The paper was published in the proceedings of the 11th International Conference on Physical Modelling in Geotechnics (ICPMG2026) and was edited by Ioannis Anastasopoulos. The conference was held from June 8th to June 12th 2026 in Zurich, Switzerland.

Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Image processing-based evaluation of shallow foundation settlement during liquefaction using a 1g physical model

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ABSTRACT: The use of image processing techniques in civil engineering has grown significantly in recent years, offering innovative tools for the observation and analysis of physical phenomena. In geotechnical engineering, evaluating the behavior of shallow foundations resting on liquefiable sandy soils remains a critical research area, particularly under dynamic loading conditions. This study presents an experimental investigation into the settlement response of shallow foundations with varying aspect ratios placed on saturated loose sand, a material susceptible to liquefaction. A 1g shaking table physical model is developed to simulate seismic loading scenarios. The experimental setup includes conventional instrumentation, displacement transducers, accelerometers, and pore water pressure sensors, to monitor the response of the soil-foundation system. In parallel, an image processing technique is employed to capture and quantify foundation settlements over time, allowing for enhanced spatial and temporal resolution in data interpretation. The results indicate a direct relationship between the foundation's aspect ratio and its seismic-induced settlement: as the aspect ratio increases, the magnitude of settlement also increases. The findings emphasize the importance of geometric parameters in foundation design for liquefiable soils and highlight the potential of image processing as a reliable, non-intrusive tool for dynamic testing in geotechnical research. This study contributes to a better understanding of soil-structure interaction under seismic conditions and supports the integration of modern imaging techniques in experimental geotechnics.

1 INTRODUCTION

Soil liquefaction is one of the most destructive phenomena in geotechnical earthquake engineering, capable of causing severe structural damage and settlement (Shahnazari et al., 2016a; 2016b). Under normal conditions, sand particles are in contact and resist deformation through shear strength. However, seismic shaking increases pore water pressure and breaks these inter-particle contacts, leading to a loss of strength and a rise in pore water pressure, which may ultimately reach zero effective stress. This is the hallmark of liquefaction.

Shallow foundations were commonly used in many residential buildings that tilted or settled during the earthquake. To design these foundations effectively, it is essential to predict settlements caused by liquefaction. However, the current procedure for estimating this settlement is highly complex (Lu et al., 2020). Therefore, one of the key research areas is understanding how structures themselves influence the onset of liquefaction and subsequent settlements. Researchers such as Yoshimi and Tokimatsu (1977), Das and Omar (1994), Karimi and Dashti (2016), Shahnazari et al. (2019), Rezvani et al. (2020), Mao et al. (2023) and Li et al. (2025), have extensively investigated this phenomenon. Some studies such as Orang and Motamed (2021) investigated the mitigation methods for improvement of shallow foundation behavior on liquefiable deposits.

Lu et al. (2025) proposed an analytical model to estimate the final settlement magnitude induced by soil liquefaction and compared the findings with the results obtained from centrifuge experiments and numerical simulations. Using 1g shaking table tests, Kuo et al., (2026) evaluated the settlement behavior of bucket jacket foundation during liquefaction. The results showed that the upward force generated within the bucket foundation significantly reduces suction bucket jacket settlement during liquefaction.

In recent years, the application of image processing techniques has gained significant traction in geotechnical engineering for the quantitative assessment of soil behavior under various loading conditions (Bogrekci and Godwin, 2007; Wu and Pai, 2022). These non-destructive methods provide invaluable insights into deformation mechanisms, strain localization, and particle-scale phenomena that are otherwise difficult to capture with conventional measurement tools.

This study experimentally investigates the relationship between the aspect ratio of shallow foundations and their seismic-induced settlement through a series of 1g shaking table tests. To overcome the limitations of conventional measurement techniques and obtain high-resolution deformation data, Particle Image Velocimetry (PIV), an advanced image processing technique, was employed. This method enabled the precise tracking of soil displacement and the detailed quantification of settlement mechanisms throughout the testing process.

2 SHAKING TABLE EXPERIMENTS

In this study, a 1g geotechnical shaking table equipped with an internal Plexiglass container (180 cm long, 45 cm wide, and 75 cm deep) was used. The system included 8 transducers (sensors): 1 displacement transducers, 2 pore pressure transducers and 5 accelerometers, with a data acquisition system operating at 2000 Hz for recording data. A schematic photo of the instrumented shaking table setup is presented in Figure 1.

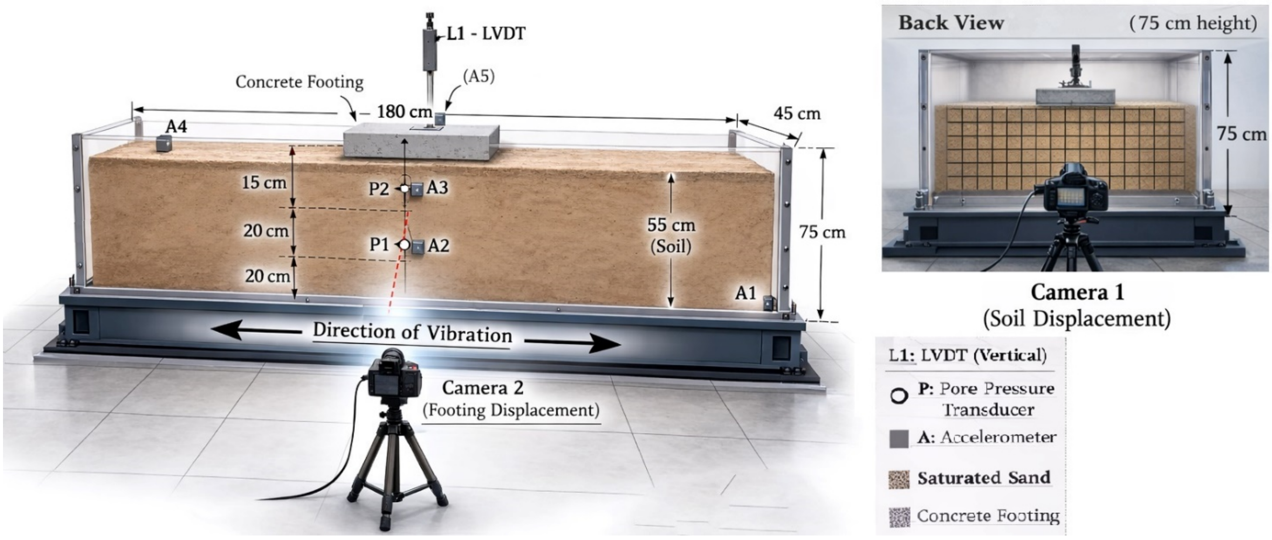


Figure 1. Schematic view of the instrumented shaking table setup and the cameras for image processing.

Firouzkooh No. 161 sand, a standard sand in Iran, was used to evaluate the seismic response of soil in this study. Based on the particle size distribution analysis, the soil used is classified as Poorly-Graded Sand (SP) according to the Unified Soil Classification System (USCS). The physical properties of Firouzkooh sand are presented in Table 1.

Table 1. Physical properties of Firouzkooh No.161.

Soil	e_{max}	e_{min}	G_S	D_{50} (mm)	F.C. (%)
Firouzkooh	0.97	0.603	2.66	0.3	0.5

To investigate the effect of foundation aspect ratio, three concrete foundation models with plan dimensions of 10×10 cm (square, L/B=1), 10×20 cm (rectangular, L/B=2), and 10×40 cm (rectangular, L/B=4) were designed and fabricated. It is important to note that the foundation width (B) was kept constant at 10 cm across all models, while the length (L) was varied to achieve the desired aspect ratios. To be sure of the rigidity of the model foundation, 2 longitudinal armatures with 6 mm diameter were used in each model foundation. To maintain consistent vertical stress application across all specimens and ensure comparable loading conditions, the height of all models was kept constant at 6 cm. This dimensional consistency resulted in a uniform contact pressure of approximately 1.5 kPa being transferred to the underlying soil stratum.

For preparing the liquefiabale sand desposit, the saturated sand layers were prepared by moist tamping (having the initial moisture content of 6%) and then saturated using CO_2 and water percolation. The final height of the soil profile beneath the foundation was 55 cm and the obtained relative density was 25%. The foundation was placed statically on the soil surface, and the immediate settlement observed under self-weight was negligible.

For dynamic loading, the input shaking motion had constant frequency and amplitude across tests. The scale factor λ was 15, following similitude principles as described by Iai (1989). This ratio is equal to the geometric ratio of the structure in the original scale (Prototype) to the structure in the model scale (Model). Input dynamic excitation, in all tests, was a harmonic wave. The frequency of shaking motion and amplitude of the base acceleration were 3.1 Hz and 0.4g, respectively. Table 2 presents the summary of the conducted experiments.

Table 2. Summary of conducted shaking table tests.

Test	Aspect ratio	Vibration direction	Acc.	Frequency
F1	4	L	0.4g	3.1 Hz
F2	2	L	0.4g	3.1 Hz
F3	1	L(or B)	0.4g	3.1 Hz
F4	2	B	0.4g	3.1 Hz
F5	4	B	0.4g	3.1 Hz

In the first two tests (F1 and F2), the length of the model foundation was oriented parallel to the direction of vibration. In the last two tests (F4 and F5), the foundation was rotated 90° in the horizontal plane. This meant that the width of the foundation was aligned with the vibration direction. For Case F3, since the foundation had a square cross-section (B = L), aligning the vibration direction with either the length or the width of the foundation makes no difference.

3 IMAGE PROCESSING

In recent years, digital video image processing has emerged as a powerful tool for motion tracking and deformation measurement. In this study, the image processing procedure was performed twice. In the first stage, image processing was conducted on the mesh pattern created on the soil wall to evaluate mesh deformations during seismic loading. This stage was carried out using Camera No. 1. For this purpose, black-colored sand was used alongside the natural-colored sand. The black sand provided the highest visual contrast with the natural sand used in the model (Figure 2).

In the second stage, image processing was performed using Camera No. 2 to measure the displacements of the small-scale shallow foundation under seismic loading. As can be seen in Figure 3, in this phase, two red light-emitting diodes (LEDs) were installed on the black-colored shallow foundation, and the displacement of these two illuminated points was evaluated through image processing.

Each video frame was analyzed using MATLAB software to extract pixel displacements using RGB color-space separation and Gaussian probability distribution modeling.

The process involved:

1. Identifying distinct color clusters corresponding to the foundation, background, and sand.
2. Determining the mean and variance of color intensity distributions.
3. Classifying each pixel based on maximum likelihood estimation.
4. Tracking the displacement of specific foundation points through consecutive frames.

The image processing method facilitated precise measurement of both horizontal and vertical displacements, eliminating the reliance on direct contact sensors. This non-contact approach minimized experimental interference, thereby enhancing measurement accuracy. To validate the results, a high-accuracy displacement transducer (LVDT) was installed on top of the small-scale foundation. The comprehensive experimental setup, including camera positioning and instrumented foundation, is depicted in Figure 3.

Figure 2. Experimental shaking table model before dynamic loading (View from camera No. 1)

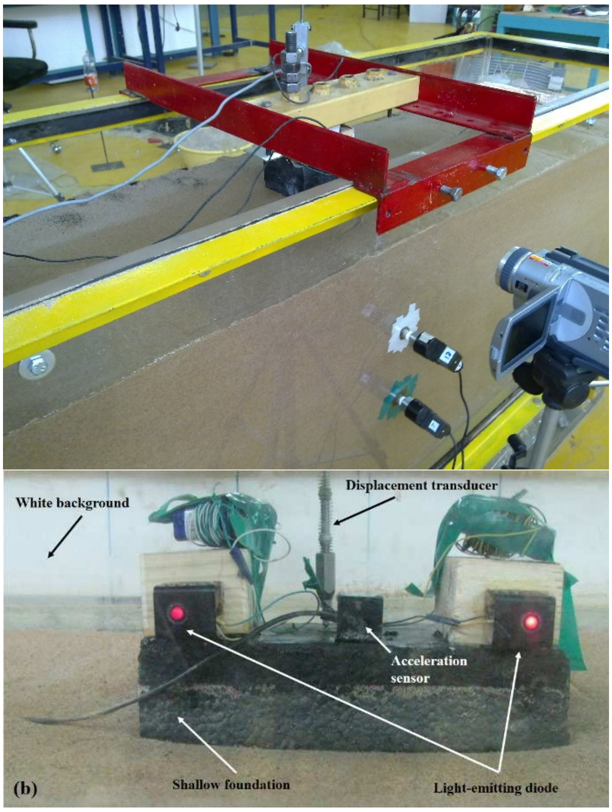


Figure 3. (a) setup of camera No. 2 and (b) view of the instrumented shallow foundation for image processing.

4 RESULTS AND DISCUSSION

The aforementioned experiments were conducted to evaluate the effect of foundation aspect ratio on settlements caused by seismic loading of a single shallow foundation on saturated loose sand. It should be noted that all results presented in this section are reported at model scale and represent direct measurements from the instrumentation. Figures 4a to 4e present the acceleration time histories of test F1 recorded by A1 to A5 accelerometers. Also, the time history of excess pore pressure time history (r_u) is presented in Figure 4f. In addition the settlement time history of model footing recorded by LVDT is illustrated in Figure 5.

As can be seen in Figure 5, the observed foundation settlement throughout the experimental procedure can be categorized into three principal stages: (i) the settlement that develops during the period of dynamic excitation, (ii) the subsequent settlement occurring throughout the system's free vibration phase, and (iii) the final stage, in which the soil–foundation system progressively stabilizes and reaches its state of physical equilibrium. It should be noted that Figures 4 ad 5 show detailed time histories for Case F1, which is presented as a representative example since similar behavioral patterns were observed across all test cases.

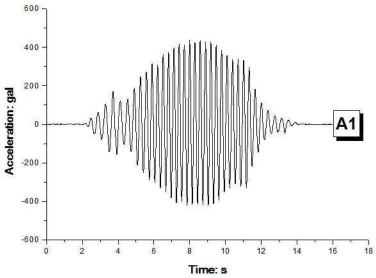
To facilitate a non-intrusive and comprehensive analysis of soil deformation, a high-contrast color grid was affixed to the transparent sidewall of the shaking table model. This grid served as a reference pattern for digital image correlation (DIC) techniques. A high-contrast colored grid was intentionally created using black sand within the natural sand matrix, and soil deformation was quantified by tracking the deformation of this grid pattern during seismic loading. To enhance the accuracy of the image processing procedure, a high-speed camera was employed to capture sequential images at a high frame rate. The displacement field was then obtained through correlation of successive digital images, consistent with the DIC methodology. No particle-based tracking (PIV) was used in this research.

This approach provided full-field displacement data, capturing both the magnitude and direction of soil movements throughout the entire soil profile during dynamic excitation. The technique proved particularly valuable in identifying localized shear strains and the formation of failure mechanisms that might otherwise be undetectable with traditional point-based sensors.

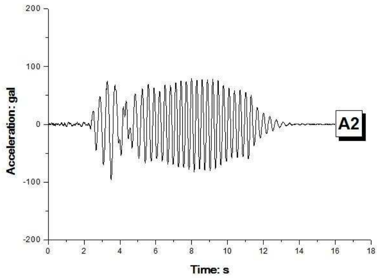
The efficacy of this methodology is demonstrated in Figures 6 and 7. Figure 6 presents the displacements of soil particles observed in the shaking table tests, while Figure 7 qualitatively illustrates the corresponding displacements obtained from the image processing analysis. The strong visual correlation between the two figures validates the image-based technique as a reliable tool for visualizing and assessing complex soil behavior under seismic loads.

In addition the displacement of the foundation before and after dynamic loading is presented in Figure 8. The water released due to excess pore water and the differential settlement of the two sides of foundation can also be seen in this figure.

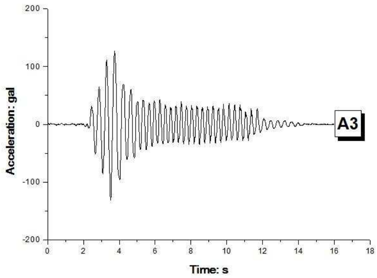
The direction of vibration applied to the model foundation demonstrated a significant influence on the settlement behavior of the liquefiable subsoil. Figure 9 illustrates the comparative settlement values recorded under different vibration orientations for the conducted tests. The results reveal a critical finding: dynamic loading induces the most substantial settlement when the shaking is aligned parallel to the shorter dimension (width) of the foundation. This suggests that seismic excitations along this specific orientation pose a greater risk for structures founded on liquefiable soils.



(a)



(b)



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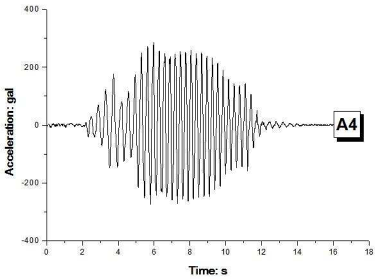

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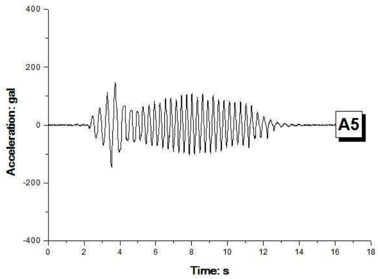
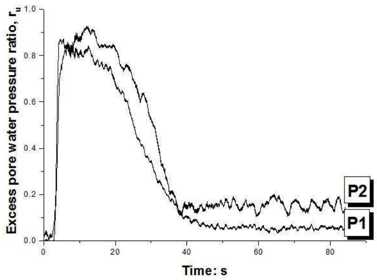


(e)



(f)

Figure 4. Time history of acceleration recorded by A1 to A5 accelerometers (a, b, c, d and e) and excess pore pressure ratio recorded by P1&P2 transducers (f) (test F1).

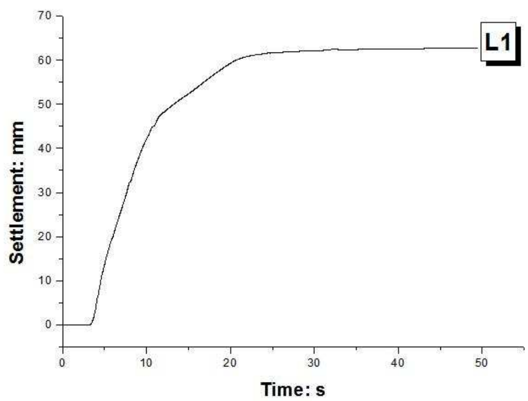


Figure 5. Observed foundation settlement recorded by L1 transducer (test F1).

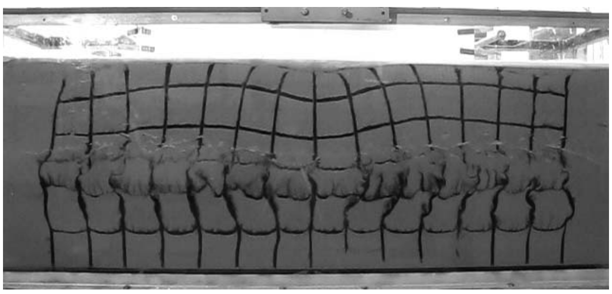


Figure 6. Qualitative displacements in the prepared sandy soil profile after application of base motion (test F4).

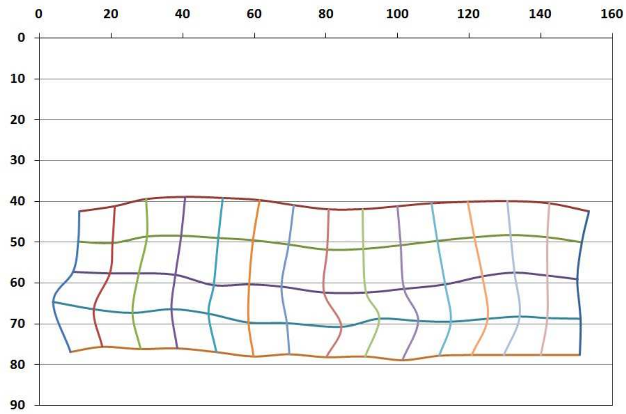


Figure 7. Final state of the network obtained by image processing method (test F4).

The graph shown in Figure 10 illustrates the recorded values for the left and right sides settlements of model foundation separately, calculated by image processing analysis. At the end of the seismic excitation, the right corner of the foundation had a displacement of 62.67 mm and the left corner had a displacement of 61.86 mm. The close agreement between the two measurement methods—with a negligible deviation of only 0.01 mm between the image processing average and the LVDT transducer readings—strongly validates the accuracy of the digital image processing technique. This correlation conclusively demonstrates that image processing serves as a powerful and reliable alternative for measuring displacements in shallow foundations subjected to dynamic loading conditions.

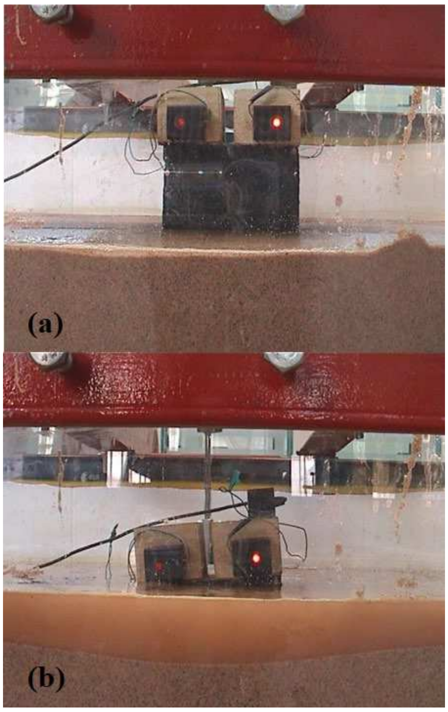


Figure 8. Photo of model foundation (a) before and (b) after dynamic loading on liquefiable sandy soil (test F4).

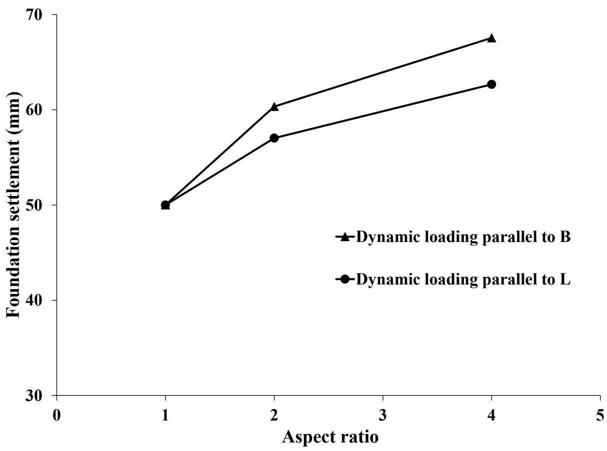


Figure 9. Effect of aspect ratio (L/B) on the observed foundation settlements in two different directions of dynamic loading.

It can also be seen in Figure 11 that the footing had a horizontal displacement of 7.2 mm at the end of the test. The maximum horizontal displacement was at the beginning of the footing settlement, and after that the displacement in the horizontal direction was more limited. The reason for this is that the footing was buried in the sand, which prevented severe horizontal movements by creating a resistive (passive) pressure against the footing. Another point is that the foundation had a kind of swaying-like movement during the settlement, meaning that the settlement of the footing corners during the stimulation period was back and forth in the vertical direction, which can be concluded that the movement was downward (settling). Furthermore, the difference in vertical displacement between the left and right sides of the foundation is attributed to tilting caused by cyclic loading.

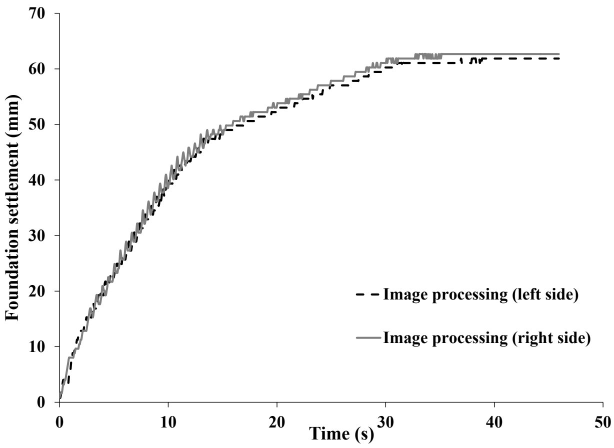


Figure 10. Comparison diagram of settlement of the two sides of the foundation using the image processing method (test F1).

5 CONCLUSIONS

This study has presented a physical modelling investigation into the seismic response of shallow foundations with varying aspect ratios resting on liquefiable sandy soil, employing an innovative combination of traditional instrumentation and advanced image processing techniques. The research addresses a critical gap in understanding how foundation geometry influences settlement behavior under dynamic loading conditions, providing valuable insights for the design of structures in seismically active regions prone to liquefaction. Based on the shaking table tests and detailed image analysis conducted in this research, the following key conclusions can be drawn:

- The aspect ratio (L/B) of shallow foundations has a profound impact on seismic-induced settlement. Foundations with higher aspect ratios experienced substantially greater settlements. Specifically, the foundation with an aspect ratio of 4 underwent settlements approximately 25-35% larger than the square footing (aspect ratio of 1) under identical loading conditions and same stress conditions.

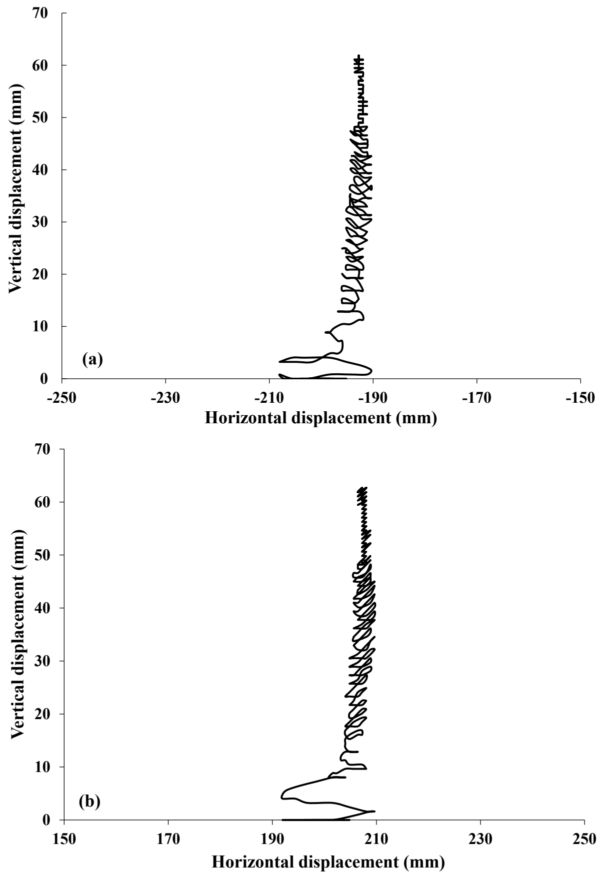


Figure 11. Settlement of the two sides of the foundation in Cartesian coordinates using the image processing method (test F1) (a) left side and (b) right side.

- The direction of seismic excitation relative to the foundation's geometry plays a decisive role in settlement magnitude. Dynamic loading applied parallel to the shorter dimension (width, B) of the foundation was found to be more critical, inducing up to 6-8% greater settlement compared to loading parallel to the longer dimension (length, L) for the same aspect ratio.
- A shallow foundation on liquefiable saturated sand may develop embedment under dynamic excitation, which consequently limits its horizontal displacement.
- The digital image correlation (DIC) technique demonstrated exceptional accuracy in measuring displacements. The close agreement between image processing results and LVDT transducer data, with a negligible deviation of only 0.01 mm, confirms its reliability as a powerful, non-intrusive method for capturing both vertical and horizontal displacements in geotechnical dynamic tests.
- The image analysis revealed a complex settlement mechanism characterized by a "swaying-like" motion. The foundation experienced an initial significant horizontal displacement of about 17 mm, which was subsequently restrained by the development of passive earth pressure as the foundation buried itself, leading to a predominantly vertical settlement pattern with differential movements at the corners.

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