally, as the input motions were applied to the centrifuge container consecutively, the structures might have some inclination at the end of each motion, affecting their performance during the next motion. Therefore, in an approach explained by Yarmohammadi et al. [28], these initial tilts, if any, were applied to the structures before applying each input motion in the numerical analyses.

3. Validation of the numerical models against experimental data

3.1 Soil response

The primary mechanisms of structural response on softened ground during earthquakes mostly depend on the response of the underlying soil [30]. Therefore, it is crucial for the numerical analyses to capture the soil response in terms of pore water pressure generation and dissipation. Fig. 3 shows the excess pore pressures generated in the middle of the liquefiable layer under and between the A_K and K_A structures during the large PRI motion. This figure suggests the numerical models are generally able to capture the generated excess pore pressures due to the dynamic loadings. Yarmohammadi et al. [31] presents a detailed discussion of the generated excess pore pressures in the loose soil.

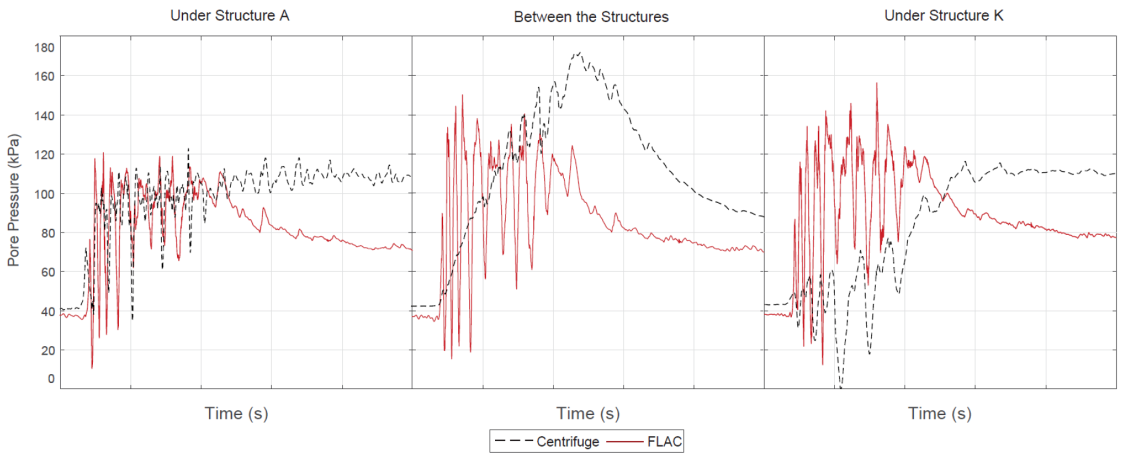


Fig. 3 – Generation of excess pore pressure in the middle of the liquefiable layer under the AK pair of structures during the large PRI motion

3.1 Structural response

The foundation accelerations are among the most important parameters in structural design as they are representative of earthquake demand on the superstructure during earthquakes. Fig. 4 demonstrates that the numerical models are able to estimate the foundation acceleration spectra of the AK pair of structures during all motions. In addition to the foundation accelerations, it is important for the numerical models to capture the settlements and rotations of the buildings. Fig. 5 shows that the numerical models are generally able to estimate the final settlement values at the middle of the foundations. However, there are some cases where the estimated settlements of the structures are not close to the experimental data. These differences are mainly due to the difference between the estimated excess pore pressures and foundation accelerations by the numerical models and the centrifuge tests. The same trend also exists for the final values of foundation rotations, which are not discussed herein due to brevity. Yarmohammadi et al. [31] provide a more detailed comparison between the predicted structural responses and the experimental data.

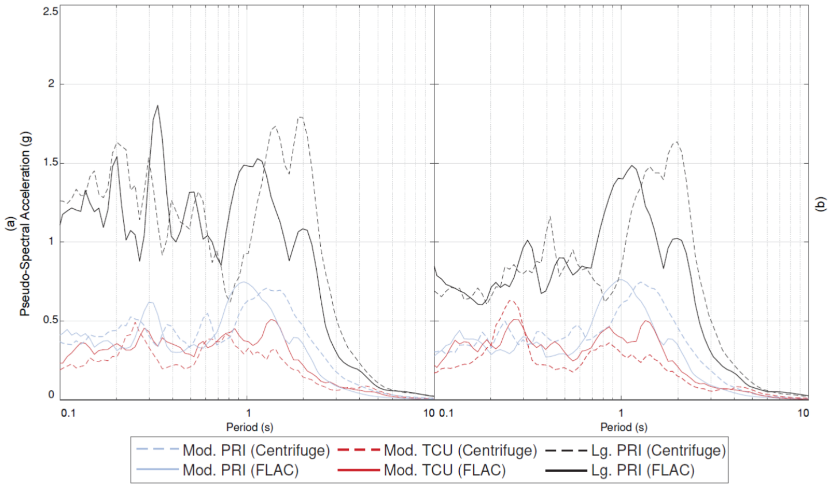


Fig. 4 – Acceleration spectra of foundations during all major shaking events (a) Structure A_K in T4.6-40 (b) Structure K_A in T4.6-40

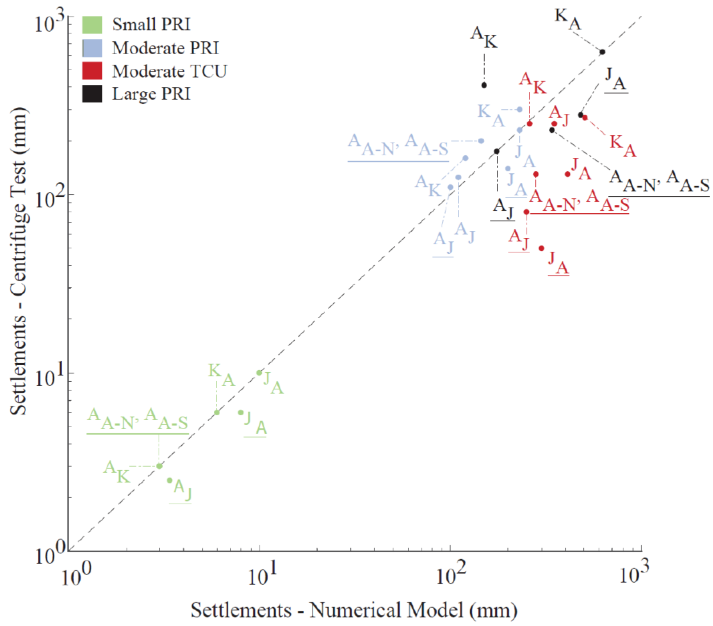
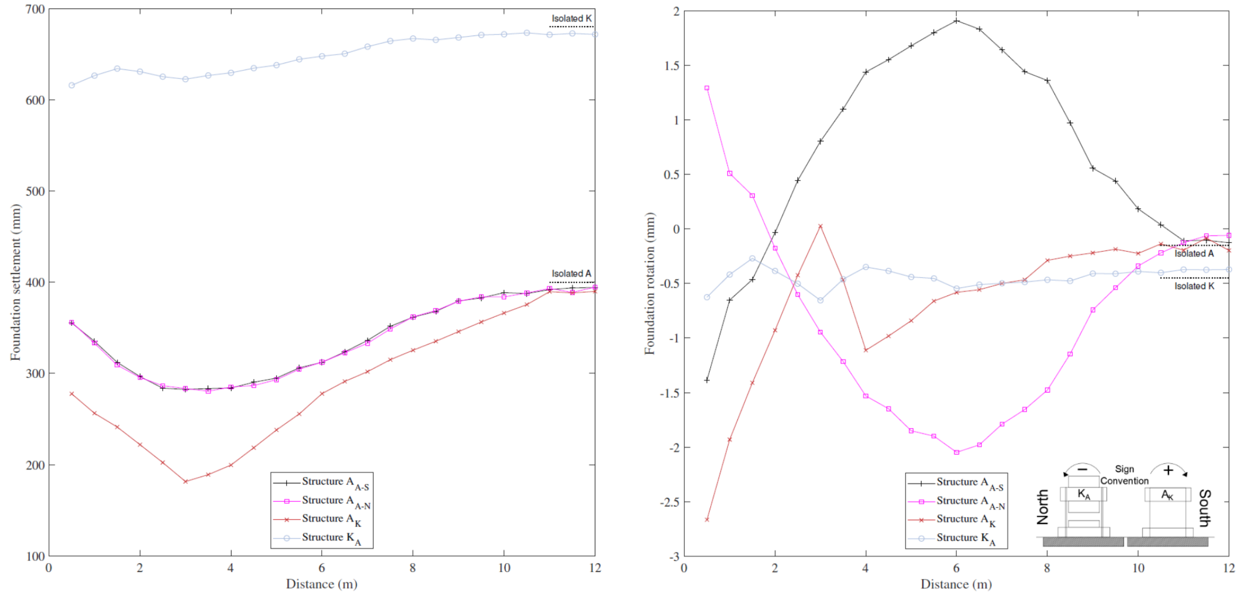


Fig. 5 – Final values of foundation settlements during all motions (underlined letters indicate T4.5-50 buildings)

4. Effect of spacing between the structures

To alleviate the negative aspects of SSSI in designing structures, it is crucial to understand when this interaction starts to influence response. For this purpose, two sets of sensitivity analyses were performed on the spacing between the structure pairs of AA and AK from the centrifuge tests. To maintain consistency, the thickness and relative density of the liquefiable layer were kept similar to T4.5-50 in both sets of analyses. The distance between the foundations was varied from 0.5 m to 12 m with 0.5 m increments, and the final settlements and rotations of the structures in each case were calculated at the end of the large PRI motion using the same methodology explained previously.

Fig. 6-a shows the change in foundation settlement for different structures as a function of their distance from the adjacent building. For the case of A-type structures, increasing the spacing decreases the foundation settlements for spacing less than around 3 m. After that, the interaction starts to decrease, and when the foundations are about 12 m from each other, the structures act similar to isolated buildings as labeled on the figure. Additionally, Fig. 6-b shows that when the AA structures are close together, they tend to tilt towards each other. As the distance between the foundations increases (i.e. about 2 m), these buildings start to tilt away from each other until the distance is large enough (i.e. about 12 m) that they begin to behave similar to isolated structures. On the other hand, Structure A_K always tends to tilt towards Structure K_A although this tendency decreases as the distance between the foundations increases. SSSI does not have a significant effect on the behavior of Structure K_A regardless of the spacing between the foundations.



(a) (b)

Fig. 6 – (a) settlements and (b) rotations of the foundations as a function of distance between the structures

Analyzing the movement of the soil under the structures can provide some preliminary explanations for the behavior observed in Fig. 6. When the AA pair of structures are close together, the underlying soil is restricted to move towards the outer edge of the foundations due to the equal bearing pressure of the structures, leading to the inward tilt of the buildings (Fig. 7-a). As the distance between the buildings increases, the soil is also able to move towards the inner edge of the foundations, leading to the formation of a soil bulge on the surface. The superposing effect of the moving soil from under the structures on the inner edges of the foundations leads to an outward tilt of the buildings as shown in Fig. 7-b. When the distance between the buildings is large enough, the buildings act independently as they are not affected by the soil movement under the nearby structure (Fig. 7-c). A similar trend occurs for AK pair of structures; however, the large bearing pressure of Structure K_A leads to a large settlement under this building, which causes the inner edge of Structure A_K to settle more than its outer edge, which leads to its tendency to tilt toward Structure K_A.

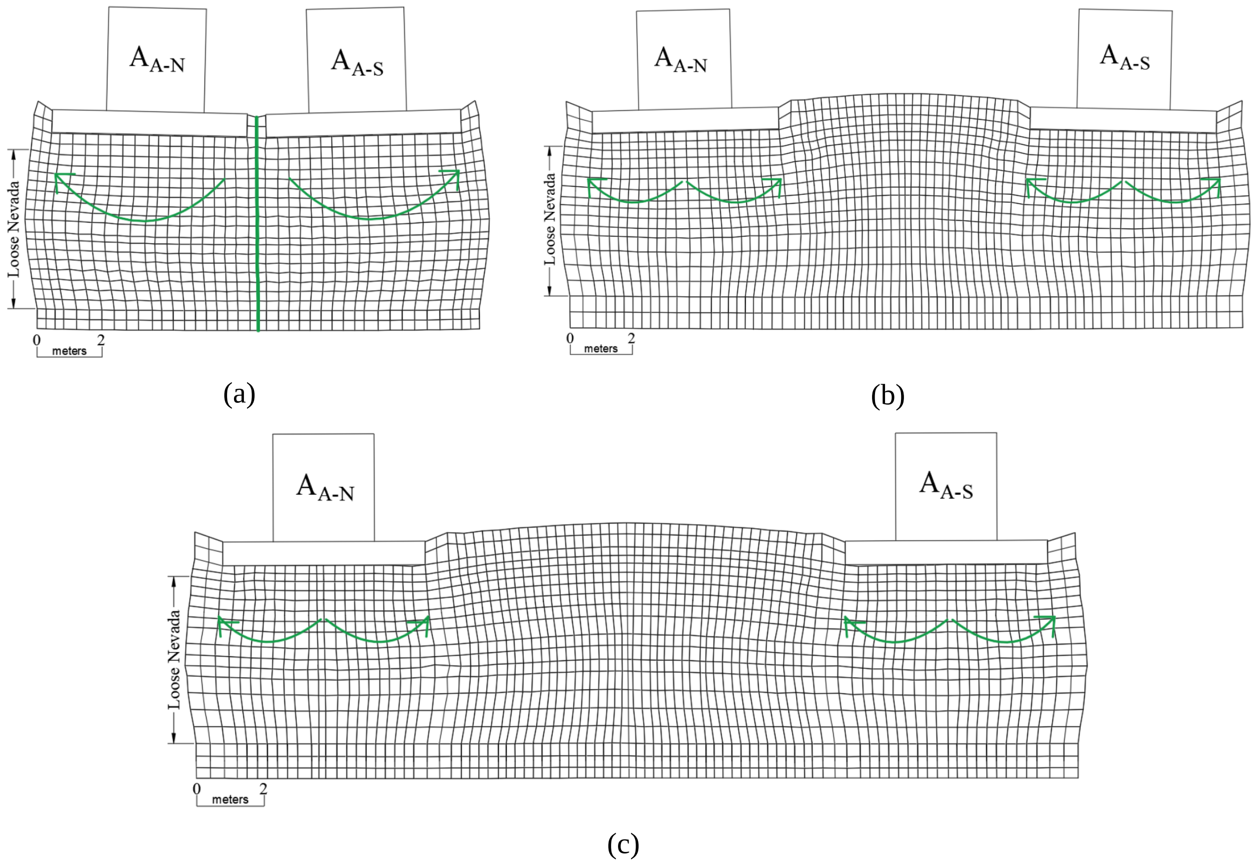
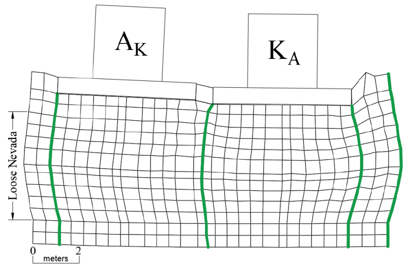


Fig. 7 – Distorted mesh (magnification factor of one) demonstrating the movement of soil under the structures for three spacings: (a) 0.5 m, (b) 7 m, and (c) 12 m

Despite the differing relative densities, a comparison between soil deformation under the structures in the numerical models and the centrifuge tests, which included initially-vertical colored columns, can provide some insight into the reliability of the aforementioned explanations. According to Fig. 8, when the structures are close together, both the centrifuge test and numerical model predict a horizontal bulge in the soil column under structure K_A after the strong shaking. However, this bulge is larger in the numerical models between the buildings. This phenomenon could be due to the higher volume of soil displaced for a given settlement in the numerical models due to plane-strain modelling of the problem and may affect the predicted settlement and rotation of Structure A_K in the numerical models. A similar effect likely occurs for the AA pair of structures in the T4.5-50 test, although no cross-section photographs are available for that structure pair. It should be noted that the comparison between the soil columns in the numerical model and the experiments is also approximate as the columns are not in exactly the same location in the models and the photographs from the centrifuge tests were taken at a slight angle. Therefore, although, the mentioned mechanisms may partially explain the responses of the nearby buildings as a function of the distance between their foundations, they might be affected by the simplifications of the numerical modelling and more research is still required to fully understand their behavior.

(a)



(b)

Fig. 8 – Soil deformation under the structures (a) centrifuge tests (b) numerical model

5. Conclusions

Fully coupled, plane-strain, finite difference, dynamic analyses were performed using the PM4Sand constitutive model implemented in FLAC to study the performance of adjacent structures located on liquefiable soil profiles. The numerical analyses were first validated against the results of two well-documented centrifuge tests. The validation showed that the numerical models were able to reasonably capture the soil response in terms of generated excess pore water pressures in the middle of the liquefiable layer as well as accelerations experienced by the soil during the shaking events. In terms of structural response, the numerical models were able to estimate the final values of foundation rotations and settlements reasonably well. Furthermore, the analyses were able to estimate the accelerations experienced by the foundations, which are representative of earthquake demand on the superstructures.

After validation of the numerical models, parametric studies were performed to analyze the effect of the spacing between the adjacent structures on their interaction. This study considered two cases for the sensitivity analyses: 1) two identical adjacent structures and 2) a heavier structure placed next to a lighter structure with one third the bearing pressure, but other structural properties remaining similar. The results of the parametric studies showed that for the limited particular scenarios analyzed:

- When the foundations are less than around 3 m apart, increasing the spacing increases the effect of SSSI on the settlement of A-type structures. Further increasing the distance between the structures causes them to approach the response of isolated buildings.
- The rotation of the AA pair of structures is highly dependent on their spacing, which controls the movement of the soil under the buildings. However, the rotation of Structure A_K is mainly controlled by the effect of large bearing pressure of Structure K_A, which decreases with increasing the distance between the foundations.
- The K-type structure is not significantly affected by SSSI when adjacent to a much lighter A-type structure, regardless of the spacing between the foundations. As expected, the difference between the bearing pressures of the nearby buildings is a key factor determining their behavior during earthquakes.

It is important to recognize that these conclusions are limited to the specific soil and structure types used in the parametric studies. More comprehensive research is still required to better understand the complex interaction between the nearby buildings and develop more generalized findings and explanations.

6. Acknowledgements

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