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Static Response of a Group of 13 Piles Tested Simultaneously

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Abstract. Static loading tests to plunging "failure" were performed on a single pile and a group of 13 piles in a loose to compact silty sand. The piles were 300-mm diameter, 9.5 m long, bored piles with an expanded pile toe, a 400 mm wide Expander Body (EB). Each pile had a bidirectional cell place just above the EB. All pile heads were free. The tests comprised a bidirectional test on the piles with the pile group cells activated via a common pressure pump, thus, ensuring that equal load was applied to all piles, allowing each pile to move individually. The pile group responded as a pier with shaft resistance equal to the shear along its side rather than as 13 single piles.

Keywords. Pile group, static loading test, bidirectional test, expander body.

1. Introduction

As a part of the 3rd Bolivian International Conference on Deep Foundations, May 2017, a comprehensive pile testing programme was undertaken at the Bolivian Experimental Site for Testing Piles, B.E.S.T. The main objective of programme was to compare the results of static loading tests on single piles constructed using different methods at a site where the geotechnical conditions would be documented by detailed investigations, using state-of-the-art testing and interpretation methods. The geotechnical conditions and the details on the piles and testing arrangement were presented by Fellenius and Terceros (2017). All the B.E.S.T. field investigations records and results of static loading tests are available for online downloading at the conference web site per the following link: http://www.cfpbolivia.com/web/page.aspx?refid=163.

2. Soil profile

The site investigation at the B.E.S.T. site, notably the CPTU sounding results, showed the soil profile to consist of essentially two soil layers: an upper 6 m thick layer of loose silt and sand on compact silty sand. The CPTU pore pressure measurements indicated a groundwater table at or near about 0.5-m depth and a hydrostatically distributed pore

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pressure. Figure 1 shows a diagram compiling borehole information, SPT *N*-indices, and the CPTU cone stress, q_t. to 14 m depth. The CPTU was pushed to 22 m depth and Figure 2 shows all the results.

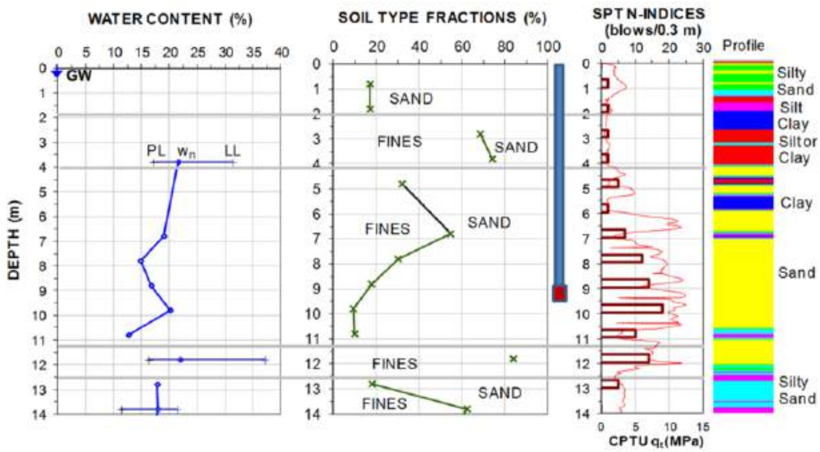

Figure 1. Soil profile from BH-E2.

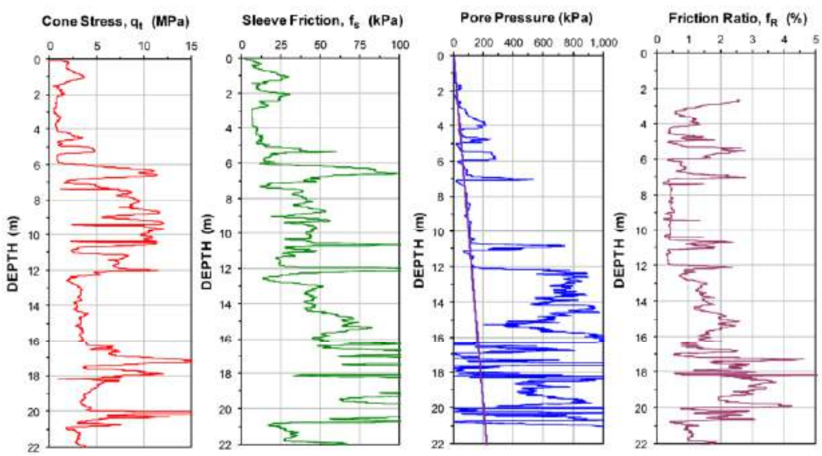

Figure 2. CPTU sounding diagram, CPTU E2.

3. Test piles

The pile group contained 13 piles, that all were 300-mm diameter, pressure-grouted Full Displacement Piles (FDP) constructed to 9.5 m depth. For reference to the group test, a single pile, the same in all respect to the group piles, was installed 5.0 m away from the nearest group pile and 3.5 m away from the nearest reaction pile. All piles were equipped with a bidirectional cell (BD) consisting of a 200 mm high and 80 mm wide hydraulic jack installed centered in each test pile at 8.3 m depth (lower end of the BD). All the BDs in the group piles were connected to a common pump, i.e., all BDs were acted upon by equal magnitude of load. Immediately below the BD, the piles were equipped with a (prior to expansion) 1.2-m long Expander Body (EBI612) that was expanded (pressurized with grout) after construction of the shaft. Twenty-four hours after the EB expansion the soil underneath the EBI was post-grouted to recompress the soil below the EBI. In most of the piles, the post grouting introduced minimal or no grout.

The Expander Body and its use is described by Terceros and Massarsch (2014). Figure 3 shows a photo of the Expander Body and BD Yellow unit) before insertion into the pile shaft. The BD is connected to the pile reinforcement cage. The location of the separation of the BD and cage from the EBI was designed to occur at the bottom of the BD.

Figure 3. Photo of the EBs and BD before pile construction.

Figure 4. Exhumed EB.

Figure 5. in-air expanded EB

Figures 4 and 5 show photos of an exhumed EBI and one expanded in air (model IDs EBI612 and EBI815, respectively, with the numbers indicating the diameter of a freely expanded unit. Figure 4 shows a photo of an exhumed EBI (EBI612) with post-expansion grout material and an in-air expanded EBI (EBI815). The grout volumes and injection pressures used for the expansion of the EBIs of the 14 test piles were very similar for the piles. The averages were 102 L and 4.0 MPa, respectively.

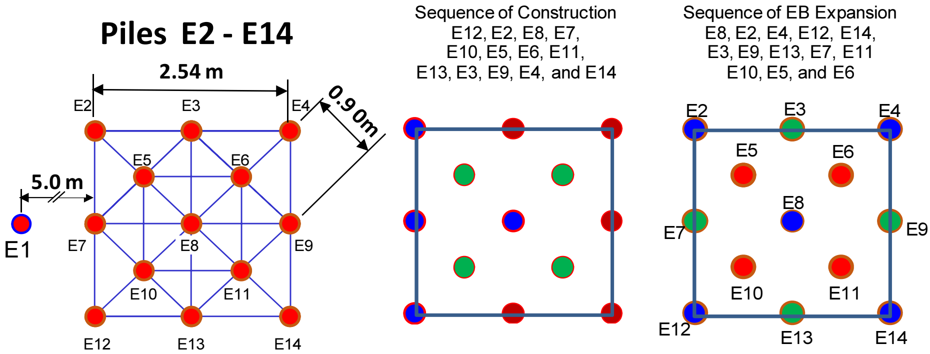

Figure 6. Pile locations and sequence of construction and EB expansion.

The piles were installed at a 3 pile-shaft diameter, center-to-center spacing, 0.90 m in the configuration shown in Figure 6. The spacing corresponds to an 11 % total footprint ratio (nominal total pile area over group footprint area excluding the EBI area).

The test piles were instrumented with one set of vibrating wire gages and three sets of electrical resistance gages. As mentioned in the report on the test results of the many other single test piles at the B.E.S.T. site, the vibrating wire gages did not provide reliable records due to difficulties in recording the data. Moreover, it was found that the EBI-expansion created an axial force in the test pile that left the pile with considerable residual force locked into the pile at inconsistent magnitude and distribution. Interpretation and presentation of the strain-gage measurements are therefore not included in this paper.

Although, the primary purpose of equipping the test piles with the EBI was to provide reaction force for the BD in forcing the pile length above the EB to move upward, telltales had been included to measure the downward movement of the EB to enable studying also the BD force versus downward movement of the EBI. Unfortunately, in all test piles, when the EBI expanded, the telltale connection of the downward telltale broke and no records of the downward movement of the EBI were obtained. The telltale measuring the upward movement of the BD upper plate functioned, however, Thus, the comparison between that movement and the pile head movement provided a measure of the pile shortening, a minimal amount, which main use was to verify the pile head movement measurements were reliable.

4. Test programme

Static loading tests were performed on the piles—the single pile and group piles—by engaging the BD cell to push the pile shaft upward with the EB providing the necessary reaction force. The BD cells in the group piles were connected to the same pump to have all group piles, Piles E2 - E14, activated with equal load per pile. The pile heads were unrestrained and the pile head movements were measured individually. Figure 7.a shows the general arrangement with beams and reaction piles locations and Figure 7.b shows a photo of the arrangement for recording the individual movements of the piles. The measurements included monitoring the ground surface movements at 10 points along the perimeter and in the interior area of the group.

The test schedule, same for the single pile, Pile E1, and the group piles, Piles E2 - E14, consisted of applying equal load increments of 50 kN/pile every 10 minutes and recording the movement of the pile head until it became excessive.

(a) (b)

Figure 7. (a) General arrangement of at the test, showing reaction piles and beams; (b) Frame for recording pile movements Phase 1 test on Piles E2 - E14.

5. Results of Field Tests

PILE E1. The measurement comprised imposing load in the BD and recording the upward movement of the pile. The compression of the pile as measured between the BD upper plate and the pile head was generally very small; <1 mm at the maximum test load. The maximum strain measured at 5 m depth was about 100 με.

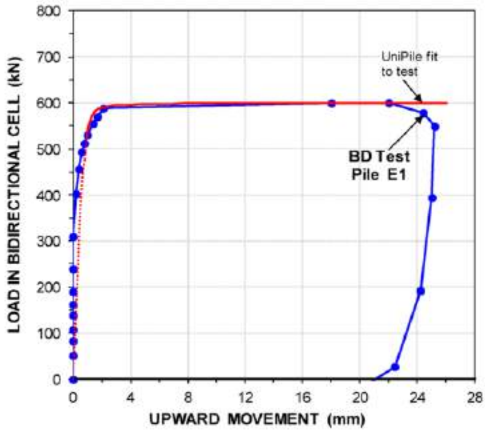

Figure 8. Pile E1 Upward load-movement of the pile length above the BD.

Figure 8 shows the measured load-movement of the upper pile length, plotted in accordance with the reporting convention of bidirectional testing as load vs. movement. The pile response to the applied BD load was quite stiff with very small movement up to 500 kN applied load at about 1 mm movement, which indicates the presence of residual compression force in the pile at the start of the test. Beyond 600 kN load and 2 mm movement, the response went into plunging. The figure also shows the result of a fit to the measured curve per an effective stress analysis and a hyperbolic t-z function with a function coefficient of 0.0099 ($1/Q_{100\,\%}$). The effective stress proportionality beta-coefficient, as applied to 1.0 m pile elements, ranged from ß = 0.4 at the ground surface to ß = 2.0 at 6 m depth, which value was then kept to the BD depth. The UniPile5 software (Goudreault and Fellenius 2014) was used to back-calculate the pile response.

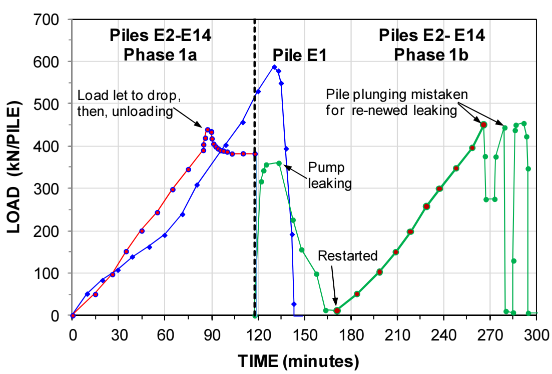

Figure 9. Loading sequence for Pile E1 and Piles E2 - E14.

PILES E2 - E14. The static loading test on the pile group, Piles E2 - E14 started on April 25, 2017, applying the same schedule of loading as used for the single pile test, Phase 1a. Nine load increments into the test, it was realized that the data collector was not recording properly and this triggered an unloading of the test to restart with a functioning collector. Unfortunately, on reaching zero BD load, the cells were let to drain further, which allowed the remaining force in the pile to move the upper BD plate against zero force. The test was then restarted three days later from zero BD load and with zeroing of all gages. Figure 9 shows the load/pile versus time applied. The load-movement measured for Pile E1 is included. Shortly after re-starting the test, it was found that the pump had sprung a leak preventing it from maintaining pressure. The BDs were then unloaded to almost zero pressure, whereupon they were locked from further release of hydraulic pressure and the pump was repaired. The re-loading was performed with the same reference of load and movements as at the start of Phase 1b.

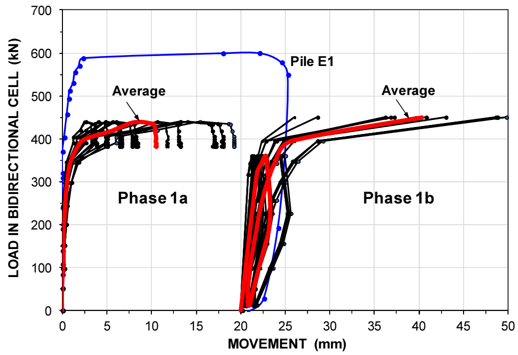

Figure 10. Pile E1 and Piles E2 - E14. Pile head upward load-movements.

Figure 10 shows the Piles E2 - E14 load-movements. The response of the 13 piles was very similar to that of the single pile: initially quite stiff and plunging after just a few millimetre of movement. However, the plunging load per pile was only about 70 % of the plunging load measured for Pile E1—430 kN versus 600 kN.

Figure 11 shows the upward movement of all pile heads across the two diagonals, including the net movements after Phase 1b unloading. Both graphs include the average of all pile head movements measured in Phase 1b for the maximum load, i.e., average of four piles, but for the center pile. The measurements showed that the center pile moved about three times more than the perimeter pile.

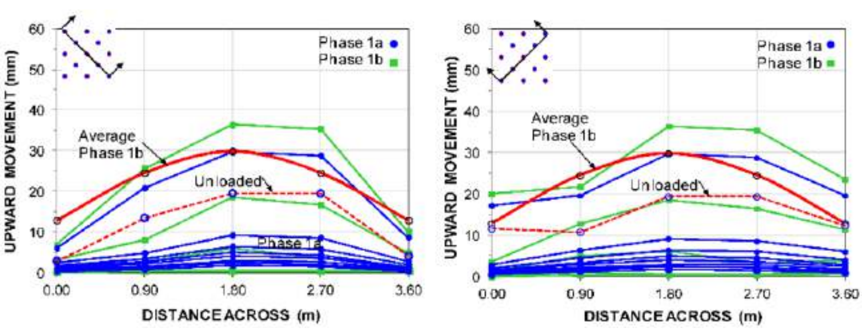

Figure 11. Upward movement of the pile heads along the diagonals, Phases 1a and 1b.

Figure 12 shows the ground-surface upward movements across the diagonals (including net movements after Phase 1b unloading) and average (at maximum load) ground surface heave, as measured in ten anchors for Phase 1b. The figures repeat the average (at maximum load) upward movement of the pile heads (c.f., Figure 11). The "zero" measurement is the start of the Phase 1b, the net effect of Phase 1a is not known. It would seem that the pile heads moved a bit more than the soil surface. However, this is misleading because the pile head movements in Phase 1a in unloading were not recorded and, as mentioned, the Phase 1a ground surface measurements were not collected by the data collector. That is, the movements of the pile heads and the ground surface at the start of Phase 1b are unknown. The trend of the ground surface movements and that of the pile heads are the similar. In unloading after Phase 1b maximum load, the unloading movements were about the same for the pile head and the ground surface. It would seem that the pile head and ground surface moved more or less in unison.

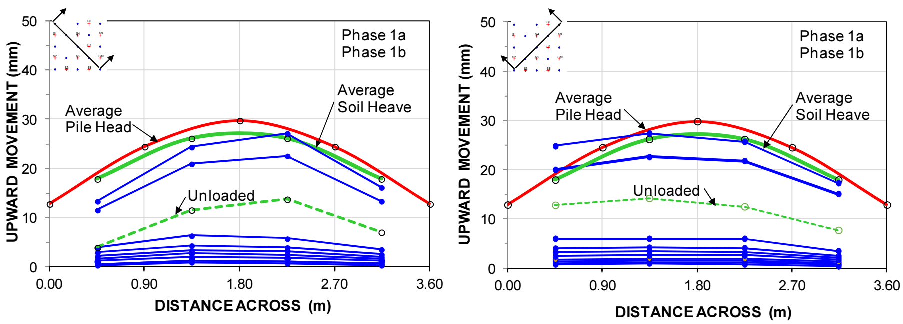

Figure 12. Upward movement of the ground surface within the pile group. Phase 1b.

The test on the single pile, Pile E1, showed plunging response at 600 kN. If we assume that each of the eight perimeter piles provided the same plunging resistance (600 kN) as the single pile and that the total load consisted of the pile resistance and the weight of the soil in-between the piles (≈700 kN), i.e., 13*430 - 700 = 4,890 kN, then, each of the eight would have carried 4,890 kN/8 = 610 kN and no contribution would have been needed from the interior piles. It would seem that the interior piles did not experience any soil resistance.

The nominal circumferential area of Pile E1 is $0.94 m^2/m$. The circumferential area of the pile group taken as a pier with a circumference equal to that of the pile group is about $10 m^2/m$ or about $1.25 m^2/m$ per perimeter pile, i.e., 32 % larger. This suggests that the perimeter piles carried the load as opposed to it being carried by the "pier".

Figure 13 and 14 are photographs of piles and ground taken after Phase 1b unloading and show cracks in the ground surface around a corner pile and from pile to pile along the perimeter of the group. The observations suggest that the pile group moved in unison encompassing piles and in-between soil.

6. Conclusions

A plunging mode developed at very small movements for the single pile as well as the pile group. The results of the test on the pile group indicated that the eight perimeter piles carried the load with the five interior piles not experiencing resistance to the upward loading. This was supported by the appearance of cracks around the pile group indicating that soil and piles had moved more or less in unison.

An effective stress analysis of the response to the maximum test load on the single pile corresponded to ß = 0.4 at the ground surface increasing linearly to ß = 2.0 at 6 m depth, which value was then kept the same to the BD depth. The 2.0-value is large and probably a result of the pile diameter being larger than the nominal value and that the FDP construction process had increased the horizontal stress against the pile.

The Expander Body proved to provide a considerable toe resistance to the pile enabling the BDs to push the piles as planned.

Figure 13. Photographs of cracks in ground surface at a corner pile and at two side piles.

Figure 14. Photographs of cracks in ground surface stretching from one pile toward the next along the side of the group.

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