GeoVirtual 2020 September 14-16
Resilience and Innovation

Seismic performance of circular foundations resting on stone columns

Habibollah Sadeghi, Amin Hasani Motlagh & Hamed Sadeghi
Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
Adel Ahmadihosseini
Department of Mining and Materials Engineering, McGill University, Montreal, Canada

ABSTRACT
Circular foundations are mainly used in projects such as liquid storage tanks, bridge piers, and silos. One of the main challenges in designing circular foundations is to control the foundation settlement, uplift, and slide, especially when the foundation is resting on loose granular soils and subjected to seismic loads. One way to reduce the displacements is to use stone columns below the foundation. Therefore, the main objective of this study is to investigate the influence of stone columns on the seismic performance of circular foundations through a parametric numerical study and to provide insights regarding these parameters for real world engineering projects. Abaqus software is used to simulate the multilateral interactions between superstructure, foundation, natural stratum, and stone columns. The parameters considered in the analyses include the length, diameter, and center to center spacing of the stone columns. The role of these factors on foundation settlement, uplift, and slide under seismic loads is presented and discussed. The results reveal that increasing the length of the stone columns up to a threshold value can decrease the settlements, but only marginal influence can be observed beyond that value. More importantly, the stone column's diameter and spacing play a more critical role than its length in decreasing the displacement due to seismic loads. In addition, the parameters related to stone columns may not reduce settlement and uplift to the same extent.

RÉSUMÉ
L'usage de fondations circulaires se retrouve principalement dans des projets de type réservoirs de stockage de liquides, piles de ponts et silos. L'un des plus gros défis que représente la conception de fondations circulaires est le contrôle du tassement, du soulèvement et du glissement de ces fondations surtout si ces dernières reposent sur un sol granulaire meuble soumis à des charges sismiques. Une des façons de réduire ce déplacement est de construire des colonnes de pierre sous les fondations. Par conséquent, l'objectif principal de cette étude est d'examiner l'influence des colonnes de pierre sur les performances sismiques des fondations circulaires à travers une étude numérique et paramétrique. Abaqus est un logiciel utilisé pour simuler les interactions multilatérales entre la superstructure, les fondations, les strates naturelles et les colonnes de pierre. Les paramètres étudiés dans les analyses incluent la longueur, le diamètre et l'espacement entre les centres des colonnes de pierre. Le rôle de ces facteurs sur le tassement, le soulèvement et le glissement des fondations soumises à des charges sismiques est présenté et discuté. Les résultats révèlent que le fait d'augmenter la longueur des colonnes de pierre à une valeur au seuil peut réduire les tassements. En revanche, on constate que l'influence est marginale au-delà de cette valeur. Plus important encore, le diamètre et l'espacement des colonnes de pierre jouent un rôle plus crucial que leur longueur dans la réduction des déplacements provoqués par des charges sismiques. De plus, les paramètres portant sur les colonnes de pierre peuvent ne pas réduire le tassement et le soulèvement dans la même mesure.

1 INTRODUCTION

Circular foundations are usually constructed under liquid storage tanks, bridge piers, silos, as they can be used in buildings too. Seismic analysis of the bearing capacity and displacement of such foundations in conjunction with the superstructure is of primary importance in the design, especially when the complex hydrodynamic interactions between the tank and the stored liquid have to be taken into account. Another practical challenge is the inevitable construction of geostructures over wide and deep weak soil strata with insufficient bearing capacity at the natural state (Sadeghi et al. 2019). Therefore, several ground improvement proposals have been put forward to cope with this limitation (Ahmadi Hosseini et al. 2019). For example, stone columns have been widely used below foundations as an effective method, which not only increases the bearing capacity but also decreases the settlement and the liquefaction potential. Different methods have been developed based on the feeding and jetting, depending on the subsurface conditions, for the construction of stone columns (McCabe et al. 2009). Liquid storage tanks are industrial structures that can be considered as lifelines. They play an essential role in providing water storage and liquid supplies including emergency firefighting liquids. They are generally manufactured with a diameter ranging from 12 to 76 m and the height to diameter ratio of less than unity. Based on their bottom fixity configuration, they can be divided into two groups of fixed-base and free-base tanks. Large-sized storage tanks with a capacity of 20,000 m^3 are extensively used in Iran. Based on the field observations made after previous earthquakes in the USA, Japan, and Turkey, such storage tanks are highly susceptible to the seismic loading, which can cause different failure modes including excessive settlement, sliding, overturning, buckling of the steel walls, and other types of structural damages. The consequences could seriously appear in terms of an explosion, major fire, and operational malfunction of the lifelines systems, which in turn poses significant economic loss. Some examples of the seismic-induced failure of circular storage tanks adapted from the American Petroleum Institute (API) are illustrated in Figure 1 to Figure 3. For more than 30 years, there was a consensus that each stone column in the stone columns assembly behaves as an independent unit, which is not influenced by other stone columns in the group. The experimental studies of Hu et al. (1997), however, revealed that the group effects obviously affect the performance of stone column groups. For example, results clarified that the induced confining stress by stone column groups decreases the displacements of individual columns significantly, in comparison with the performance of an isolated single column. Bae et al. (2002) conducted a series of experimental tests on stone column groups constructed in Kaolin clay. Results were analyzed and compared in terms of displacement and different failure modes under static loads. Similar studies on the bearing capacity of foundations resting on the stone column groups were conducted by McCabe et al. (2009), as well as Ambily and Gandhi (2007). However, most of these studies only considered static loads, and much less attention has been given to seismic loads. Therefore, the main incentive of the present work is to investigate the seismic performance of circular foundations resting on stone column groups with particular attention to vertical and horizontal displacement characteristics. In addition, the natural unimproved soil stratum comprising of a typical medium dense sand is considered as the reference state for comparisons of the results in terms of various influencing factors.

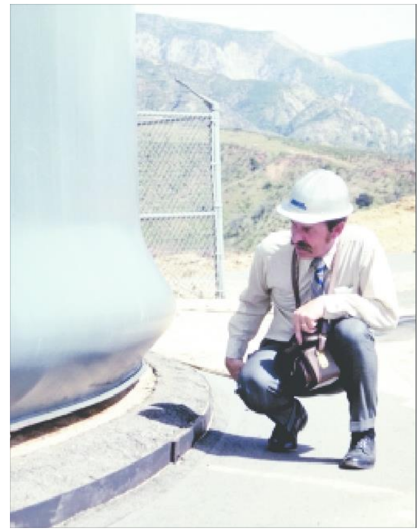

Figure 1. “Elephant’s Foot Buckling” failure mode (API 2001)

Figure 2. Overturning failure of a circular storage tank due to the lack of bearing capacity (API 2001)

Figure 3. Explosion and major fire occurred after the failure of a fuel storage tank (API 2001)

2 FAILURE EXAMPLES OF STORAGE TANKS IN PREVIOUS EARTHQUAKES

In order to highlight the practical significance of the studied subject, a series of well-documented case studies on the failure of circular storage tanks during the past earthquakes are summarized and listed accordingly (Japan Gas Association 2000).

2.1 The 1933 Long Beach earthquake

Three liquid storage tanks were subjected to failure. Two of them were constructed at a distance of 16 km, and the third one was located 48 km away from the earthquake epicenter.

2.2 The 1964 Alaska earthquake

Many storage tanks that were at a distance of 130-160 km from the epicenter of the earthquake and close to the beach were heavily damaged.

2.3 The 1971 San Fernando earthquake

In this earthquake, many storage tanks were damaged in the northern side of the fault. A water storage tank with a 30 m diameter and 7.3 m height was damaged from the top. The thickness of the wall was 24 mm, which is more than the specifications required by the design standards. As a result of the overdesigned wall thickness of the storage tank, the Elephant's foot buckling did not occur, but the connected pipelines to the tank were damaged due to their limited flexibility and large displacements.

2.4 The 1979 Imperial Valley earthquake

Four fuel tanks located close to a terminal were damaged during this earthquake. The surrounding shell and also the bottom of one of the storage tanks were damaged. In addition, three other tanks were suffered from Elephant's foot buckling. All of the tanks were filled with liquid to 70-90% of their capacity.

2.5 The 1989 Loma Prieta earthquake

There were four storage tanks that had the Elephant's foot buckling failure at a location 105 km north of the earthquake epicenter. The connecting pipes were damaged, and the liquid inside them leaked out.

2.6 The 1994 Northridge earthquake

A fire-water storage tank was extensively damaged, and bucking occurred. Moreover, the ceiling shells of some other tanks were damaged. The damage was mainly due to the uplift pressure under the foundation, which also caused breakage in the connecting pipes.

3 NUMERICAL SIMULATION

The ABAQUS recognized as a user-friendly simulation tool with distinct features was used in the present study. The software is robust in the simple generation of the model geometry, mesh, and desired boundary conditions. In addition, several versatile constitutive models available in the library can be called and assigned to different materials engaged in the problem at hand. More importantly, it has been equipped with a powerful solver that usually converges with the minimum computational efforts.

3.1 Simulation of the storage tank

In order to mimic the behavior of the storage tank as reliable as possible, it is necessary to use a practical and straightforward method to consider the influence of stored liquid inside the tank under dynamic loading. Malhotra et al. (2000) proposed a mechanical model for the flexible tanks using two masses, springs and dashpots (Figure 4). According to Malhotra et al.'s method, the liquid inside the tank is modeled using two simplified equivalent impulsive (m_i) and convective masses (m_c). It is worth mentioning that this method has been used in recent years for the analysis of storage tanks and is accepted by the Eurocode 8 standard (Raoul et al. 2012).

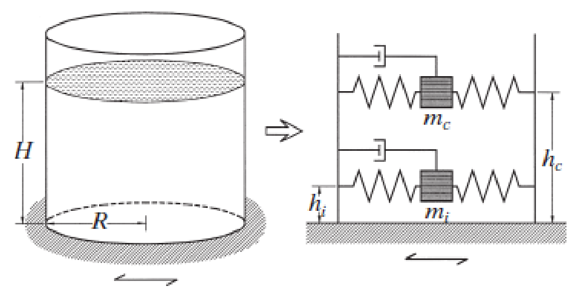

Figure 4. A mechanical model for simulating the dynamic behavior of liquid tanks (Malhotra et al. 2000)

The properties of the storage tank used in the present study are summarized in Table 1, where R is the tank's radius, H is the liquid level in the storage tank, T is the thickness of the steel plate, ρ_L is the liquid density, E is the elastic modulus of the tank, υ is the steel's Poisson's ratio, and ρ_s is the density of the tank's steel material.

Table 1. Properties of the storage tank

Parameter	value
R (m)	6
H (m)	6
T (m)	0.02
ρ_L(kg/m^3)	800
E (N/m^2)	20.67e7
υ	0.22
ρ_s (kg/m^3)	7840

3.2 Constitutive model

In numerical and analytical studies on soil-structure interactions, the reliable prediction of the overall behavior mainly depends on the adopted constitutive models. Based on this fact, the elasto-plastic Drucker-Prager constitutive model was used in the current study for simulations. Accordingly, the corresponding model parameters for the stone columns and soil are presented in Table 2.

Table 2. Material properties of soil and stone columns

Parameter	Soil	Stone columns
E (N/m^2)	7e6	2e7
υ	0.35	0.25
γ (kg/m^3)	1800	2000
ϕ (˚)	35	47
C (N/m^2)	0	0
ψ (˚)	2	4

3.3 Model geometry

The dimensions of the domain modeled are 100×100×30 m^3. The defined model geometry for the square stone column pattern is presented in Figure 5. The storage tank is placed over the stone columns and is simulated according to the simplified modeling approach proposed by Malhotra et al. (2000).

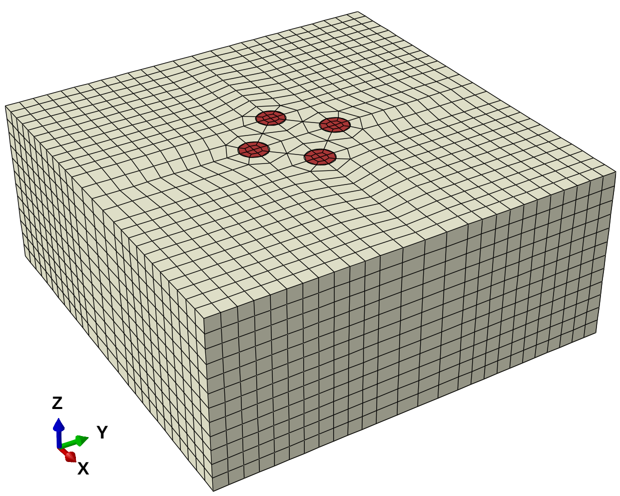

Figure 5. The geometry of the model for the square pattern of stone columns

3.4 Interface properties

Another challenging step in numerical simulation of soil-structure interactions is accurately defining the interface properties. In the present study, there are two interfaces; one at the bottom of the tank and the other one at the contact surface of stone columns and the surrounding soil. The suggested friction coefficient by the API 650 standard for the surface between the bottom of the tank and the underneath soil is 0.5; however, we used a value of 0.4, conservatively due to the importance of storage tanks. In addition, it was assumed that the contact surface between the stone columns and the tank had the same contact properties as the soil (Okpala and Jombo 2012). On the other hand, the friction coefficient between the stone columns surfaces, and the soil was 0.6. The reason for assuming a higher soil-stone column friction compared with the soil-steel friction was due to the fact that better interlocking is expected in the former compared to the latter as both materials are particulate. The coefficient of lateral earth pressure at rest (K_0) was 0.4.

3.5 Time series analysis

Considering that the primary goal of the current study was to explore the seismic performance of liquid storage tanks in the southern part of Iran, the record of the "Bam" earthquake occurred in that region in 2003 was used. The earthquake record and its Fourier transform, which shows the frequency content of the record used in the analysis are presented in Figure 6 and Figure 7, respectively. It should also be noted that in the time series analysis, the time steps were 0.01 s, as the record used had a time step of 0.01 s.

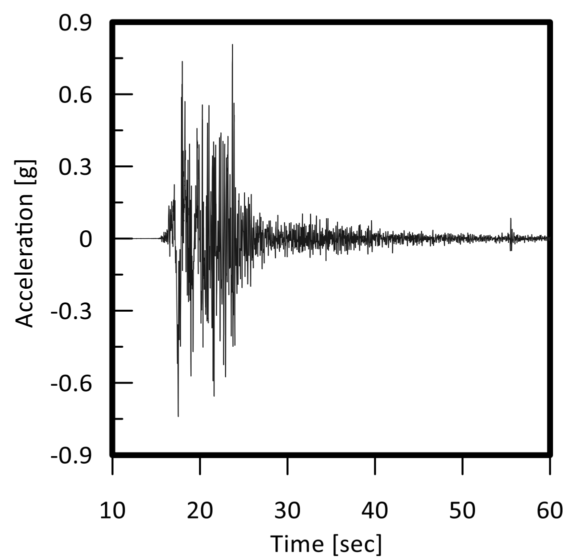

Figure 6. The Bam earthquake record

4 RESULTS

Stone columns are used as a soil improvement technique to enhance the bearing capacity and decrease the settlement of foundations. In this study, a parametric study was carried out to specifically examine the effects of diameter, length, and spacing of the stone columns on the seismic performance of circular storage tanks in terms of settlement, uplift, and slide. In the analyses, the length of stone columns was 8, 10, and 12 m, and the diameter was

0.4, 0.8, and 1.2 m. In addition, the center-to-center spacing between the stone columns for the square installation was 2 and 3 m. The results of numerical simulation are hence presented in this section for both unimproved and improved ground conditions for the sake of comparison. The results of bare ground conditions without the inclusion of stone columns are presented in Figure 8 and Figure 9.

Figure 8 and Figure 9 represent the main 20 s of the duration of the earthquake, and the maximum settlement, uplift, and slide for the bare ground were 42, 50, and 25 mm, respectively. It can also be observed that the maximum displacements were proportional to the peak ground acceleration (PGA) of the input earthquake motion and occurred almost concurrent with the PGA.

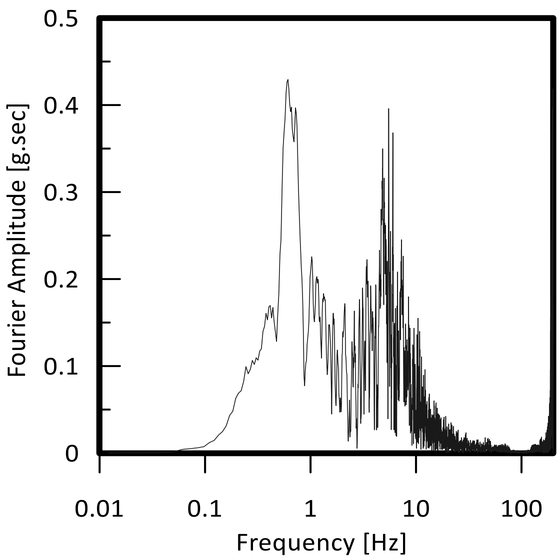

Figure 7. The Bam earthquake Fourier transform

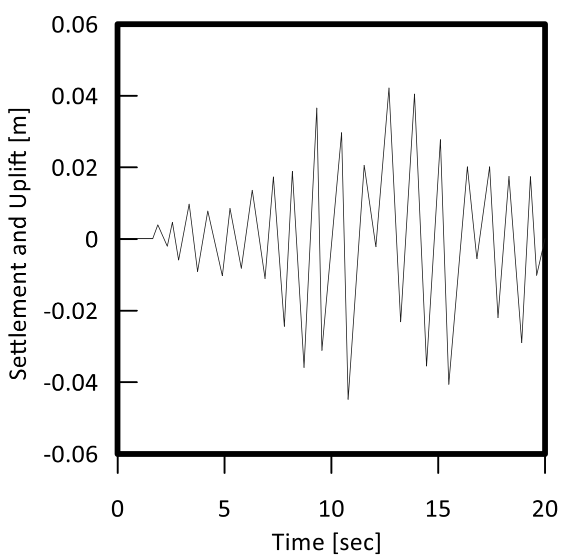

Figure 8. Settlement and uplift of the foundation on the bare ground without stone columns

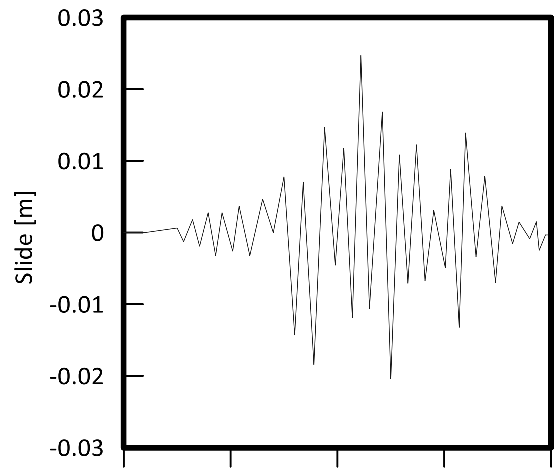

Figure 9. Foundation slide for the bare ground without stone columns

4.1 Foundation settlement and uplift in the improved ground

The results of the parametric study in terms of the maximum settlement and uplift are tabulated in Table 4. According to the results, an increase in the column spacing resulted in a rise in both settlement and uplift. For instance, when the 8-m stone columns were spaced 3 m and 2 m apart, the settlement decreased by 46% and 60% in comparison to the bare ground conditions, respectively. For the stone columns with a length of 10 m and spacings of 3 and 2 m, the settlement decreased by 48% and 62% in comparison to the ground without any stone columns, respectively. In addition, for the stone columns with a length of 12 m and spacing of 3 and 2 m, the settlement decreased for 54% and 67% in comparison to the ground without any stone columns, respectively.

The results also show that, when the diameter of the stone columns increases, the settlement decreases. Again, for the 8-m stone column, when the diameter increased from 0.4 to 0.8 m, the settlement decreases by 38%, and then when the diameter increased from 0.8 to 1.2 m, the settlement decreased by 15%. This observation implies that for diameters larger than 0.8 m, the influence of diameter on the reducing rate of the settlement became marginal. Additionally, the results revealed that by increasing the length of the stone columns, the settlement decreases; however, the rate of decrease in the settlement with elongation of the column is less pronounced than that corresponding to a change in diameter or spacing. Regarding the uplift, a decrease of 23% and 41% can be determined from the results of Table 3 for 8-m stone columns with a spacing of 3 and 2 m, respectively. The corresponding amount of decrease in uplift for the 12-m stone columns enhanced to 35% and 45%, respectively. Indeed, the influence of column length on uplift was revealed to be more significant compared with the settlement. The result of foundation settlement and uplift for the improved ground condition with stone columns with L=10 m, D=0.8 m, and S=3 m is presented in Figure 10.

Table 4. The max. settlement and uplift values at the edge of the foundation for different influencing factors

Length (m)	Diameter (m)	Spacing (m)	Max. settlement (mm)	Max. uplift (mm)
8	0.4	3	28	34
		2	21	26
	0.8	3	18	22
		2	13	17
	1.2	3	15	18
		2	11	14
10	0.4	3	27	30
		2	20	25
	0.8	3	16.5	20
		2	12	15
	1.2	3	13.5	17
		2	10	12
12	0.4	3	24	28.5
		2	17	24
	0.8	3	14	18
		2	11	14
	1.2	3	12	15
		2	9.5	12.5
Ground with no stone columns			42	50

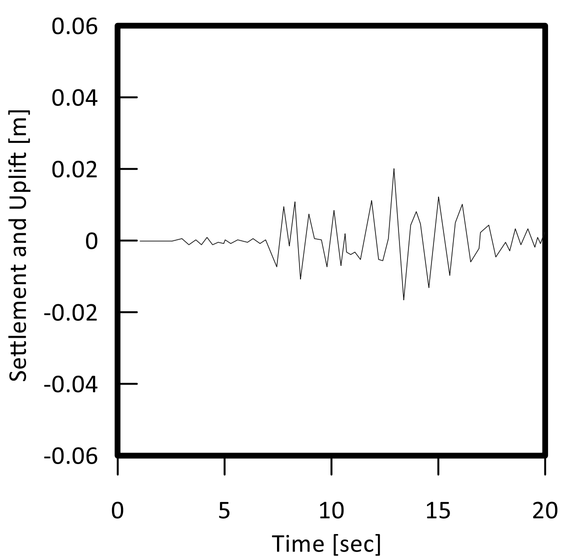

Figure 10. Foundation settlement and uplift for the improved ground with stone columns with L= 10 m, D=0.8 m, and S=3 m

4.2 Foundation slide in the improved ground

The results of the parametric study in terms of the maximum foundation slide are presented in Table 5. According to the results presented in Table 5, an increase in the length and diameter of stone columns showed a positive influence on the foundation slide. In other words, the foundation slide declines due to a rise in column length or diameter. Similarly, the closer spacing of the stone columns resulted in a further reduction of the slide. For instance, for 8-m stone columns spaced 3 and 2 m apart, the slide decreased by 32% and 52% compared with the results of bare ground, respectively. For the stone columns with a length of 10 m and spacings of 3 and 2 m, the corresponding reductions were 56% and 72%, respectively. Finally, the longest stone columns considered in this study, resulted in a reduction in the slide as much as 70% and 80% when spaced 3 and 2 m apart, respectively. As it is observed, when the spacing decreases, the slide decreases, which is because of the enhanced confinement induced by the closer spacing of the stone columns. An increase in the length of the stone columns also decreases the slide of the foundations due to the greater fixity of the stone column's end at the bottom of the model.

Of particular interest was the influence of stone column diameter on foundation slide. The results of the parametric study confirmed that the effect of diameter was much more significant on the foundation slide than the foundation settlement and uplift, which can be due to the fact that the increased lateral stiffening due to the presence of the stone columns is more considerable than the vertical stiffening. Following a hierarchical categorization of the influencing parameters, the effect of diameter is more significant on foundation settlement than the foundation uplift. This is mainly because of the connection type defined at the surface of the bottom of the circular foundation and the stone columns, which is only frictional and can only transfer compressional and shear stresses and is not able to transfer the tensile stresses between the body of the tank to the stone columns; if one defines an anchored connection between the bottom of the tanks and the stone columns below it, the uplift behavior will undoubtedly be different.

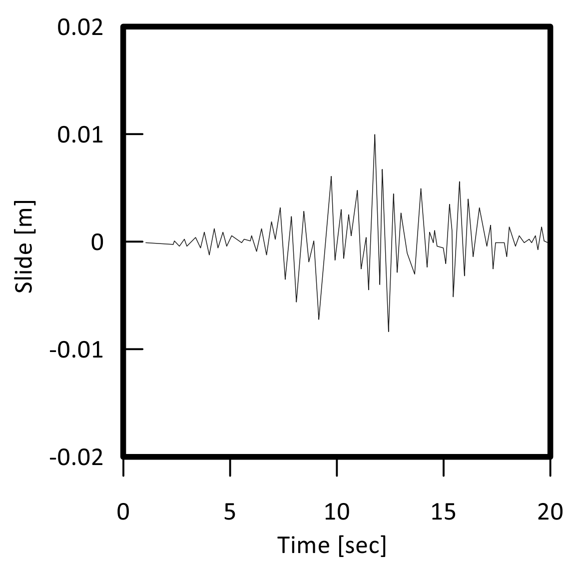

Figure 11. Foundation slide for the improved ground with stone columns with L= 10 m, D=0.8 m, and S=3 m

The result of the foundation slide for the improved ground condition with stone columns with L=10 m, D=0.8 m, and S=3 m is presented in Figure 11. This figure shows that the foundation slide decreases significantly in comparison to the bare ground condition.

Table 5. The max. slide for the edge of the tanks with different stone column variables

Length (m)	Diameter (m)	Spacing (m)	Max. slide (mm)
8	0.4	3	17
		2	12
	0.8	3	13
		2	9
	1.2	3	9
		2	4
10	0.4	3	11
		2	7
	0.8	3	9
		2	6
	1.2	3	5
		2	3
12	0.4	3	7.5
		2	5
	0.8	3	6.5
		2	4
	1.2	3	4
		2	2.5
Ground with no stone columns			25

5 DISCUSSION

As expected, the results of the numerical study confirmed that settlement and uplift decrease significantly when the stone column ground improvement method is used, in comparison to the bare ground conditions of the parametric study is presented in Figure 12.

Increasing the stone column diameter from 0.4 to 0.8 m decreases the foundation settlement and uplift significantly. The settlement and uplift also decrease when the diameter increases from 0.8 to 1.2 m; however, the amount of decrease is not that significant. Therefore, increasing the diameter from 0.8 to 1.2 m may not have economic justification.

Another critical point is that when the stone columns' spacing increases from 2 to 3 m, the amount of settlement and uplift increase significantly. This means that the most suitable spacing between the stone columns in the square construction pattern is less than 2 m. This can be because of the enhanced confinement effect in the stone column groups when they are closer to each other, and the stress zone around them overlap.

When the length of the stone columns increased from 8 to 12 m in two equal intervals, the settlement and uplift decreased significantly; this might be explained by the improvement caused by the stone columns in the deeper soil layers. Based on the results of the parametric study, a new critical length for stone columns was defined as the length beyond which marginal changes in the bearing capacity and settlement occurred. Results revealed that the critical depth varied in the range of 6 to 9 times the diameter of the stone column.

The diameter and spacing of the stone columns have more significant effects in comparison to the effects of the length on the displacements. This point becomes more critical, especially when the length of the stone columns reaches the critical length, which is the length that overpassing it would have negligible effects on decreasing the displacements.

Moreover, the spacing of stone columns has a vital role in the settlement and uplift of the storage tanks, as the spacing of the stone columns could affect the failure mode of the stone columns from a single stone column failure to group failure. The results of the parametric study show that the most suitable center to center spacing for the stone columns is 2.5 times the diameter of the stone columns.

More importantly, the effect of diameter was found more significant on the foundation settlement than the foundation uplift, which is mainly because of the frictional connection type at the surface of the bottom of the circular foundation and the stone columns which is not an anchored connection and does not have tensile resistance. In the analyses for the foundation slide, the stone columns' diameter and length decrease the slide. This is mainly due to the presence of the developed surface that the passive stresses behind the stone columns are applied over them when the diameter and length increases.

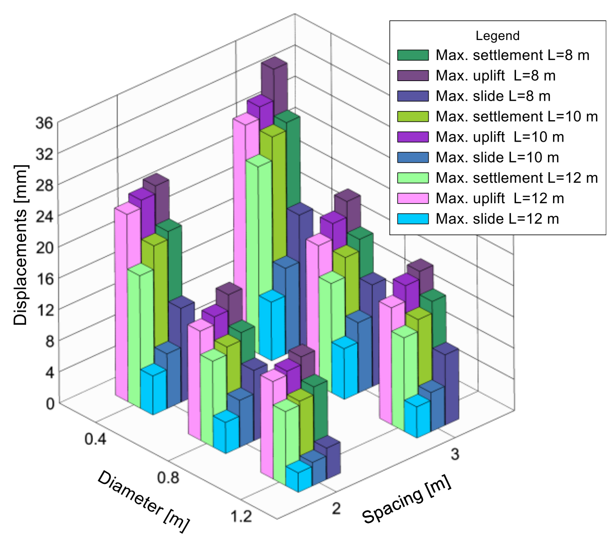

Figure 12. Summary of the parametric study

6 CONCLUSIONS

A numerical parametric study was conducted to explore the effects of the stone columns' diameter, length, and spacing on the settlement, uplift, and slide of circular foundations that are generally used for liquid storage tanks. Base on the results of numerical simulations, the followings principal conclusions can be drawn:

1. Increasing the stone columns' spacing increases the foundation settlement, uplift, and slide. This is mainly due to the enhanced confinement induced by the group effects of stone columns, which is only effective up to a threshold spacing.
2. Increasing the length and diameter of the stone columns decreases the settlement and uplift; however, the effect of increasing the diameter of the stone columns is more pronounced than the effect of increasing the length.
3. Increasing the diameter of the stone columns from 0.4 to 0.8 m decreases the settlement and uplift. Furthermore, increasing the diameter from 0.8 to 1.2 decreases the settlement at a slower rate, which is not economically justifiable.
4. Increasing the diameter of the stone columns has a more significant effect on the foundation slide than on the settlement.
5. Stone columns do not affect the reduction in settlement and uplift to the same extent. The reason is mainly because of the connection type used between the foundation and the stone columns, which is frictional and cannot transfer tensile stresses.

7 REFERENCES

(API), API. 2001. Welded Steel Tanks for Oil Storage, API Standard 650. American Petroleum Institute, (November 2001).

Ahmadi Hosseini, S.A., Mojtahedi, S.F.F., and Sadeghi, H. 2019. Optimisation of deep mixing technique by artificial neural network based on laboratory and field experiments. Georisk, 14(2): 142–157. doi:10.1080/17499518.2019.1612526.

Ambily, A.P., and Gandhi, S.R. 2007. Behavior of stone columns based on experimental and FEM analysis. Journal of Geotechnical and Geoenvironmental Engineering, 133(4): 405–415. doi:10.1061/(ASCE)1090-0241(2007)133:4(405).

Bae, W.-S., Shin, B.-W., An, B.-C., Kim, J.-S., and others. 2002. Behaviors of foundation system improved with stone columns. *In* The Twelfth International Offshore and Polar Engineering Conference.

Hu, W., Wood, DM, and Stewart, W.M. 1997. Ground improvement using stone column foundations. *In* International Conference on ground Improvement Techniques. pp. 247–256.

Japan Gas Association. 2000. Recommended practice for earthquake resistant design of gas pipeline. May.

Malhotra, P.K., Wenk, T., and Wieland, M. 2000. Simple procedure for seismic analysis of liquid-storage tanks. Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE), 10(3): 197–201. doi:10.2749/101686600780481509.

McCabe, B.A., Nimmons, G.J., and Egan, D. 2009. A review of field performance of stone columns in soft soils. Proceedings of the Institution of Civil Engineers: Geotechnical Engineering, 162(6): 323–334. doi:10.1680/geng.2009.162.6.323.

Okpala, A.N., and Jombo, P.P. 2012. Design of Diesel Storage Tank in Consonance with Requirements of American Petroleum Institute (API) Standard 650. Industrial Engineering Letters, ISSN,: 224–6096.

Raoul, J., Sedlacek, G., Tsionis, G., Raoul, J., Sedlacek, G., and Tsionis, G. 2012. Eurocode 8 : Seismic Design of Buildings Worked examples. doi:10.2788/91658.

Sadeghi, H., Kiani, M., Sadeghi, M., and Jafarzadeh, F. 2019. Geotechnical characterization and collapsibility of a natural dispersive loess. Engineering geology, 250: 89–100. Elsevier.