Artículo de investigación

Effect of loading due to building construction on liquefaction potential of sand deposits

Efecto de la carga debida a la construcción de edificios sobre el potencial de licuefacción de los depósitos de arena

Efeito do carregamento devido à construção civil sobre o potencial de liquefação dos depósitos de areia

Recibido: 20 de abril de 2018. Aceptado: 10 de mayo de 2018

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Abstract

Liquefaction is one of the most important seismic geotechnical titles and mainly occurs in the non-dense saturated sandy soils during the dynamic loading such as earthquake. The construction of structures on the sand deposits susceptible to liquefaction may prevent liquefaction from occurring or increase the potential and severity of liquefaction. In this study, the FLAC2D software was used for modeling. The liquefaction of the sandy soil mass was studied in three cases: (1) without loading, (2) loading due to the construction of 10- and 20-story buildings, and (3) loading due to the construction of 10-, 15- and 20-story buildings. The results show that by increasing the number of building floors, and consequently, increasing the applied load, the effective depth was increased due to the increase in the amount of effective stress that could decrease the liquefaction potential.

Keywords: Liquefaction, FLAC, loading, geotechnical engineering, finite difference method

Resumen

La licuefacción es uno de los títulos geotécnicos sísmicos más importantes y se produce principalmente en los suelos arenosos saturados no densos durante la carga dinámica, como un terremoto. La construcción de estructuras en los depósitos de arena susceptibles a la licuefacción puede evitar que ocurra la licuefacción o aumentar el potencial y la gravedad de la licuefacción. En este estudio, el software FLAC2D se usó para modelar. La licuefacción de la masa de suelo arenoso se estudió en tres casos: (1) sin carga, (2) carga debida a la construcción de edificios de 10 y 20 pisos, y (3) carga debida a la construcción de 10-, 15 - y edificios de 20 pisos. Los resultados muestran que al aumentar el número de pisos del edificio y, en consecuencia, al aumentar la carga aplicada, la profundidad efectiva se incrementó debido al aumento en la cantidad de tensión efectiva que podría disminuir el potencial de licuefacción.

Palabras claves: Licuefacción, FLAC, carga, ingeniería geotécnica, método de diferencias finitas.

Resumo

A liquefação é um dos títulos geotécnicos sísmicos mais importantes e ocorre principalmente nos solos arenosos saturados não densos durante o carregamento dinâmico, como o terremoto. A construção de estruturas nos depósitos de areia suscetíveis à liquefação pode impedir a ocorrência de liquefação ou aumentar o potencial e a gravidade da liquefação. Neste estudo, o software FLAC2D foi utilizado para modelagem. A liquefação da massa arenosa do solo foi estudada em três casos: (1) sem carga, (2) carga devido à construção de edifícios de 10 e 20 andares, e (3) carga devido à construção de 10, 15 - e edifícios de 20 andares. Os resultados mostram que, aumentando o número de andares de construção e, conseqüentemente, aumentando a carga aplicada, a profundidade efetiva foi aumentada devido ao aumento na quantidade de estresse efetivo que poderia diminuir o potencial de liquefação.

Palavras-chave: Liquefação, FLAC, carregamento, engenharia geotécnica, método de diferenças finitas.

Introduction

Liquefaction is one of the most important, complex, and controversial seismic geotechnical titles and its devastating effects were first studied about 50 years ago in the great Niigata, Anchorage, and Alaska earthquakes. There have been many advances in understanding the basic mechanics of liquefaction, empirical prediction of occurrence, and its effects (Kramer et al., 2016). Soil liquefaction is a phenomenon that occurs in low-density saturated sandy soils due to the increased pore pressure and loss of shear strength (Seed and Tokimatsu, 1985). During and after the earthquake, the pore overpressure caused by the earthquake is noticeably dissipated by the upward flow of the pore water. This flow creates the upward forces in the soil particles and caused the upper part of the soil mass to be loose (Adaliera et al., 2003). When applying dynamic or static loads, the low density saturated soil tends to reduce volume, and if this volume reduction is so rapid that no equivalent pore water could be drained, the applied load would increase the pore water pressure. Since the pore water is incompressible, the pore overpressure during the application of shear forces creates liquefaction in the soil (Shahir et al., 2012).

Today, there are numerous software in the field of numerical modeling that can provide and analyze some developed models related to the simulation of soil liquefaction, among which the FLAC software can be mentioned here (FLAC, 2005). Sharifi et al. (2015) investigated the effect of load caused by the construction of surface structures on the liquefaction potential. The results show that in the center of the foundation and at near-ground level, because of the increased impact of surcharge on increasing the effective stress of soil, there is a significant decrease in the liquefaction potential of the soil, which is very effective in maintaining the integrity of the structure in the event of an earthquake. In this study, the FLAC finite difference software was used to model the surcharge caused by the construction of structures on a liquefiable soil.

Effect of buildings on liquefaction potential of sand deposits

Construction of the structures is effective on the liquefaction potential, and the observation of the destruction of structure caused by the previous earthquakes may not actually indicate the negative effect of the structure on the underlying soil relative to the free field, because the existence of the structure may prevent the occurrence of a more massive phenomenon. The effect of the structure on the occurrence of liquefaction depends on the soil density, type of earthquake, shape of structure and depth of saturation, and has a different effect on the occurrence of liquefaction depending on the ground and earthquake conditions (Ardeshiri Lajimi et al., 2015). The field observations, experiments and analyses of models show that there is a significant difference between the occurrence of liquefaction near the buildings and in a free field with the same soil conditions; in other words, the field observations, experiments and analyses performed on the loose sand show that the increase in pore pressure due to the cyclic loading is greater than that of the free field with the same depth. Rollins and Seed (1990) show that in order to investigate the liquefaction potential of the sand deposits on which the building is located, at least five factors should be considered: 1) initial static shear stress; 2) confining pressure; 3) over-consolidation ratio; 4) effective stress; 5) structural response. They investigated the effects of these factors on sand with the relative density of 35%, 45% and 55%. The results of this study show that the factor of safety against liquefaction is increased for various buildings located on the sand of 55% density, especially in the high-rise structures. On the other hand, the factor of safety against liquefaction is decreased for different buildings on sand deposits of 35% density, especially in low-rise and/or deep-foundation buildings. Later, Pillai (1991) suggested two correction factors of $K\alpha$ and $K\sigma$ in order to consider the initial static shear stress and high confining pressure, respectively.

Numerical modeling code selection

There are numerous numerical codes for liquefaction modeling. The choice of numerical codes for liquefaction modeling depends on the following criteria:
Ability of code to model liquefaction and its remediation by simultaneously coupling dynamic mechanical calculation with flow calculation; ability to include user-defined models; ability to apply free-field boundaries, model structural elements and interfaces; practical viability accepted by geotechnical engineers and researchers (Almani et al., 2012).
The FLAC software operates on the basis of the finite difference method and features the explicit and Lagrangian solving methods that allow for observing the behavior of the system in the large deformations (FLAC, 2005). The behavioral model available in FLAC for static loading operates on the basis of the effective stress; first, the total stress is calculated, then, the effective stress is obtained by calculating the pore water pressure.

Defining mass and mesh

In this study, the soil profile is divided into two mass sections of loose or semi-loose sand with the height of 30 m in addition to a 2-m moderately thick surface layer of sand. The length of the soil mass is 400 m. For meshing the model in the areas far from the building, the coarse mesh was used; in the areas near the building, the medium mesh, and in the areas below the building, the fine mesh was used.

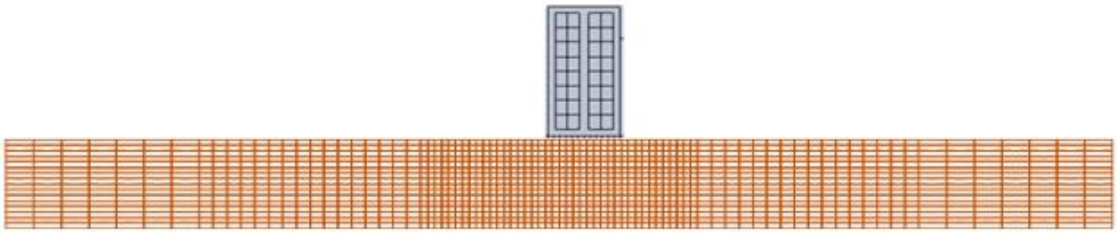

Figure 1. Meshing of soil mass

Dynamic load

In order to apply the dynamic load, the great earthquake of Bam was considered. The acceleration nomogram of the Bam earthquake of magnitude 6.5 and the maximum acceleration of 0.42 g is shown in Figure 2.

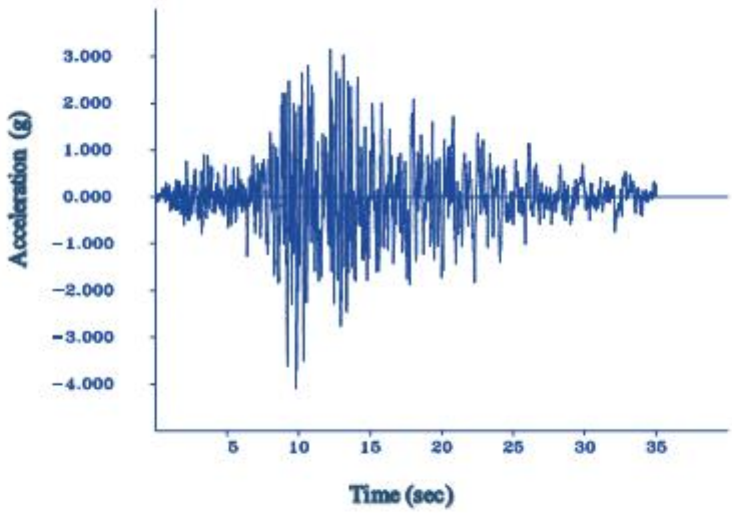

Figure 2. Bam earthquake acceleration nomogram

Input numerical values for soil mass

The soil mass properties were determined based on the fact that whether the sand mass is loose, semi-dense or dense. According to the Fish function written in the FLAC software, the Byrne's (1991) relation was used to define the liquefaction properties:

$$\frac{\Delta\epsilon_{vd}}{\gamma} = C_1\, exp\left(-C_2\left(\frac{\epsilon_{vd}}{\gamma}\right)\right) \tag{1}$$

Here, $\Delta\epsilon_{vd}$ is the decrement of volumetric strains and γ is the amplitude of cyclic shear strain. Byrne (1991) noted that the C1 value can be obtained using equation (2) and from the relative density of soil. Finally, the numerical value of C2 can be obtained from equation (3) (FLAC, 2005). The relative density (Dr) can be determined using the normalized value of standard penetration test [(N1)60] (Equation 4). Considering $e_{max} = 0.8$ and $e_{min} = 0.25$ for the sand mass, the e value is obtained according to equation (5). Table (1) shows the numerical values of soil properties in the model.

$$C_1 = 8.7(N_1)_{60}^{-1.25} \tag{2}$$

$$C_2 = 0.4/C_1 \tag{3}$$

$$D_r = \sqrt{{(N_1)_{60}}/{46}} \tag{4}$$

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{5}$$

Table 1. Numerical values of soil properties in model

Density of soil mass	Loose Soil	Semi-Dense Soil	Dense Soil
Numerical value of (N1)60	8	15	25
Numeric value of Dr	0.417	0.571	0.373
Numerical value of porosity e	0.57	0.485	0.394
$\gamma_d (KN/m^3)$	17	18	19.5
$\gamma_{sat} (KN/m^3)$	20	20.5	22
Internal friction angle ϕ	31.1	35.2	39.6

In order to investigate the changes in the pore water pressure of the soil mass during the earthquake, the ru parameter was defined using the Fish function in the FLAC software. In theory, if ru approaches to 1, the effective stress approaches to zero and the liquefaction occurs.

Loading

In this study, the load of each building was applied taking into account the loads without light-weighting in the construction of the building and considering the foundation load of 2 ton/m2 for each building floor, and then, converting the unit into Pascal. Table (2) shows the number of floors and the applied loads for each building.

Table 2. Numerical values of loading

Number of Floors	5	20
Loading (Kpa)	100	400

Results and discussion

In this section, two types of loose $[(N_1)_{60} = 8]$ and semi-dense $[(N_1)_{60} = 15]$ sand mass, which have liquefaction potential, were considered for loading and evaluation of liquefaction potential. First, the performance of soil mass was modeled without applying the load in three cases of loose, semi-dense and dense soil mass (Figure 3). The figure (a) indicates that nearly all the mass (except for small blue spots) reached a value greater than $r_u = 0.9$. Also, the graphical results of figure (b) indicate that most of the regions reached a numerical value greater than 0.9. In figure (c), all ru values were less than 0.9 and, as expected, the liquefaction did not occur in the mass.

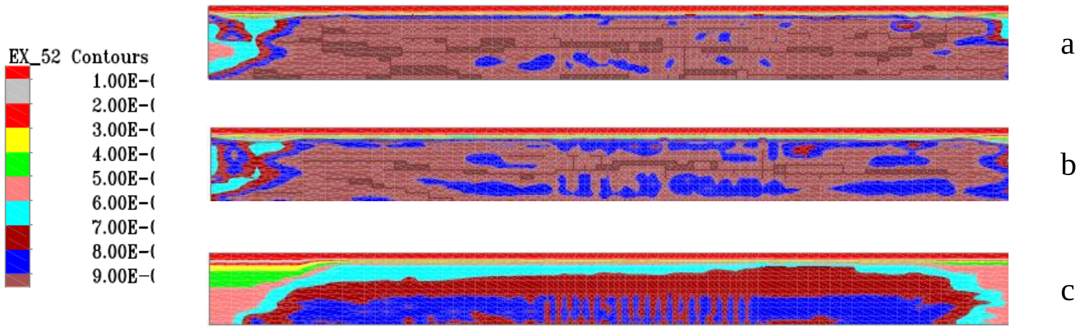

Figure 3. Mass liquefaction in (a) $(\boldsymbol{N_1})_{60} = \mathbf{8}$, (b) $(\boldsymbol{N_1})_{60} = \mathbf{15}$, and (c) $(\boldsymbol{N_1})_{60} = \mathbf{25}$

Results of loading from building construction on loose soil $[(N_1)_{60} = 8]$

As shown in Figure 4, the construction of a 5-story building reduced ru in the areas under the building foundation (about 10 m), which could be due to the increased loading, resulting in an increase in the effective stress of the deposit mass as well as the increased density in the higher layers.

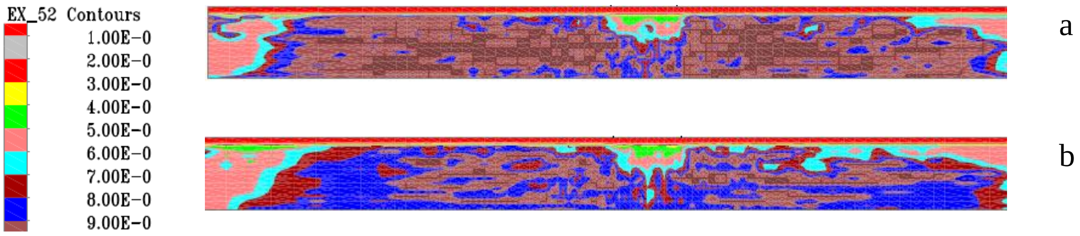

Figure 4. Mass liquefaction in (a) $(\boldsymbol{N_1})_{60} = \mathbf{8}$ and (b) $(\boldsymbol{N_1})_{60} = \mathbf{15}$ from a 10-story building

As shown in Figure 5, the construction of the 20-story building has reduced the ru value to 0.7 in the areas below the building to the depth of 25–30 m.

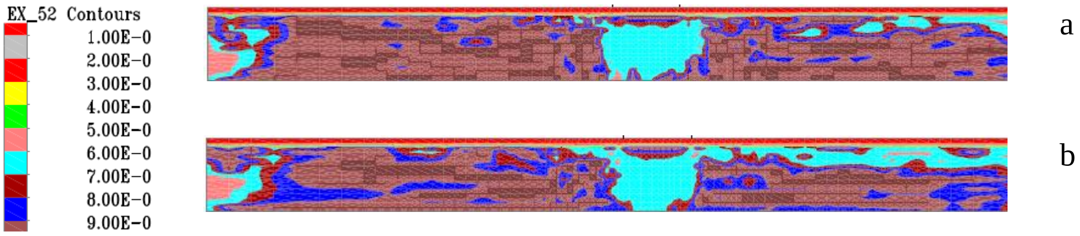

Figure 5. Mass liquefaction in (a) $(N_1)_{60} = 8$ and (b) $(N_1)_{60} = 15$ from a 20-story building

Results of loading from construction of 10-, 15- and 20-story buildings on loose soil $[(N_1)_{60} = 8]$

Figures 6(a) and 6(b) show the liquefaction of the loose and semi-dense soil masses in the loading cases of 10-, 15- and 20-story buildings, respectively. As can be seen, beneath the foundation of the 10- and 15-story buildings, the ru value is slightly different from the loading values obtained from each of the buildings in case there is no adjacent building. The mechanism of soil mass slightly changes probably due to the load-induced stress for each building. The rationale for this change is the difference in the stress levels caused by the load applied on the soil mass, meaning that, due to the interaction of the stresses below and in the center of the shorter buildings, the more effective initial confining stress is developed than the previous case.

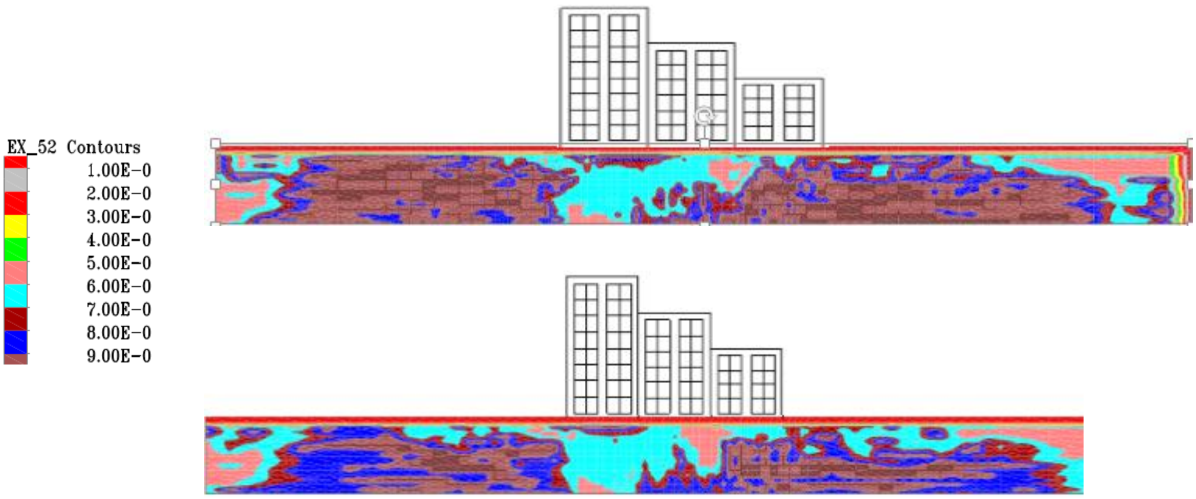

Figure 6. Mass liquefaction in (a) $(N_1)_{60} = 8$ and (b) $(N_1)_{60} = 15$ from 10-, 15- and 20-story buildings

Figure 7 and 8 show the maximum shear strain increment for each loading case. As can be seen, by increasing the number of building floors, and consequently, increasing the load caused by the building construction, the shear strain increment is also increased.

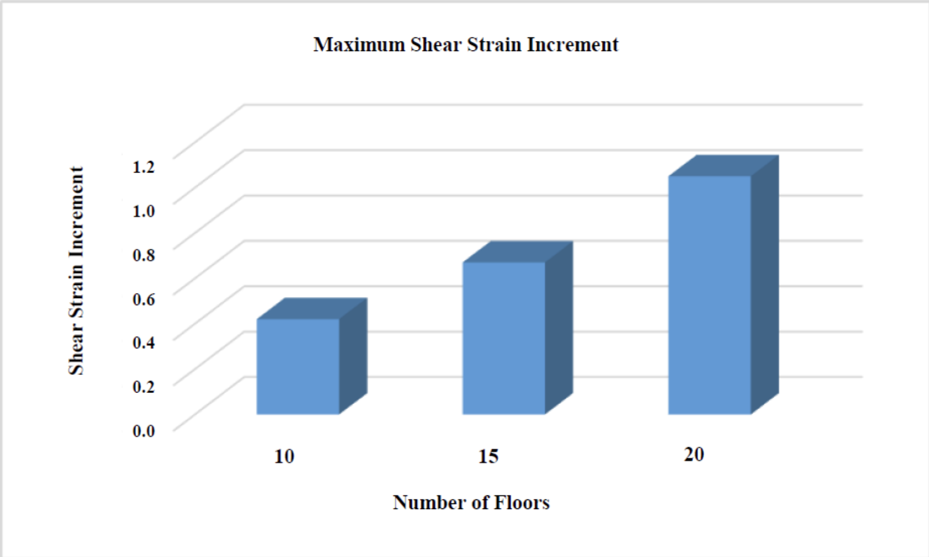

Figure 7. Maximum shear strain increment in $(N_1)_{60} = 8$

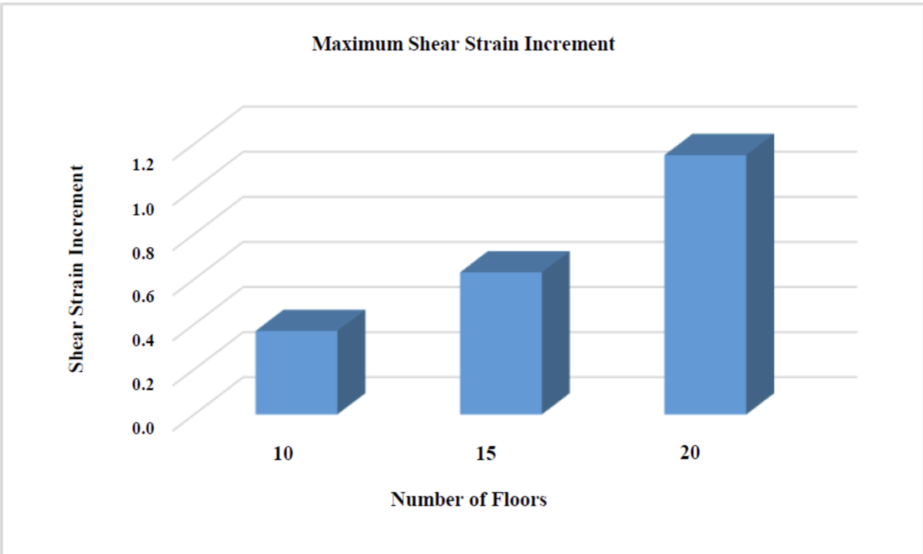

Figure 8. Maximum shear strain increment in $(N_1)_{60} = 15$

Conclusion

The results of the study show that increasing the load caused by the construction of building will increase the effective stress level. Furthermore, as the number of building floors, and consequently, the applied load is increased, the effective depth caused by the effective stress is increased, which could be a factor in reducing the liquefaction of the mass. The study by Sharifi et al. (2015) show that under equal stress conditions, by increasing the initial effective stress, the liquefaction potential is decreased, which is consistent with the present study. Since the weight of high-rise buildings is higher than that of low-rise buildings, it leads to the settlement of deposit mass and the increase in the compression ratio in the layers beneath the building foundation. However, this can cause a large settlement and tilt the building. In general, the increase in the liquefaction potential caused by the building construction can be attributed to the high stress concentration and effective confining stress of the soil mass. The construction of a building on the deposits exerts a large load on the soil mass and changes soil behavior due to the stress concentration on both sides of the loaded area.

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