Measured Soil-Pile Interaction Pressures for Small-Diameter Laterally Loaded Pile in Loose Sand

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ABSTRACT

The Soil-Structure Interaction (SSI) facility at Lafayette College, which was funded by the National Science Foundation, was recently used to investigate the soil-pile interaction for laterally loaded piles with the main focus on the interaction pressure between the pile and surrounding soil. A precast concrete pile, that was 101.6 mm in diameter and 1.17 m long, was reinforced with one No. 4 rebar (diameter = 12.7 mm) located at the center of the pile cross-section. The pile was instrumented with strain gauges along the length of the pile, displacement and tilt gauges at the point of loading, displacement sensors along the length of the pile, and thin pressure sensors wrapped around the pile. The soil, which was rained around the pile, was classified as well-graded sand.

This paper focuses on measuring the soil-pile interaction pressure for a laterally loaded pile. The paper also describes the installation procedure, the soil properties, the measured pile force-displacement relationship and the measured strain along the length of the pile. Measured interaction pressures present the first step to develop the soil force-displacement relationship (i.e., the soil reaction or the p-y curve) based on direct measurements. The experiment described in this paper presents the initial effort of the research team, which will be followed by further experimental work focusing on the behavior of laterally loaded piles in soft soils.

Key Words: Soil-Structure Interaction, Laterally Loaded Pile, P-y Curves

INTRODUCTION

Piles subjected to lateral loads have been receiving widespread attention due to their common occurrence in practice. Piles can be subjected to lateral force commonly applied at the pile head (known as active piles) or lateral soil movement (known as passive piles). Active pile loading is experienced in piles supporting retaining walls, pier fenders, and various types of offshore structures and drilling platforms. Passive pile loading occur in cases of piles used to stabilize failing slopes where piles are subjected to lateral soil displacement and piles subjected to liquefaction-induced lateral spreading. The behavior of laterally loaded piles (both subjected to active and passive loading) mainly depends on the interaction between the pile and surrounding soil. Although both cases of pile lateral loading are currently under investigation by the research team, this paper will focus on the behavior of piles subjected to lateral loads.

The key to better understanding soil-pile interaction is *measuring the interface contact pressure between the pile and surrounding soil and the movement of the pile or soil along the length of the pile.* Although attempts have been made to directly measure the soil response (i.e., soil-pile interaction pressure and lateral movement along the pile length), these attempts were not successful (Reese et al. 2004). For active piles, the soil reaction is commonly modeled using the force per unit length (P) vs. displacement (y) relationship of soil, commonly known as p-y curve. The p-y curves represent compression-only nonlinear springs that account for the soil resistance in the direction of pile movement (Fig. 1a and b). The p-y curves of soil in the case of active piles have been extensively studied and several methods were developed to generate them (i.e., API, 1987; Cox et al. 1974; Matlock 1970; O'Neill and Murchison; Reese and Welch 1975; and Terzaghi 1955). These researchers used empirical methods to develop soil p-y curves to match measured pile response – mainly the pile force-displacement response measured at the pile head or strain profiles along the pile length. To develop the force-displacement relationship of soil, these matching procedures used back-calculation procedures, and empirical relationships with soil stress-strain response measured in the laboratory or in-situ soil properties.

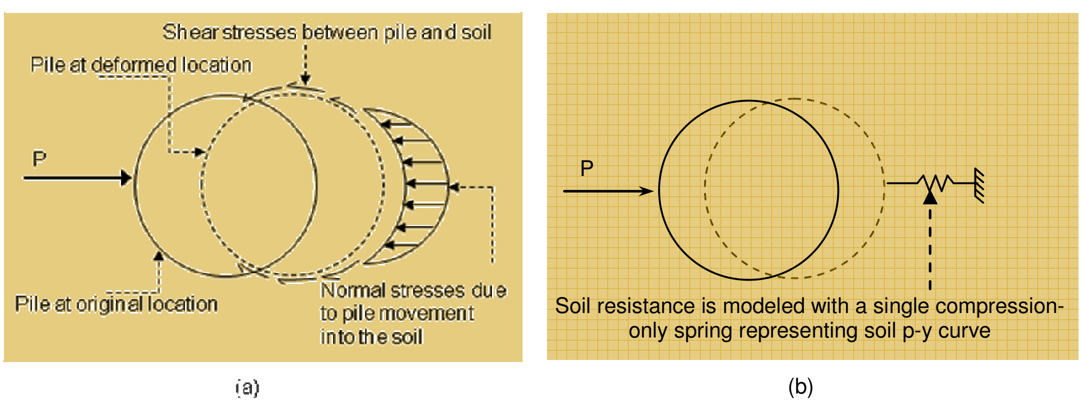


Fig. 1: Soil-pile foundation interaction for active piles, (a) stresses distribution around active pile case, and (b) modeling soil reaction or resistance to pile movement using compression-only springs (p-y curves).

This paper presents the results of recent research focusing on the soil-pile interaction for a pile installed in loose well-graded sand subjected to lateral loading. Advanced sensors were used to measure the pressure at the soil-pile interaction and the lateral movement of the pile along its length. Unlike the empirical methods, these measurements were used to directly measure the soil force-displacement relationship (p-y curves). However, this paper will focus on measured soil-pile interaction pressures.

Testing Facility and Experiment Details

The Soil-Structure Interaction facility at Lafayette College, which was funded by the National Science Foundation (NSF) includes flexibly designed soil boxes, advanced sensors, state-of-the-art instrumentation and equipment. As shown in Fig. 2, the soil box has three main parts - drainage base and two soil boxes. The dimensions of the soil boxes are 1.5 m x 1.5 m x 1.5 m and 1.5 m x 1.5 m x 0.75 m, which were designed to have flexible assembly. They can be assembled as two boxes as shown in Fig. 2 or one large box if needed. The use of one box, two boxes on top of each other, or one large soil box depends on the set-up and scale of the experiment as well as the required soil height.

In addition to the soil boxes, advanced sensors, state-of-the-art instrumentation and data acquisition, soil testing equipment, and video conferencing capabilities are also part of the this facility. Advanced sensors include flexible sheet pressure and deformation sensors. Thin sheet pressure sensors are used to measure the contact pressure between a structural member and surrounding soil. The sheet pressure sensors consist of a matrix of very small sensing cells allowing for discrete pressure measurement at any point in the contact region. The pressure sheets, which have dimensions of 33 x 33 cm and 43 x 43 cm, are less than 0.7 mm thick and have 1,024 sensing points. The deformation sensors consist of several micro-machined electromechanical sensors, which enables gravity-based shape calculation over the sensed area. Customized thin and flexible sensors measuring deformation at intervals of 90 mm were used. These pressure and deformation (or movement) sensors coupled with data acquisition systems, and interface hardware and software produce complete measurement systems that deliver high resolution data in real time.

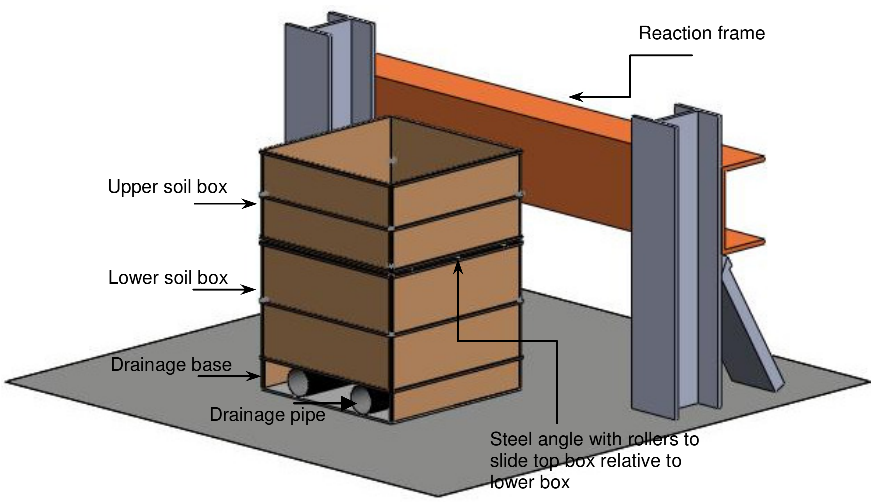
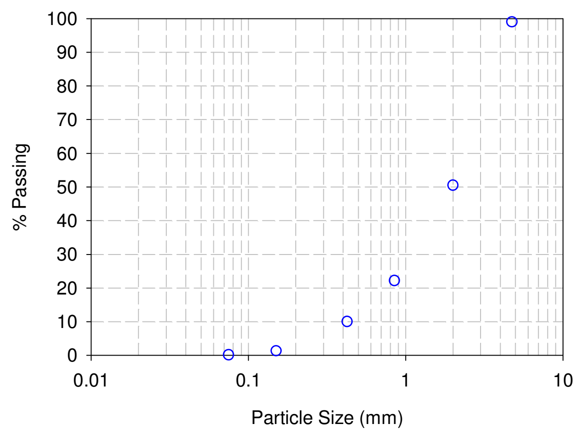


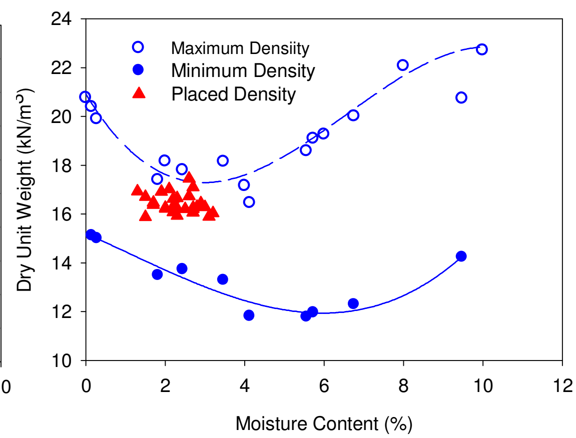
Fig. 2: Setup of Soil-Structure Interaction facility at Lafayette College.

Material Properties and Installation Procedure

The soil used in this experiment was classified as well-graded sand (SW) according to the Unified Soil Classification System (Fig. 3a). The soil was also characterized using the minimum and maximum relative density vibrating table tests conducted at several moisture contents. Test results shown in Fig. 3b show that the maximum and minimum unit weights of the well-graded sand were 20.8 kN/m^3 and 16.5 kN/m^3, respectively, and the bulking moisture content was approximately 3%. The soil was placed around an instrumented precast concrete pile by raining the soil from a height of approximately 1.5 m (see Fig. 3c). The dry unit weight and moisture content of the placed soil were measured for each soil layer using the nuclear density gauge (see Fig. 3d) and the results are summarized in Fig. 3b. The average dry unit weight of the soil was 16.4 kN/m^3 (i.e., relative density of 31.1%) at an average moisture content of 2.4%. The test pile, which was 101.6 mm in diameter and 1.17 m long, was reinforced with a single No. 4 (diam. = 12.7 mm) steel rebar placed in the middle of pile cross-section. The unconfined compressive strength of 101 mm x 203 mm concrete cylinders tested on the day of the lateral load test was 44.6 MPa and the split tensile strength was 4.1 MPa.



(a)



(b)

(c)

(d)

Fig. 3: Properties and installation of soil material used in the lateral load test, (a) gradation of the soil classified at well-graded sand, (b) relative density tests with minimum and maximum density curves conducted at different moisture contents compared with measured dry density and moisture content from the nuclear density gauge, (c) raining the soil from a height of approximately 1.5 m, and (d) nuclear gauge device used to measure soil properties.

Test Setup and Instrumentation

The test pile was 101.6 mm in diameter and 1.17 m long with a loading stub at the top of the pile that has dimensions of 152.4x152.4x101.6 mm (Fig. 4a). Threaded rods embedded in the loading stub along the loading direction were used to connect the loading jack and load cell. The loading point was at the center of the loading stub (i.e., length of pile below loading point was 1.11 m). The surface of the soil was located at 101.6 mm below the point of load application.

At the pile head (i.e., point of load application), the applied load, lateral movement, and rotation (tilt angle) were measured during the test (Fig. 4b). The interaction pressure between the pile and surrounding soil during the test was measured using sheet pressure sensors. Two pressure sheets, one with dimensions of 33 x33 cm and one with 43 x 43 cm, were wrapped around the pile with the top row of sensors located at 50.8 mm below the soil surface (i.e., 101.6 mm below the point of loading). The bottom pressure sheet extended to 854.3 mm below the point of loading. Since the bottom pressure sheet was longer than the perimeter of the pile, parts of the sheet were wrapped twice around part of the pile circumference. To illustrate the location of the pressure measurements on the pile circumference, four points were marked in Fig. 4c and the corresponding location of measurements on the pressure sheet were identified in the 2D pressure images for both pressure sheets (Fig. 4d and e). The pile was also instrumented with a flexible acceleration array to measure the lateral movement along the length of the pile (Fig. 4b) and strain gauges were mounted along the length of the steel reinforcement rebar. The locations of these strain gauges along the length of the pile were determined based on preliminary LPILE analysis performed before casting the pile.

RESULTS

Fig. 5 shows the measured lateral force-lateral displacement relationship of the test pile. The pile shows a nonlinear response as the pile displacement increases. The initial stiffness of the test pile was 35.27 N/mm and a maximum lateral displacement measured during the test was 144 mm at a lateral load of 3566 N. This figure indicates that at the end of the test the ultimate capacity of the soil-pile system was not reached. In fact, the test was terminated when approaching the maximum stroke of the hydraulic jack. The load-displacement relationship indicates an estimated capacity of the pile-soil system of approximately 4300 N at a lateral pile head displacement of approximately 200 mm.

The strains measured along the length of the reinforcing rebar increased to a depth of 482 mm below the point of loading and then started decreasing (see Fig. 6). The strain recorded at a depth of 864 mm was insignificant. The strain profile indicates a location of maximum moment at 482 mm below the point of loading (i.e., at a distance of 4.75 pile diameters). The strain profile also shows a high strain measured at a depth of 711 mm at applied load of 3558.4 N, which could have resulted from a crack forming at that location. Investigation of the pile surface after the test shows that two cracks were visible at depth of 482 mm and 711 mm, which correspond to strain gauges 6 and 8 as shown in Fig. 6b and c.

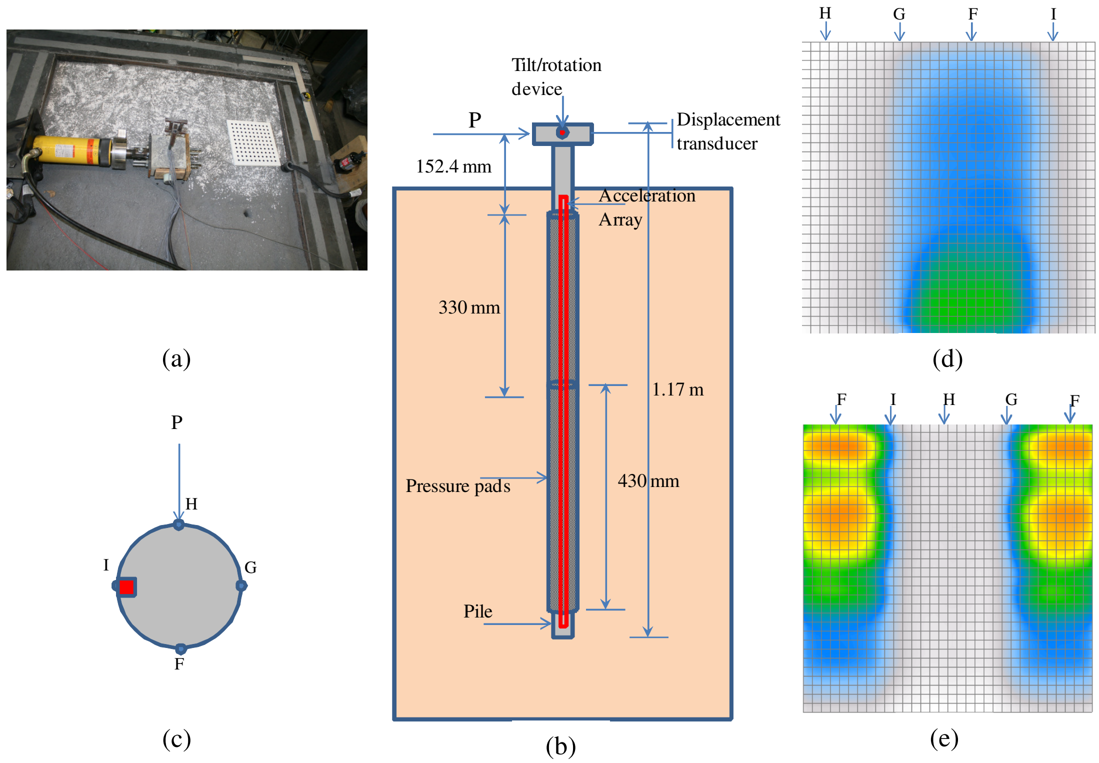


Fig. 4: Test setup and instrumentations of the soil-pile system, (a) soil box with the loading setup, displacement and rotation instrumentation, (b) dimensions and locations of instrumentation, (c) location of reference points used for pressure measurements with the acceleration array embedded on the side of the pile (square shape), (d) top pressure sheet, and (e) bottom pressure sheet.

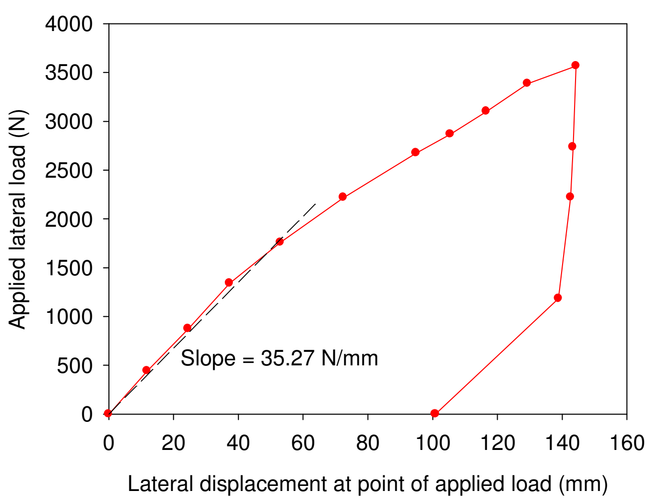
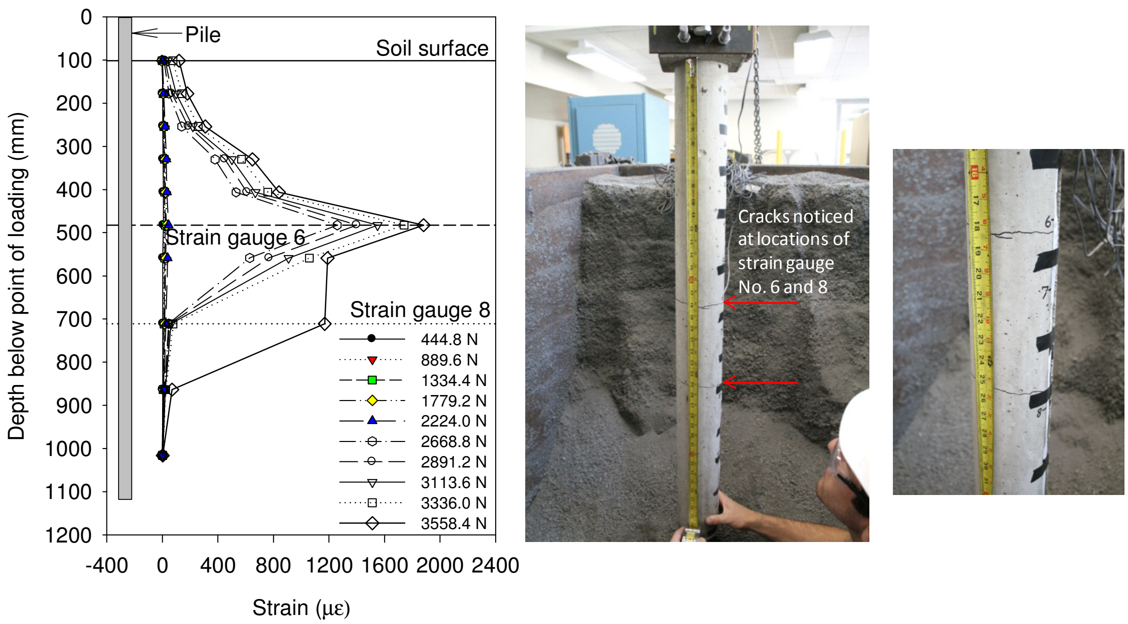


Fig. 5: Measured lateral load vs. lateral displacement of the test pile.

Fig. 7 shows the measured interaction pressure between the pile and surrounding soil at depths ranging from 43.1 cm to 86.1 cm (i.e., lower pressure sheet) at several stages during the lateral load test. Fig. 7 clearly shows the increase in the soil-pile interaction pressure in front of the pile (between points F and I, and F and G) as the load increases. As the pile displacement increases, the interaction pressure between the pile and surrounding soil increases. Furthermore, as the pile displacement increases, the zone of mobilized soil pressure in front of the pile increases. Along the distance covered by the lower pressure sheet, the zone of mobilized soil pressure progressively increases. When considering one pressure sensor located at point F at a specific distance below the point of loading, the measured pressure increases as the pile displacement increase. To obtain the full soil reaction force, the pressure distribution in front of the pile (along surface IFG in Fig. 4c) needs to be integrated at different stages of the test.

The location of the maximum measured pressure along the pile ranged from 47.2 cm to 56.6 cm. The depth of the maximum pressure for laterally loaded piles depends on several factors, mainly, the weakening influence caused by the stress-free soil surface and the relative stiffness between the pile and surrounding soil (Briaud et al. 1984).



(a) (b) (c)

Fig. 6: Strain profile and pile after testing, (a) strain profile along the length of the pile, (b) pile after test with marked cracks, and (c) close view of the cracks with marks showing the locations of strain gauges 6 and 8.

SUMMARY AND CONCLUSIONS

Unlike previous attempts, the soil-pile interaction pressure and the lateral movement along the length of the pile were successfully measured for a laterally loaded small-diameter pile installed in loose well-graded sand. A circular precast concrete pile, which is 101.6 mm in diameter and 1.17 m long reinforced with No. 4 steel rebar, was fully instrumented and tested under lateral load. Following is a summary of the findings presented in this paper:

1. The maximum measured displacement of the test pile was 144 mm at 3566 N. Extrapolation of the measured force-displacement response indicate an ultimate load of 4300 N at 200 mm lateral displacement.
2. The initial stiffness of the force-displacement response of the pile was 35.27 N/mm.
3. The location of maximum measured strain was at a depth of 482 mm, which is 4.75x pile diameter.
4. The soil-pile interaction pressure was successfully measured and the location of the maximum pressure ranged from 47.2 cm and 56.6 cm, which is influenced by the free soil surface and the relative stiffness between the pile and the soil.

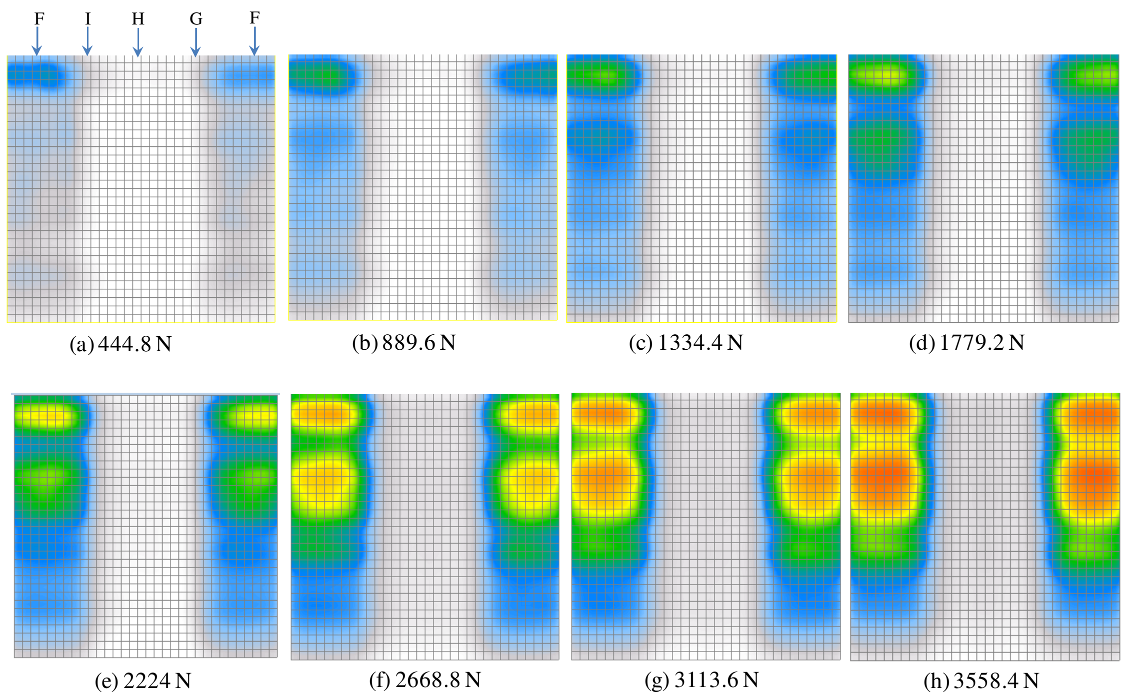


Fig. 7: Soil-pile interaction pressure measured at depth ranging from 43.1 cm to 86.1 cm at several stages during the test.

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