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Evaluation of the liquefaction resistance of sandy soil for shaking table tests

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ABSTRACT

Seismic liquefaction of loose saturated cohesionless soils is one of the most dangerous and catastrophic phenomena that involves a temporary loss of soil shear strength and stiffness as a consequence of increase pore pressure and reduced effective stress. Therefore, the evaluation of the excess pore pressure induced by shaking is important to predict the liquefaction behaviour of soils at a large scale. In this regard, the study provides the static and dynamic characterisation of a liquefiable sand. For this purpose, a laboratory testing programme, which included the execution of cyclic direct simple shear (CDSS) tests, was performed. The CDSS tests were carried out by means of the CDSS device at the Soil Dynamics and Geotechnical Engineering Laboratory of the University "Kore" of Enna (Italy). The device is designed to allow the soil specimen to be consolidated one-dimensionally and then sheared under constant volume conditions, which replicates the undrained shear condition of the soil specimen. The CDSS tests were conducted to evaluate the liquefaction resistance of the sand under several test conditions, i.e. initial relative density, vertical effective stress or cyclic stress ratios. Results of this study provide useful information for the geotechnical characterisation of the liquefiable sand to be used in shaking table tests at the Laboratory of Earthquake Engineering and Dynamic Analysis (L.E.D.A.) of the University "Kore" of Enna. The laboratory is equipped with a large biaxial laminar shear box for reduced-scale model tests developed to monitor liquefaction under two-dimensional shaking.

Keywords: liquefaction; cyclic direct simple shear tests; sandy soil.

1. Introduction

The destructive impacts of earthquake-induced soil liquefaction were observed during large seismic events, such as the 1964 Niigata earthquake (Japan), the 1989 Loma Prieta earthquake (California), the 1990 Luzon earthquake (Philippines), the 1995 Kobe earthquake (Japan), the 1999 Chi-Chi earthquake (Taiwan), the 1999 Kocaeli earthquake (Turkey), the 2011 Christchurch earthquake (New Zealand), the 2011 Tohoku earthquake (Japan) and the 2018 Indonesia earthquake (Forcellini 2020; Chakraborty and Sawant 2024). Seismic liquefaction phenomena were also reported by historical sources after the 1693 and 1818 strong earthquakes in South-Eastern Sicily (Italy) (Cavallaro, Grasso and Sammito 2022; Grasso, Massimino, and Sammito 2021; Grasso and Sammito 2022).

Advanced tests to evaluate the liquefaction behavior of soils in laboratory involve cyclic triaxial (CTx) and cyclic direct simple shear (CDSS) tests (e.g. Castelli et al. 2019; Lentini and Castelli 2019; Viana da Fonseca, Soares, and Fourie 2015). Viana da Fonseca, Molina-Gómez, and Ferreira (2023) performed several CTx and CDSS tests under different test conditions to derive the liquefaction resistance of a sand, called TP sand, collected from the 'Terreiro do Paço' in Lisbon (Portugal). This natural sand experienced liquefaction during the 1755 Lisbon earthquake. Viana da Fonseca, Soares, and Fourie (2015) carried out CDSS tests on two sands collected from Ain Beniam (Algeria) and Coimbra (Portugal) to study the influence of the confining stress level on the Cyclic Resistance Ratio (CRR) with principal stress rotation.

An extensively examined sand is the Hostun 31 (HN31) sand. It is a clean quartz sand characterized by uniform subangular grains. Yazan and Madabhushi (2023) performed dynamic centrifuge tests at the Schofield centre (University of Cambridge) using the HN31 sand to understand the backfill-abutment interaction under cyclic loading. Zhu et al. (2021) performed undrained cyclic triaxial tests using the HN31 sand to investigate the impact of loading waveforms on the cyclic liquefaction resistance. Kassas (2021) conducted series of element tests to fully characterize the Hostun HN31 sand. In particular, CDSS tests were performed to determine cyclic stress resistance.

Nong, Park and Lee (2021) compared the CTx liquefaction resistances with those obtained under CSS conditions using the Nakdong River sand. As stated by Cappelaro et al. (2021), that conducted CDSS tests on Christchurch soils, CDSS tests are advantageous compared to CTx tests given their capacity to more realistically reproduce earthquake-induced cyclic loading under free field conditions.

In this study, CDSS tests were performed to derive the liquefaction resistance of a liquefiable sand to be used in shaking table tests at the Laboratory of

Earthquake Engineering and Dynamic Analysis (L.E.D.A.) of the University of Enna "Kore" (Sicily, Italy). In this regard, Grasso, Lentini and Sammito (2022) designed a new laminar shear box at L.E.D.A. (Fig. 1) based on the large flexible laminar shear box developed by Ueng et al. (2006) to investigate the liquefaction phenomenon. The laminar box was designed for biaxial shaking on a 6-DOF large shaking table (Navarra et al. 2015). The box is rectangular in cross section and consists of 16 layers for a total height of 1600 mm. Each layer is composed of two frames with internal dimension of 2570 mm by 2310 mm for the inner frame and 2744 mm by 2770 mm for the outer frame (Fig. 2).

CDSS tests will be used to extract parameters for advanced constitutive models developed to simulate the liquefaction phenomenon, such as the UBC3D-PLM model and the PM4Sand model implemented in the finite element code PLAXIS and in the finite difference code FLAC. The calibrated models will be validated against shaking table tests that will be conducted at L.E.D.A. of the University "Kore" of Enna using the liquefiable sand investigated in this study.

Figure 1. Laminar shear box at L.E.D.A. of the University of Enna "Kore".

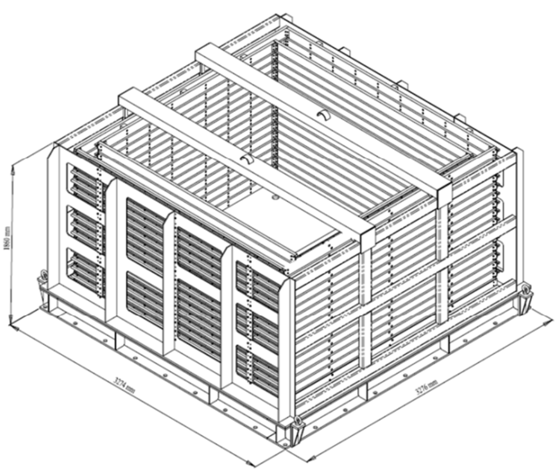


Figure 2. The isometric view of the laminar shear box.

2. Physical properties

Physical properties of the sand under consideration are described in this Section. The grain size distribution (GSD), obtained according to the sieve method ASTM6913, is reported in Fig. 3. Moreover, the comparison between the GSD and the boundaries proposed by Tsuchida (1970) to estimate the liquefaction susceptibility is also shown. It is possible to observe that the sand is highly susceptible to liquefaction.

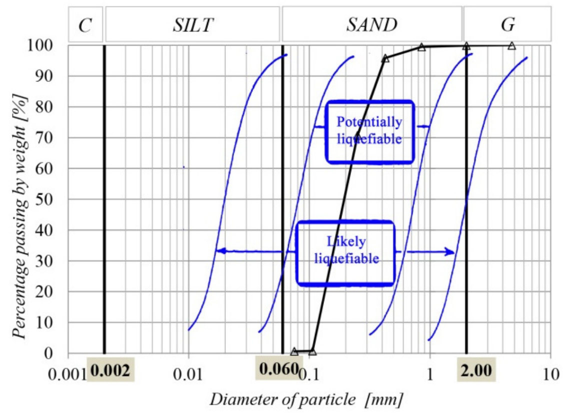


Figure 3. Grain size distribution and boundaries proposed by Tsuchida (1970).

The maximum and minimum void ratio (e_{max} and e_{min}) were evaluated by the ASTM standard procedures (D4254 for the maximum-index void ratio and D4253 for the minimum-index void ratio).

For estimating e_{max}, a standard mold (volume of 2830 cm^3) was filled by a standard pouring device (diameter of 13 mm) using the air pluviation technique. For evaluating e_{min}, the same mold was placed on a vertically vibrating table. The procedure also involves a base plate and an appropriate surcharge weight (total weight required of 25.6 ± 0.2 kg). The mold with the specimen was vibrated for 8 ± ¼ min at 60 ± 2 Hz.

The used apparatus for estimating e_{max} and e_{min} is reported in Fig. 4.

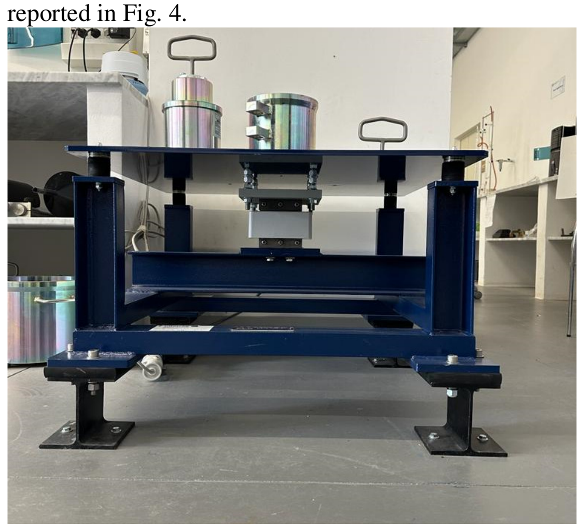


Figure 4. Apparatus for estimating e_{max} and e_{min} at the Soil Dynamics and Geotechnical Engineering Laboratory of the University "Kore" of Enna (Italy).

For comparison, values of e_{max} and e_{min} were also evaluated using the procedure proposed by Mijic et al. (2021) for small quantities of soil, showing non-significant differences. Table 1 reports the specific gravity of solid particles (Gs), the diameter corresponding to 60% finer in the particle-size distribution (D_{60}), the diameter corresponding to 30% finer in the particle-size distribution (D_{30}), the diameter corresponding to 10% finer in the particle-size distribution (D_{10}), the coefficient of curvature (Cc), the coefficient of uniformity (Cu) and the maximum and minimum void ratio (e_{max} and e_{min}) measured in the laboratory.

Table 1. Physical properties of the studied sand.

Parameter	**Value**
G_S	2.67
D_{60} [mm]	0.23
D_{30}[mm]	0.17
D_{10}[mm]	0.12
Cc	0.97
Cu	1.82
e_{max}	0.86
e_{min}	0.65

3. Testing conditions

The CDSS device used in study is an advanced apparatus manufactured by Controls Group designed to allow a sample to be consolidated and then sheared under constant volume conditions simulating an undrained shear of a saturated specimen. The CDSS device at the Soil Dynamics and Geotechnical Engineering Laboratory of the University "Kore" of Enna is reported in Fig. 5 and a full description of the apparatus is available at https://controls-group.com/product/cyclic-simple-shear-apparatus-controls/.

The apparatus includes a control and data acquisition system with two 5 kN actuators that have internal displacement transducers. The standard sample is 70 mm diameter. It is positioned on a pedestal and restrained by a rubber membrane and a series of slip rings.

The CDSS tests were conducted on very loose samples with a relative density of 15% considering a variability of ±3%. The remoulding of the soil sample was carried out by the moist tamping.

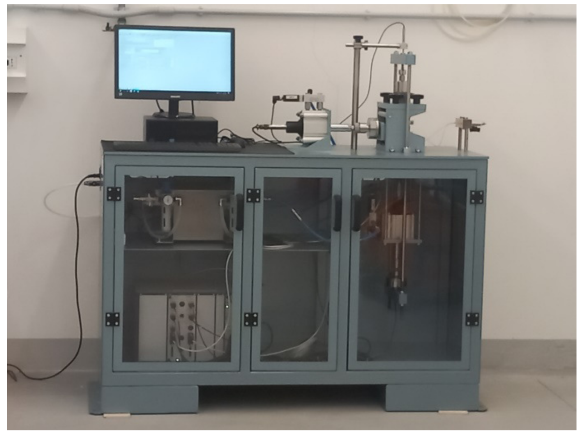


Figure 5. Equipment at the Soil Dynamics and Geotechnical Engineering Laboratory of the University "Kore" of Enna used for CDSS tests.

Remoulded samples were consolidated under an effective vertical stress, σ'_{v0}, of 50 kPa. The series of rings induced an anisotropic condition on the soil samples during the consolidation phase (Viana da Fonseca, Molina-Gómez, and Ferreira 2023).

The cyclic shearing was applied using sine waves with amplitudes equal to the cyclic shear stress, $\pm\tau_{cyc}$, and a frequency of 0.5 Hz. In CDSS, the Cyclic Stress Ratio (CSR) is defined as:

$$CSR = \frac{\tau_{cyc}}{\sigma'_{v0}} \quad (2)$$

The height of the samples was kept constant during the shearing process using the active height control.

4. Liquefaction resistance

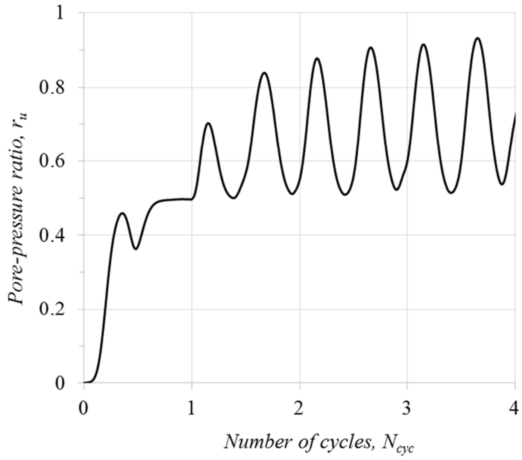
The liquefaction onset can be determined based on the number of cycles, N_{liq}, required to reach a limiting double amplitude shear strain or a single amplitude shear strain. The cyclic strength can be also identified through the pore-pressure ratio, r_u, criterion:

$$r_u = \frac{\Delta\sigma_v}{\sigma'_{v0}} \approx 1 \quad (1)$$

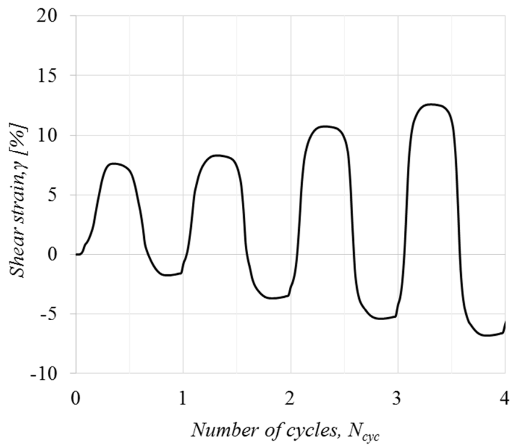
where r_u is the change in effective vertical stress, $\Delta\sigma_v$, during shearing divided by effective vertical stress, σ'_{Vc}.

In this work, the liquefaction onset was determined when the single amplitude of shear strain exceed 3% (Quintero et al. 2023).

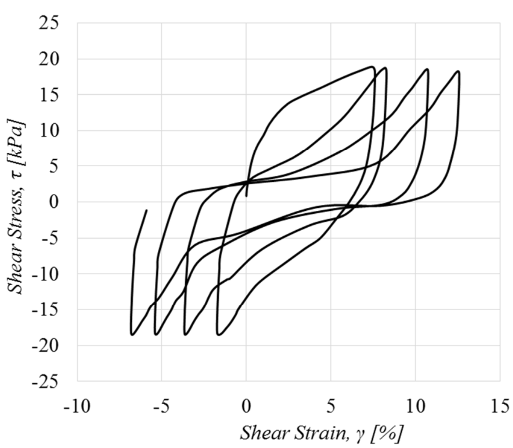
Typical results obtained from CDSS tests are reported in Fig. 6 in terms of r_u over the number of cycles (N_{cyc}) (Fig. 6 (a)), shear strain (γ) over N_{cyc} (Fig. 6 (b)) and shear stress (τ) against γ (Fig. 6 (c)) for a Cyclic Stress Ratio (CSR) of 0.38.



(a)



(b)



(c)

Figure 6. Typical results obtained from CDSS testing (σ'_{v0}=50 kPa and CSR=0.38).

The results of CDSS tests allowed defining a curve of liquefaction resistance (LRC=Liquefaction Resistance Curve) obtained from the Cyclic Stress Ratio (CSR) and the number of cycles of liquefaction onset (N_{liq}) (Fig. 7).

The LRC was defined by using the following equation:

$$\mathrm{CSR} = \mathrm{a}\left(\mathrm{N}_{liq}\right)^{-b} \tag{2}$$

where the fitting parameters a and b are equal to 0.381 and 0.149. Moreover, in Fig. 7, results are compared with those obtained by Kassas (2021) for the HN31 Sand showing a higher liquefaction resistance for the studied sand.

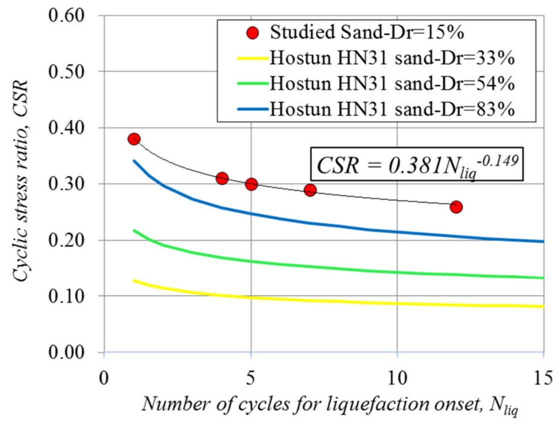


Figure 7. LRC obtained from CDSS testing.

5. Conclusions

In this work, physical properties and results obtained from CDSS testing for a liquefiable sand are discussed. The liquefaction resistance was assessed based on CDSS results in terms of Cyclic Stress Ratio (CSR) and the number of cycles of liquefaction onset (N_{liq}).

The physical properties of the sand under consideration are comparable to other sand in literature for liquefaction studies, e.g. Vietnam sand (Ueng et al. 2006), Skopje Sand (Bojadjieva et al. 2014), Nevada 120 sand (Zeghal, El Shafee and, Abdoun 2018). Therefore, the outcomes of this study can provide important information for the calibration of advanced constitutive models developed to simulate the liquefaction phenomenon to be employed in similar sandy soil.

The calibrated models will be validated against shaking table tests. Indeed, future developments consist in conducting experimental studies by the laminar shear box at L.E.D.A. of the University “Kore” of Enna to exactly capture the liquefaction phenomenon.

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References

ASTM D6913/D6913M - 17 Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, 2017.

ASTM D4253 - Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table, 2016.

ASTM International. D4254 - Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density, 2016.

Bojadjieva, J., Sesov, V., Edip, K., Gjorgiev, I. "Some important aspects in experimental setup for liquefaction studies on shaking table tests", 2nd Eur. Conf. Earthquake Engineering and Seismology, 2014.

Cappellaro, C., Cubrinovski, M., Bray, J. D., Chiaro, G., Riemer, M. F. Stringer, M. E. "Liquefaction resistance of Christchurch sandy soils from direct simple shear tests." Soil Dyn Earthq Eng 141, 106489, 2021 https://doi.org/10.1016/j.soildyn.2020.106489.

Castelli, F., Cavallaro, A., Grasso, S., Lentini, V. "Undrained Cyclic Laboratory Behavior of Sandy Soils". Geosciences, 9(12), 512, 2019. https://doi.org/10.3390/geosciences9120512.

Cavallaro, A., Grasso, S., Sammito, M. S. V. "A Seismic Microzonation Study for Some Areas Around the Mt. Etna Volcano on the East Coast of Sicily, Italy". In: Proceedings of the 4th International Conference on Performance Based Design in Earthquake Geotechnical Engineering, Beijing, China, 15-17 July 2022. https://doi.org/10.1007/978-3-031-11898-2_61

Chakraborty, A., Sawant, V. A. "Response of embankment on liquefiable soil to sequential ground motions considering mitigation measures." Soil Dyn Earthq Eng 176:108278, 2024. https://doi.org/10.1016/j.soildyn.2023.108278.2

Forcellini, D. "Soil–structure interaction analyses of shallow-founded structures on a potential-liquefable soil deposit." Soil Dyn Earthq Eng 133:106108, 2020. https://doi.org/10.1016/j.soildyn.2020.106108.

Grasso, S., Massimino, M. R., Sammito, M. S. V. "New stress reduction factor for evaluating soil liquefaction in the coastal area of Catania (Italy)." Geosciences (Switzerland), 11(1), pp. 1–25, 12, 2021 https://doi.org/10.3390/geosciences11010012

Grasso, S., Sammito, M. S. V. "Uncertainties in Performance Based Design Methodologies for Seismic Microzonation of Ground Motion and Site Effects: State of Development and Applications for Italy." In: Proceedings of the 4th International Conference on Performance Based Design in Earthquake Geotechnical Engineering, Beijing, China, 15-17 July 2022. https://doi.org/10.1007/978-3-031-11898-2_23

Grasso, S., Lentini, V., Sammito, M.S.V. "A New Biaxial Laminar Shear Box for 1g Shaking Table Tests on Liquefiable Soils". In Proceedings of the 4th International Conference on Performance Based Design in Earthquake Geotechnical Engineering, Beijing, China, 15-17 July 2022. https://doi.org/10.1007/978-3-031-11898-2_132

Kassas, K. "Structure-Soil-Structure Interaction (SSSI) of adjacent buildings founded on liquefiable soil". 2021, ETH Zurich.

Lentini, V., Castelli, F. "Liquefaction Resistance of Sandy Soils from Undrained Cyclic Triaxial Tests." Geot and Geol Eng J, 37(1): 201-216, 2019. https://doi.org/10.1007/s10706-018-0603-y.

Mijic, Z., Bray, J.D., Michael, F., Riemer, M.F., Cubrinovski, M, Rees, S.D. "Test method for minimum and maximum densities of small quantities of soil." Soils Found, 61, 2, 533-540, 2021. https://doi.org/10.1016/j.sandf.2020.12.003.

Navarra, G., Lo Iacono, F., Oliva, M., Tesoriere, G. "A new research facility: The Laboratory of Earthquake engineering and Dynamic Analysis (L.E.D.A.)." In Proc. of XXII Congresso - Associazione Italiana di Meccanica Teorica e Applicata - AIMETA 2015, ISBN 978-88-97752-55-4, 297-306, Genoa, Italy, September 14-17, 2015.

Nong, Z. Z., Park, S. S., Lee, D. E. "Comparison of sand liquefaction in cyclic triaxial and simple shear tests." Soils Found 61, 4, 1071–1085, 2021. https://doi.org/10.1016/j.sandf.2021.05.002

Quintero, J., Carrilho Gomes, R., Rios, S., Ferreira, C., Viana da Fonseca, A. "Liquefaction assessment based on numerical simulations and simplified methods: A deep soil deposit case study in the Greater Lisbon." Soil Dyn Earthq Eng, 169, 2023. https://doi.org/10.1016/j.soildyn.2023.10786615

Tsuchida, H. "Prediction and countermeasure against the liquefaction in sand deposits." In Seminar in the port and harbour research institute,1970. [in Japanese].

Ueng, T. S., Wang, M. H., Chen, M. H., Chen, C.H., Peng, L.H. "A large Biaxial Shear Box for Shaking Table Test on Saturated Sand." Geotech Test J 29, 1, 2006.

Viana da Fonseca, A., Molina-Gómez, F., Ferreira, C. "Liquefaction resistance of TP-Lisbon sand: a critical state interpretation using in situ and laboratory testing" Bull Earthquake Eng 21, 767–790, 2023. https://doi.org/10.1007/s10518-022-01577-8

Viana Da Fonseca, A., Soares, M., Fourie, A. B. "Cyclic DSS tests for the evaluation of stress densification effects in liquefaction assessment." Soil Dyn Earthq Eng 75:98–111, 2015. https://doi.org/10.1016/j.soildyn.2015.03.016

Yazan, B. A., Madabhushi, G. "Subsoil stiffness effects on the bridge-abutment dynamic behaviour". In: Proceedings of the 8th International Symposium on Deformation Characteristics of Geomaterials, Porto, 3rd - 6th September 2023.

Zeghal, M., El Shafee, O., Abdoun, T. "Analysis of soil liquefaction using centrifuge tests of a site subjected to biaxial shaking." Soil Dyn Earthq Eng 114:229-41, 2018.

Zhu, Z., Zhang F., Peng, Q., Dupla, J. C., Canou, J., Cumunel, G., Foerster, E. "Assessment of the loading waveform on the cyclic liquefaction resistance with Hostun 31 sand." Soil Dyn Earthq Eng 150: 106919, 2021.