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PROOF OF CONCEPT OF A RESOURCE-SAVING SOIL IMPROVEMENT TECHNIQUE FOR LIQUEFACTION MITIGATION

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ABSTRACT

Saturated layers of loose soils, primarily sands with a minor content of silt, are critical subsoil conditions in many cases, due to their susceptibility to liquefaction under dynamic loads such as seismic events. Liquefaction is characterized by an increase in pore water pressure that reduces effective stresses to zero, resulting in a loss of soil strength and a liquid-like behaviour until the excess pore pressure dissipates over time. There are a variety of liquefaction mitigation methods available, which are based on different approaches, such as an increase of strength (e.g., grouting), an increase of permeability (drainage), and an increase of relative density (densification). The extensive use of raw materials and the heavy machinery of conventional methods are the primary contributors to high carbon emissions, emphasizing the need for an innovative, resource-saving improvement technique.

In this soil improvement concept, the densification of the soil is achieved by dynamically applying pressure surges on the water to increase the pore pressure up to a level where it reaches the magnitude of the effective stresses, generating a localized liquefaction. Consequently, the soil behaves almost like a liquid until the excess pore pressure dissipates, allowing the particles to rearrange into a denser state and thereby reducing the liquefaction potential. The current paper introduces the concept and experimental results of a small-scale test box using various measurement devices, such as pore pressure sensors, accelerometers, and a particle image velocimetry camera, to analyse the soil's response during and after the applied impulses. These tests lay the groundwork for future laboratory tests and the subsequent development of a practical system for field tests.

Keywords: liquefaction mitigation, soil improvement, sustainable geotechnics.

INTRODUCTION

Liquefaction depicts a serious risk for sandy and silty soils at a loose state and under full saturation. Due to dynamic loads (e.g., earthquakes), the pore water pressure increases while subsequently decreasing the effective stresses. This mechanism can reach an extent at which the grain-to-grain contact may be lost, leading to a liquid-like behaviour of the soil-water mixture. The excess pore water pressure then dissipates over time, leading to settlements and an increase in effective stresses.

Huang and Wen (2015) describe three main issues when it comes to liquefaction mitigation, namely (1) preventing existing structures from damages, (2) the methods must be economical for large areas, and (3) the carbon emission must be kept at a minimum.

Therefore, a variety of existing mitigation methods are available, thus not all tackling all the above-mentioned challenges. Different techniques are applicable for different compositions of soil. While for rather coarse-grained soils, multiple methods exist for liquefaction mitigation, for soils with a higher fines content, the amount is limited. An overview of these is given by Mitchell (2012, c2008).

Methods with high CO_2 emissions, especially if cement is used, must be considered critical when it comes to sustainability. In cases of large improvement areas, this is even more crucial. Furthermore, methods like vibratory compaction and vibro replacement (Priebe, 1998) are limited in their impact radius, which might lead to uneconomical production grids.

As a result of these current problems encountered in the mitigation process, the idea of a novel approach emerged: The Dynamic Water Impulse Compaction (DYWIC). The loosely packed soil should be transferred into a denser state by using the in-situ groundwater as a densification medium, thereby reducing the risk of liquefaction. By dynamically applying surges on a water column that communicates with the surrounding soil, the pore pressure should be increased to create a similar effect to the soil liquefaction. Due to this localized artificial liquefaction and the subsequent dissipation of the excess pore pressure,

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densification occurs, followed by settlements, and the risk of liquefaction is reduced.

The technique DYWIC is currently in the laboratory test phase, in which small-scale laboratory tests are conducted, investigating the behaviour during and after the impulses. Besides checking if the main target, the densification, is achieved, also, effects on the pore water pressure and movements of soil particles are of interest. These laboratory tests lay the groundwork for upcoming field tests, which are currently in discussion. Small-scale effects and possible boundary effects might influence the tests. However, the goal is to make a general statement about the impact of DYWIC.

This paper introduces the laboratory test set-up, including the installation process of the soil, measurement devices and the impulse trigger system, as well as the presentation and discussion of the first test results.

METHODOLOGY

The test was conducted in an acrylic glass box with an aluminum frame, measuring 76×46×56 cm. A semicircular, perforated steel profile was securely attached to the front glass and sealed to ensure water tightness along the entire height of the box. To control water flow, an impervious acrylic glass inliner was installed inside the perforated profile in the upper 16 cm, allowing only the lower section to remain perforated and connected to the water. Additionally, a filter fleece was placed on the outer side of the semicircular profile to enhance filter stability and prevent soil particle infiltration.

Next, the soil was installed with a two-layer sieve system similar to the one used by Gade and Dasaka (2016). This system allowed the sand to be rained into the box, which was pre-filled with approximately 3 cm of water, ensuring a saturated installation in a loose state. The process was carried out in multiple layers until a final height of approximately 49 cm was achieved, with the top 9 cm placed in a partially saturated state. Laboratory tests characterized the sand as predominantly medium sand with some fine sand content and a minimal amount of silt (2%).

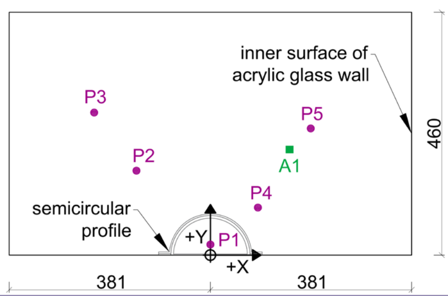

Figure 1 *Top view of the test box*

During the installation, five pore pressure sensors and an accelerometer were positioned inside the soil body and the steel profile, respectively (see Figure 1). The first pore pressure sensor, P1, was placed at the bottom of the box, inside the steel profile. P2, P3, and the accelerometer were placed in the soil at a height of 10 cm, whereas P4 and P5 are situated at a height of 25 cm. Sensors P2 and P4 are placed closer to the steel profile than P3 and P5 in order to measure both the pore pressure at different heights and its propagation.

Furthermore, eight markers were mounted at the top of the box (Figure 2) to measure changes in soil surface height before and after the impulses using photogrammetry. In addition, a particle image velocimetry camera (PIV) was positioned in front of the box to capture the movement of the soil particles during the test. It captured the lower right area of the test box, and its data was evaluated using the MATLAB® tool PIVlab developed by Thielicke and Sonntag (2021).

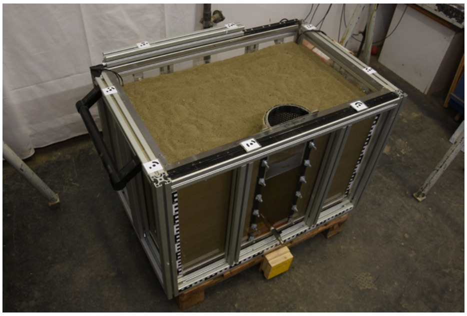

Figure 2 *Picture of the test box*

The impulses were generated using a computer-controlled pneumatic cylinder to regulate the frequency. A plunger connected to the cylinder transferred the impulses to the water surface inside the steel profile. In total, 48 impulses were applied over a duration of 30 seconds.

RESULTS AND DISCUSSION

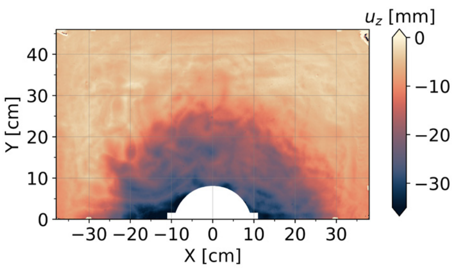

Figure 3 *Settlements of the sand surface*

Figure 3 presents the vertical settlements that occurred during the impulses. A semicircular settlement trough with a radius of approximately 25 cm is observed around the steel profile along the central axis of symmetry. The maximum settlements, reaching about 35 mm, are concentrated on the area close to the perforated profile, while settlements at the box corners are around 5 mm.

The evaluation of the PIV-data is shown in Figure 4, where the vertical settlements of the lower right area of the test box are plotted. Settlements in zones covered by structural elements were not measured and, therefore, interpolated.

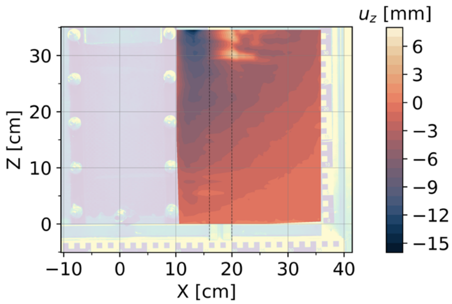

Figure 4 *Vertical settlements along the axis of symmetry*

Up to a height of 30 cm, settlements near the perforated profile range from 10 to 12 mm, while settlements at the corners reach approximately 3 mm. A comparison of surface settlements measured by photogrammetry and PIV shows good agreement. Additionally, four cross-sections were analyzed at X = 12, 15, 22, and 24 cm based on PIV data, as illustrated in Figure 5.

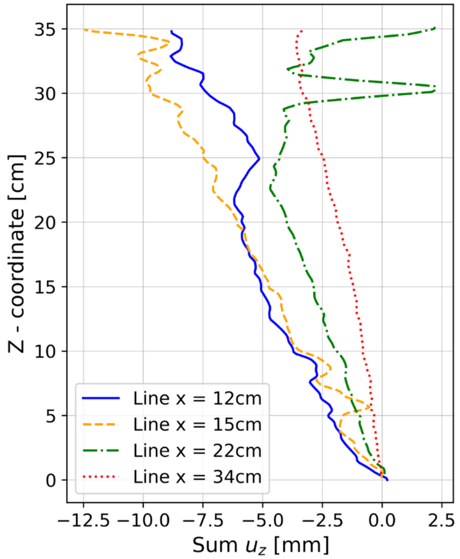

Figure 5 *Cross-sections showing the vertical settlements*

These results indicate that approximately two-thirds of the total settlements occur within the top 18 cm of the soil, where the steel profile lacks perforation. Video analysis suggests that hydraulic failure occurred around the semicircular profile during testing, explaining the increased settlements in the upper section while leaving the lower part mostly unaffected.

The pore pressure development during the first three impulses, shown in Figure 6, confirms that sensor P1, located at the center of the perforated profile, responds immediately to pressure surges as expected. Sensors P2 and P4, positioned near the perforated profile, exhibit a damping effect, while sensors P3 and P5 (dashed lines) follow a similar trend but with even lower amplitudes. It should be noted that the pore pressure sensors were calibrated for low-pressure tests. However, their readings should be interpreted with caution, and the qualitative distribution of the data should be prioritized over quantitative values.

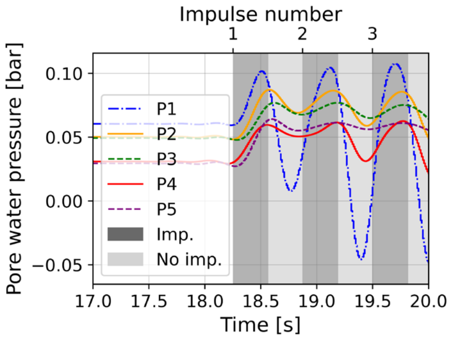

Figure 6 *Pore water pressure during the first three impulses*

Each impulse causes a spike in pore pressure, a pattern reflected in the accelerometer data. This effect persists throughout the test, as shown in Figure 7, which illustrates the pore water pressure distribution during the final two impulses.

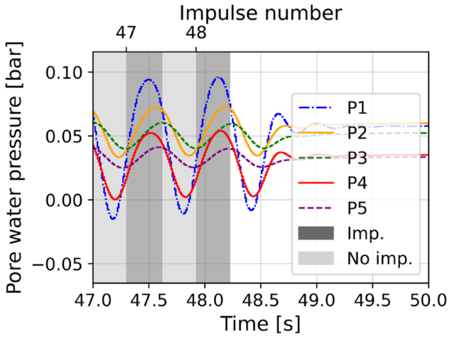

Figure 7 *Pore water pressure during the last two impulses.png*

CONCLUSION

The results of the first test provide valuable insights into soil behavior under dynamic pore water surges, demonstrating the intended increase in pore water pressure and the desired densification of the soil body.

All measurement devices functioned reliably and collectively provided a clear picture of the mechanisms occurring during the impulses. While hydraulic failure at the top influenced overall surface settlements, its impact on the lower soil body is considered minor. To verify this, ongoing lab tests use a longer inlay in the semicircular steel profile, reducing the perforated section relative to the total soil height.

Small-scale effects and boundary influences are inherent but challenging to quantify. Therefore, in the near future, it is the plan to develop a practical system and conduct field tests to assess the method's effectiveness under in-situ conditions.

REFERENCES

Gade, V.K., Dasaka, S.M. (2016) Development of a Mechanized Traveling Pluviator to Prepare Reconstituted Uniform Sand Specimens, Journal of Materials in Civil Engineering, 28(2), ***https://doi.org/10.1061/(ASCE)MT.1943-5533.0001396***

Huang, Y., Wen, Z. (2015) Recent developments of soil improvement methods for seismic liquefaction mitigation, Natural Hazards, 76(3), pp. 1927-1938, ***https://doi.org/10.1007/s11069-014-1558-9***

Mitchell, J.K. (2012, c2008) Mitigation of Liquefaction Potential of Silty Sands, From Research to Practice in Geotechnical Engineering, Symposium Honoring Dr. John H. Schmertmann for His Contributions to Civil Engineering at Research to Practice in Geotechnical Engineering Congress 2008, New Orleans, Louisiana, United States, March 9-12, 2008. Reston, VA: American Society of Civil Engineers, pp. 433-451, ***https://doi.org/10.1061/40962(325)15***

Priebe, H.-J. (1998). Vibro replacement to prevent earthquake induced liquefaction, In: Eleventh European Conference on Earthquake Engineering, Paris, France, 06.11.-11.11.1998.

Thielicke, W., Sonntag, R. (2021) Particle Image Velocimetry for MATLAB: Accuracy and enhanced algorithms in PIVlab, Journal of Open Research Software, 9(1), p. 12, ***https://doi.org/10.5334/jors.334***

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SOIL STABILIZATION AND IMPROVEMENT