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Bearing capacity assessment of a shallow foundation under cyclic inclined load in a liquefiable soil: A case study.

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ABSTRACT: The bearing capacity of granular soils under dynamic loads is usually studied and associated with the phenomenon of liquefaction, during which the soil undergoes a transformation from a solid state to a viscous fluid. At this stage, effective stress within the soil mass becomes null due to an increase in pore pressure. In contrast, when full liquefaction is not reached, the bearing capacity of a foundation under dynamic loading is typically assessed using pseudo-static solutions. Nevertheless, the pore pressure generated when a cyclic load is applied plays a significant role in the bearing capacity of shallow foundations, even when the liquefaction state is not reached. In this research, a case study is presented to assess the bearing capacity of a shallow foundation on sandy soil under a cyclic inclined load. The soil used in this research is Ottawa sand, a naturally rounded well-graded natural silica sand. Cyclic direct simple shear tests were performed in this soil obtaining the geotechnical parameters of the soil and a correlation between pore water pressure generated and cyclic shear stress. The bearing capacity assessment has been done using FLAC2D finite difference software. The procedure followed implies the application of a static vertical load defined as a fraction of the ultimate static load. Afterwards, a cyclic inclined load is applied, calculating the pore-water pressure generated within the soil mass using an empirical formula based on shear and effective stresses. Finally, it is verified that the cyclic inclined load, together with the static vertical load, represents the ultimate bearing pressure of the foundation. The results obtained show a significant reduction in the bearing capacity of the foundation when the pore-water pressure generated is considered, highlighting the importance of considering this pressure in the assessment of the bearing capacity.

KEYWORDS: Cyclic loading, finite difference method, pore pressure generation, bearing capacity.

1 INTRODUCTION

Two different independent approaches are usually employed when assessing the bearing capacity of granular soils under dynamic loads. The first is to estimate the probability of the liquefaction phenomenon occurring, during which soil becomes a viscous fluid. If the liquefaction state is not reached, the second approach employed implies using a pseudo-static analysis to estimate the bearing capacity of foundations. The first analysis using this approach is attributed to Meyerhof GG (1951; 1953). Nowadays, this pseudo-static approach is commonly used with different calculation methods. For example, Jadar and Ghosh (2017) used a pseudo-static method to determine the seismic bearing capacity of shallow strip footing using the horizontal slice method. Izadi et al. (2019) analyzed the pseudo-static bearing capacity of shallow foundations on heterogeneous marine deposits using the limit equilibrium method. And Beygi et al. (2022) used a pseudo-static horizontal earthquake coefficient for finite element limit analysis of the seismic bearing capacity of strip footing adjacent to excavations. In this pseudo-static approach, the pore pressure generated due to cyclic load when liquefaction is not reached is neglected.

In liquefaction analyses, the characterization of excess pore water pressure is of significant importance. Therefore, research is currently underway to better understand this phenomenon. Do et al. (2023) studied excess pore water pressure generation in fine granular materials under undrained cyclic triaxial loading, observing that pore pressure exhibited a slight increase at low Cyclic Stress Ratio (CSR) values, but a sharp increase for higher CSR values. Wei et al. (2024) developed pore water pressure models based on different fines contents, packing densities, confining pressures, and loading amplitudes. Most of this research is primarily focused on pore pressure generation for liquefaction analysis. Nevertheless, the pore pressure generated by cyclic loading can play a significant role in the bearing capacity of shallow foundations, even when the liquefaction state is not fully reached.

In this work, the effect of liquefaction induced by applied structural loads on the dynamic bearing capacity of sandy soil is studied. The first step was to analyze the results of cyclic shear tests on Ottawa sand samples. Based on these results, a relationship between the shear stresses developed in the tests and the generated pore water pressure was obtained. This pore pressure generation model was implemented in the FLAC2D software (Itasca, 2000). Finally, the maximum cyclic load for several load inclinations was calculated, highlighting the importance of considering the pore pressure generated under cyclic loading in the bearing capacity of shallow foundations.

2 TESTS DESCRIPTION

2.1 *Soil used*

The soil used in the present research is standard Ottawa silica sand with subrounded shape grains. The main characteristics of this sand are summarized in Table 1.

Table 1. Main characteristics of Ottawa sand.

Parameter	Value
D_{10} (diameter at 10% finer)	0.139 mm
D_{30} (diameter at 50% finer)	0.177 mm
D_{60} (diameter at 60% finer)	0.234 mm
G_s (specific gravity)	2.65
e_{max} (maximum void ratio)	0.76
e_{min} (minimum void ratio)	0.52

2.2 *Cyclic simple shear*

Tests were performed using a simple cyclic shear apparatus. This equipment allows tests to be carried out under constant volume conditions (undrained) and constant axial load conditions (drained). Constant volume cyclic simple shear tests are equivalent to undrained tests, where a change in the applied vertical stress is equivalent to a change in pore water pressure within the sample if drainage had been prevented by maintaining a constant vertical pressure (Bjerrum and Landva, 1966; Dyvik et al., 1987). In this situation, the change in pore water pressure is equal to the change required in the effective normal stress to maintain constant volume. A total of 12 cyclic simple shear tests were performed to obtain data for assessing a model of pore water pressure generation under cyclic loading. Table 2 shows the initial conditions of the cyclic simple shear tests performed. The amplitude of shear stress is defined as a percentage of the confining vertical stress with the Cyclic Stress Ratio (CSR). Tests were performed until the pore water pressure equals the initial vertical confining stress.

Table 2. Initial conditions of the cyclic simple shear tests.

Test number	Initial effective stress σ'_{v0} (kPa)	Initial void ratio (e_0)	Cyclic Stress Ratio (CSR)
1	40	0.60	0.12
2	40	0.60	0.13
3	40	0.60	0.14
4	40	0.60	0.15
5	40	0.60	0.16
6	40	0.60	0.17
7	100	0.59	0.11
8	100	0.59	0.12
9	100	0.59	0.13
10	100	0.59	0.14
11	100	0.59	0.15
12	100	0.59	0.16

Figure 1a shows the relationship between shear strain and shear stress for test number 1, while Figure 1b between the axial stress and the shear stress for the same test.

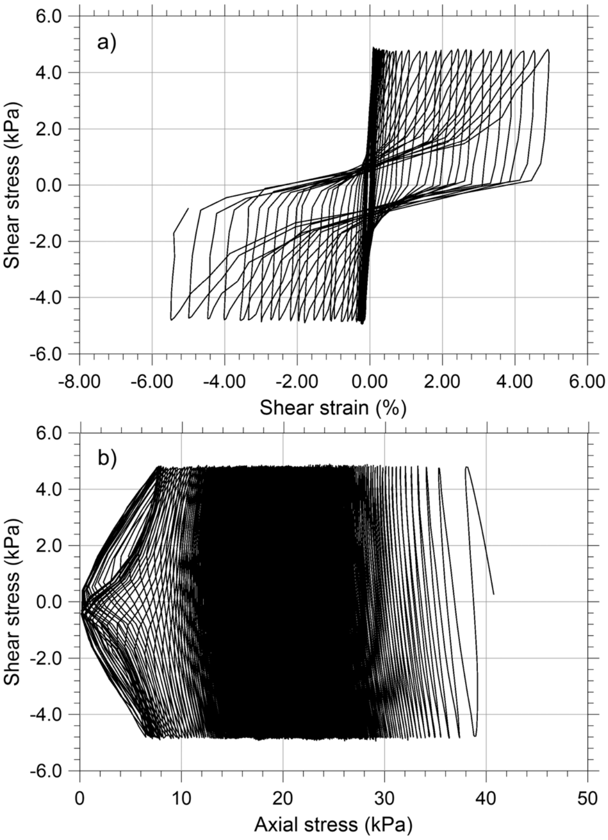

Figure 1. Cyclic shear test results for test number 1.

3 SOIL FAILURE POINT DEFINITION AND MOHR-COULOMB ENVELOPE

From the cyclic simple shear test results, it can be seen that the shear strain remains approximately constant as the number of cycles increases, up to a certain point where it sharply rises, reaching the liquefaction state with a small additional increase in the number of cycles. Figure 2 shows the relationship between shear strain (in percentage) and the ratio of excess pore pressure to the initial vertical effective stress (r_u), plotted against the number of cycles for test number 1. In this research, the onset of sudden failure is defined as the point at which shear strain sharply increases with the number of cycles. For test 1, this definition of failure corresponds to 345 cycles, marked by the intersection of the two red lines in Figure 2a. The corresponding r_u value can then be obtained for this number of cycles (Figure 2b). Shear stress and vertical effective stress at failure were obtained for all the tests according to the previous definition of failure point. The angle of internal friction of the Mohr-Coulomb envelope was determined as the slope of the best-fit line through all pairs of shear stress and vertical effective stress. An internal friction angle of 25° was obtained as the slope of the failure envelope from the 12 tests performed.

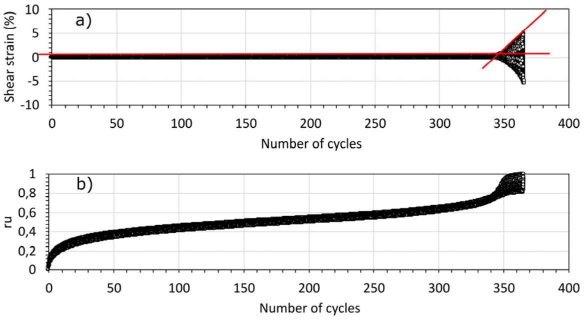

Figure 2. Test number 1. a) Shear strain (%) vs. number of cycles. b) the ratio of excess pore pressure to the initial effective vertical stress (r_u) vs. the number of cycles.

4 PORE WATER PRESSURE GENERATION

A pore water pressure analysis was conducted considering the relationship between r_u and CSR for 5, 10 and 15 cycles. This relationship between the normalized pore water pressure and the normalized cyclic shear stress is shown in Figure 3. Cyclic shear stress increases from a null value, corresponding to the static case, to 0.17. The lowest cyclic shear stress generates the lowest pore water pressures, obtaining pore water pressures close to 1.00 for the highest cyclic shear stresses. These values close to 1 are commonly observed in cyclic shear tests in sands.

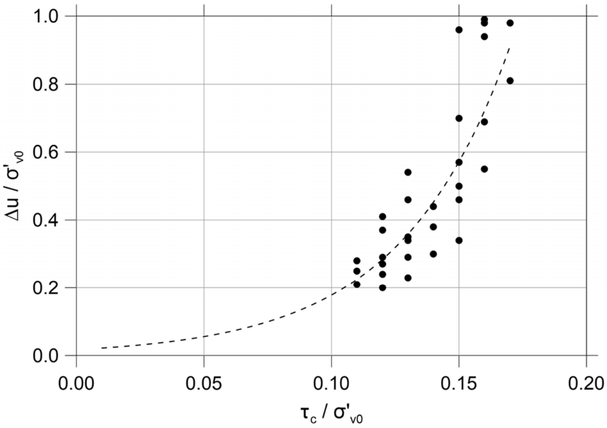

Figure 3. Relationship between normalized pore water pressure and the normalized cyclic shear stress for 5, 10 and 15 cycles.

Equation (1) shows the correlation between pore water pressure and cyclic shear stress for the fit line shown in Figure 3.

$$\frac{\Delta u}{\sigma'_{v0}} = \beta_0 \cdot e^{\beta_1 \cdot \frac{\tau_c}{\sigma'_{v0}}} \tag{1}$$

Where:

Δu	Pore water pressure generation
σ'_{v0}	Initial effective vertical stress
τ_c	Cyclic shear stress
β_0, β_1	Empirical constants

The best correlation was found for $\beta_0 = 0.0173$ and $\beta_1 = 23.313$, with an R-squared value of 71%.

5 NUMERICAL METHODOLOGY

In this research, the bearing capacity of a foundation is determined by considering the pore pressure generated within the soil mass due to cyclic shear stresses induced by a cyclic load. This load is considered cyclic for its effects on pore pressure, implemented using Equation (1). The foundation is under a permanent load, defined as a fraction of the static bearing capacity, followed by the application of a cyclic load, which generates an increase in the vertical and shear stresses within the soil body. The pore water pressure increases directly due to the vertical stress increase produced by the cyclic load in an undrained situation and due to the shear stress increase, as defined by Equation (1). Under these conditions, the cyclic load that causes collapse is determined for different cyclic load inclinations.

The software FLAC2D was used for calculations. This software is a finite difference computational program that includes a programming option called FISH, which allows users to control the analysis process. The pore water pressure was specified within the model before running the foundation bearing capacity analysis and calculated according to Equation (1). Calculations were performed using a plane strain analysis. The Mohr-Coulomb criterion was considered with a dilation angle of zero.

The model dimensions used in this research were a depth equal to 12 times the width of the foundation, and a horizontal distance that avoids border effects on the model. The foundation was located on the left side of the model, as load inclination was set toward the right side. A mesh size of 0.5 m was used in the model. These parameters were based on previous studies (Panique Lazcano, Galindo Aires and Patiño Nieto, 2020; 2022) and validated for the calculations performed.

The calculation process used in this research follows the 6 stages defined for the assessment of the bearing capacity of shallow foundations under cyclic load on cohesive soil (Panique Lazcano, Galindo Aires and Patiño Nieto, 2020). These 6 stages can be summarized as follows: 1) Grid generation, soil and water properties definition, boundary conditions and self-weight assessment. 2) Permanent load applied on the footing and effective load outside the foundation. 3) Application of the cyclical load on the footing with an inclination angle from 0º (vertical load) to 90º (horizontal load). 4) Pore water pressure generation. 5) Equilibrium state between soil stress and pore water pressure to obtain the effective vertical stresses. 6) Bearing capacity calculation applying a downward velocity to the footing nodes. When the bearing capacity in this stage equals zero, the bearing capacity of the foundation is equal to the cyclical load applied in Stage 3. This procedure implies an iterative process until the bearing capacity is obtained. During this process, the Mohr-Coulomb failure criterion must be satisfied to consider the calculations valid.

The investigation conducted does not reproduce the intermediate steps of pore-water pressure increase during each load cycle, only the last step once the critical state has been reached.

6 APPLICATION EXAMPLE

The proposed methodology has been applied to an example to evaluate the influence of load inclination on the dynamic bearing capacity of a foundation. A foundation with a width of 6.0 m and an embedment depth of 1 m was considered, corresponding to a 20 kPa effective load on the surrounding soil. The first step was to determine the static bearing capacity for this foundation on sandy soil with a saturated unit weight of 20 kN/m^3 (estimated from physical properties and testing conditions in Tables 1 and 2, respectively), an internal friction angle of 25º, and zero cohesion. The static bearing capacity obtained for this soil without pore water pressure was 730.3 kPa. Then, a permanent load equal to 20% of the static bearing capacity was applied in Stage 2, and the cyclic bearing capacity of the foundation was determined for cyclic load inclinations of 0º (vertical), 5º, 10º, 15º, 30º, 45º, 60º, 75º, and 90º (horizontal).

As an example, the results for a 30º cyclic load inclination are presented. Figure 4 shows the shear stress beneath the foundation after applying a 30º cyclic load that causes the foundation to collapse. The resulting pore water pressure generation due to this cyclic load is shown in Figure 5.

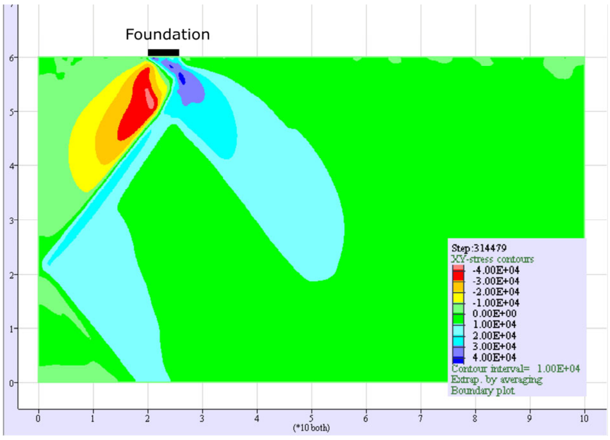

Figure 4. Shear stress beneath the foundation for a cyclic load inclination of 30º.

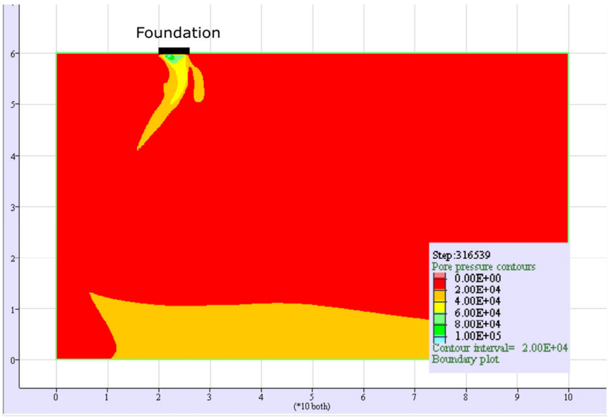

Figure 5. Generation of pore water pressure for a cyclic load inclination of 30º.

As was previously stated, the Mohr-Coulomb failure criterion must be satisfied during the process to consider the calculation as valid. The Mohr-Coulomb failure envelope for a cyclic load inclination of 30º is shown in Figure 6.

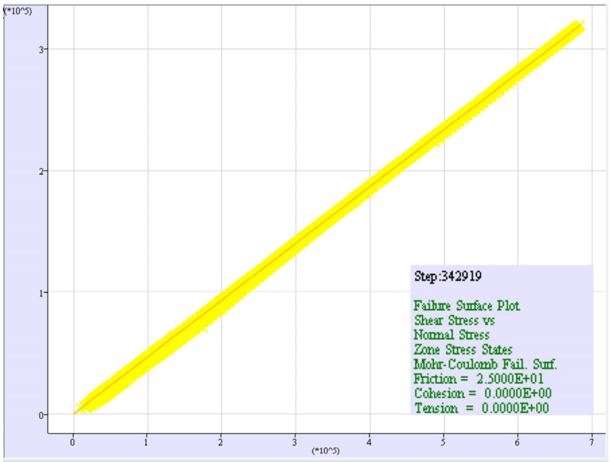

Figure 6. Mohr-Coulomb failure envelope for a cyclic load inclination of 45º.

The magnitude of the cyclic load that produces the collapse of the foundation, depending on its inclination, is shown in Figure 7. A main conclusion that can be drawn from this figure is that the bearing capacity of the foundation sharply decreases when considering the pore water pressure generated due to the cyclic loading. The vertical cyclic load that causes the collapse of the foundation is 66.0 kPa. When added to the 135.0 kPa permanent load, this means the foundation collapses under a total vertical load of 201.0 kPa, only 28% of the static bearing capacity when no pore pressure is generated.

Figure 7 also highlights the importance of the cyclic load inclination angle. The cyclic load that produces the collapse of the foundation when the load is inclined 15º is 80% of the vertical cyclic load that produces the collapse, decreasing up to 43% and 38% when the cyclic load inclination is 45º, and 75º, respectively.

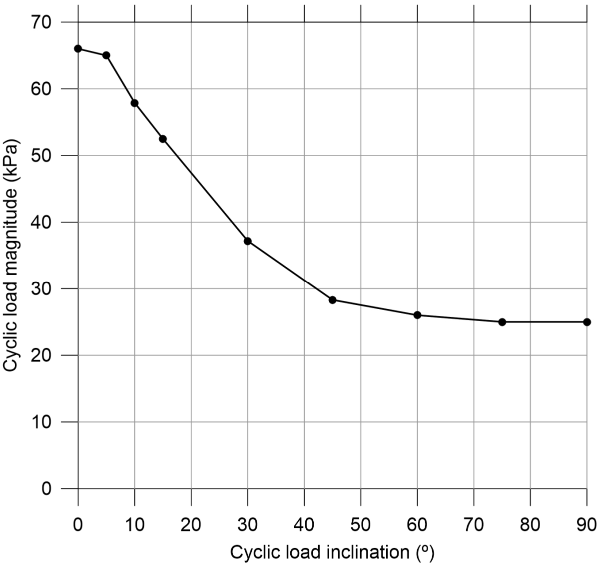

Figure 7. Cyclic load magnitude causing foundation collapse as a function of cyclic load inclination.

7 CONCLUSIONS

The influence of pore water pressure generation on the bearing capacity of a shallow foundation in a sandy soil has been evaluated. First, an equation relating the shear stresses induced by cyclic loading to pore water pressure generation was obtained from cyclic simple shear tests conducted in the laboratory. This equation was implemented in FLAC2D software to assess the influence of pore water pressure generation through an application example estimating the bearing capacity of a shallow foundation.

The results show that the bearing capacity of the foundation clearly decreases when pore water pressure generated by cyclic loading is considered, even under vertical loads. Regarding the effect of cyclic load inclination, it was observed that the cyclic load required to cause foundation collapse decreases with the inclination angle by up to approximately 60%. Beyond this angle, the cyclic load required to induce collapse does not change significantly.

Finally, the soil's initial void ratio was not considered in this research when obtaining the correlation between pore water pressure and cyclic shear stress. Nevertheless, the initial void ratio is expected to play an important role in the equation relating to both parameters. This should be addressed in future research.

8 REFERENCES

Beygi, M., Keshavarz, A., Abbaspour, M., Vali, R., Saberian, M. and Li, J., 2022. Finite element limit analysis of the seismic bearing capacity of strip footing adjacent to excavation in c-φ soil. Geomechanics and Geoengineering, [online] 17(1), pp.246–259. https://doi.org/10.1080/17486025.2020.1728396.

Bjerrum, L. and Landva, A., 1966. Direct Simple-Shear Tests on a Norwegian Quick Clay. Géotechnique, [online] 16(1), pp.1–20. https://doi.org/10.1680/GEOT.1966.16.1.1.

Do, T.M., Laue, J., Mattsson, H. and Jia, Q., 2023. Excess pore water pressure generation in fine granular materials under undrained cyclic triaxial loading. International Journal of Geo-Engineering, [online] 14(1), pp.1–17. https://doi.org/10.1186/S40703-023-00185-Y/FIGURES/10.

Dyvik, R., Berre, T., Lacasse, S. and Raadim, B., 1987. Comparison of truly undrained and constant volume direct simple shear tests. Géotechnique, [online] 37(1), pp.3–10. https://doi.org/10.1680/GEOT.1987.37.1.3.

Itasca Consulting Group Inc, 2000. FLAC, Fast Lagrangian analysis of continua.

Izadi, A., Nazemi Sabet Soumehsaraei, M., Jamshidi Chenari, R. and Ghorbani, A., 2019. Pseudo-static bearing capacity of shallow foundations on heterogeneous marine deposits using limit equilibrium method. Marine Georesources and Geotechnology, [online] 37(10), pp.1163–1174. https://doi.org/10.1080/1064119X.2018.1539535;PAGE:STRING:ARTICLE/CHAPTER.

Jadar, C.M. and Ghosh, S., 2017. Seismic bearing capacity of shallow strip footing using horizontal slice method. International Journal of Geotechnical Engineering, [online] 11(1), pp.38–50. https://doi.org/10.1080/19386362.2016.1183074;PAGE:STRING:ARTICLE/CHAPTER.

Meyerhof GG, 1951. The ultimate bearing capacity of foundations. Geotechnique, 2(4), pp.301–332.

Meyerhof GG, 1953. The bearing capacity of foundations under eccentric and inclined loads. In: Proceedings of the 3rd international conference on soil mechanics and foundation engineering. pp.440–445.

Panique Lazcano, D.R., Galindo Aires, R. and Patiño Nieto, H., 2020. Bearing capacity of shallow foundation under cyclic load on cohesive soil. Computers and Geotechnics, [online] 123, p.103556. https://doi.org/10.1016/J.COMPGEO.2020.103556.

Panique Lazcano, D.R., Galindo Aires, R. and Patiño Nieto, H., 2022. Long-term dynamic bearing capacity of shallow foundations on a contractive cohesive soil. Acta Geotechnica, [online] 17(5), pp.1897–1915. https://doi.org/10.1007/S11440-021-01317-3/TABLES/6.

Wei, X., Zhuang Ii), Y., Yang Iii), J. and Zhang, L., 2024. Excess pore pressure generation in silty sands subjected to cyclic triaxial loading. Japanese Geotechnical Society Special Publication, [online] 10(17), pp.552–557. https://doi.org/10.3208/JGSSP.V10.OS-6-01.