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PILING PRACTICE IN THE SEDIMENTARY GRANULAR SOILS OF SANTA CRUZ, BOLIVIA

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ABSTRACT

The city of Santa Cruz, Bolivia, is historically dominated by houses and three to five storey buildings. The geology in and around the city is such that even very light buildings need to be supported on piles. The recent increase of the Bolivian economy, notably that of Santa Cruz, has created a demand for new residential as well as office and industrial buildings, which mostly consist of multi-storey or high-rise buildings with significantly larger foundation loads. Foundation piles have become larger and longer, and the load on individual piles is increased. The development has resulted in an increase in the demand for more sophisticated design and construction methods and stricter approach to verifying the quality of the construction processes and results.

This paper describes to geology of the Santa Cruz region and how the geotechnical conditions are considered in the design and construction of piled foundations. The improvement of past construction and design techniques, based mostly on bored piles constructed with bentonite slurry, is being replaced with new methods of constructing bored piles, e.g. the Full Displacement Pile (FDP) and incorporation of techniques such as enlarging the pile toe, e.g., with the Expander Body. This paper presents the results of several full-scale tests and discusses the incorporation of the test results in design and construction.

1 GEOLOGY OF THE REGION

Santa Cruz de la Sierra is located in the eastern lowlands and sub-Andean zone of Bolivia, South America. The area lies at an elevation of about +400 m and the geology is a Paleozoic (250 million years old) sedimentary basin. The soils of interest to civil engineering construction are quaternary with the dominant minerals being calcite, silica, and feldspar. The main agent is the Piray River and its tributaries, which past meandering over the area has resulted in a sedimentation-erosion-sedimentation process and a profile dominated by fine to medium sands with intermittent layers of clay or clayey sand. With increasing distance from the river, the clay-containing layers are thicker.

Fig.1.- View of Bolivia with location of Santa Cruz and map of Santa Cruz

The upper about 15 to 18 m thick part of the profile consists of normally consolidated layers of clays, silts, sands, in various combination and thickness. Below, the soil is more homogeneous and consists mostly of sand and gravel. The groundwater table lies typically at a depth of about 6 m in the highest part of the city and at about 1 to 3 m depth in the lowest part of the city.

Dense layers or zones can occasionally be found within in the upper 15 to 18 m depth and, frequently, looser or softer layers are located below such dense layer. The spatial variation can be radically different between short horizontal distances.

The geology in and around the city is such that even light buildings need to be supported on piles.

2. LOCAL GEOTECHNICAL PRACTICE

The local practice uses almost exclusively standard penetration tests, SPT, in boreholes. Since a few years, geophysical studies, mainly seismic refraction and surface waves, is used as complement to the SPT. The cone penetration test, CPT or CPTU, has not been used at all until very recently.

A main problem is that the SPT is operated manually—not even a cat head is used—and the weight of the rods differ between rigs, and the control of height of the drop of the hammer is not accurately maintained, etc. Therefore, the reliability of the N-indices is low, necessitating the local practice to apply empirical correction factors with all the uncertainty of this approach.

The typical laboratory tests performed on the recovered split-spoon samples are natural water content, grain size distribution, and Atterberg limits. Unconfined compression tests and direct shear tests are sometimes performed on split-spoon samples of cohesive material.

With all these questions in mind, the estimation of pile capacity and settlement of the piled foundations, be it based on empirical or theoretical methods, becomes difficult and uncertain. Foundation design in Santa Cruz is therefore very conservative. As the city is dominated by three to five storey buildings, the conservatism has not appreciably affected the costs of the foundation construction. However, as the current resource-based economy results in the design and construction of considerably taller and heavier buildings, the demand for economical yet safe foundations is increasing.

3. TYPE OF PILES CURRENTLY USED

The annual total length of pile installed in Santa Cruz is estimated to about 40,000 m and the gross annual value of the piling construction is about 5 million US dollars.

The main system used for pile foundations in Santa Cruz is a bored pile, drilled using bentonite slurry. The process is as follows: A hole is advanced using a rotating cutting tool with a helix attached to the end of a kelly. The tool has the same diameter as the diameter of the shaft. The drilling is pursued with continuous pumping of bentonite slurry to a swivel entry at the top of the kelly, down through the kelly, and out through the cutting tool. The cutting tool mixes the soil with the slurry and the continuous injection of slurry sends the soil-slurry mix up the hole to the ground surface. Here, the mix flows by gravity in channels dug on the ground to a collection pit, where it is desanded and pumped back to the kelly. When the cutting tool has reached the desired depth, circulation of desanded slurry is continued until the sand content in the mix at the ground is deemed acceptably low. The acceptance criterion for viscosity applied is generally 40 seconds for a liter of slurry to flow out of a Marsh funnel and no more than 2 % of sand contained in the slurry. On confirming the proper slurry condition, the kelly is withdrawn and a reinforcing cage is lowered into the slurry to a desired depth. Then, a tremie pipe is inserted through the slurry to the pile toe and the slurry is replaced with concrete in a regular tremie process. Figure 2 shows a photo from a typical project involving the standard bored pile, demonstrating the mess at the site created by the construction process.

Considerable clean-up of the site is required after the piles have been constructed. The construction method results in a very soft pile toe, and, therefore, the design usually employs a very conservative estimate for the toe resistance. Moreover, because of the soils are very susceptible to erosion, the shaft will exhibit frequent bulges and neckings.

In the past, the most common piles used for foundation of industrial constructions, bridges, and urban buildings was wood piles. In 1970, precast concrete piles were introduced and almost all the industrial and residential buildings built before 1980 are supported on 250-mm thorough 400- mm square diameter, up to 15 m long, precast concrete piles. Then, urban regulations prohibited pile driving in urban areas because driving piles near existing, older buildings (frequent in the older part of the city), showed to cause significant settlement of existing foundations from the vibrations originating from the pile driving. An additional reason was the limitation to 15 m depth (splicing was not used) and the difficulty in driving through the occasionally encountered stiff layers at shallow depths. Penetrating these layers necessitated hard driving and, as the layers are frequently underlain by soft soils, damaging tension developed in the piles creating construction issues due to pile breakage. Steel driven piles are rarely used.

Fig. 2 Photos from a construction site in Santa Cruz, Bolivia, showing rig and collection pit

The construction industry uses mainly gravity (drop) hammers weighing from about 20 kN through about 40 kN. Air/steam or diesel hammers have only been used on a few occasions.

Piled foundations are designed using principles of working stress with a factor of safety of about 2.6 applied to the pile capacity determined from theoretical/empirical analysis and about 2.0 applied to the capacity determined in a static loading test.

The theoretical/empirical analysis is based on the methods by Meyerhof (1976) or Decourt (1988), which calculate ultimate shaft resistance and toe resistance by applying correlation factors to the SPT N-indices. Sometimes, the SPT N-indices are used to estimate a soil friction angle according to methods presented by Kishida (1967) and Poulos and Davis (1980). The so determined friction angle, which considers the construction process, is then used as input to empirical methods for calculating expected pile capacity.

Since 1994, the Expander Body (EB) system (Broms and Nord 1985, Massarsch and Wetterling 1993, Terceros Herrera 1995, Terceros Herrera 2013) is employed in Bolivia. The EB consists of a folded steel balloon that is installed at the pile toe of the pile prior to concreting the shaft. When injected with grout, the balloon is inflated to several times its folded diameter. The grout volume and grouting pressure are recorded during the process. After the grout has hardened, the bottom of the EB is post grouted. Figure 3 shows the procedure of inflating (expanding) the EB. The local practice has developed to consider, conservatively, the EB-equipped pile to have three times the toe resistance of that calculated for the standard bored pile. Until now, more than 11.000 Expander Bodies has been installed in Bolivia for different type of structures (bridges, tall buildings, silos, industries), combined with different type of piles (bored under bentonite, vibrated metallic shafts, FDP) and in various geotechnical conditions (clays, silts, sands and gravels).

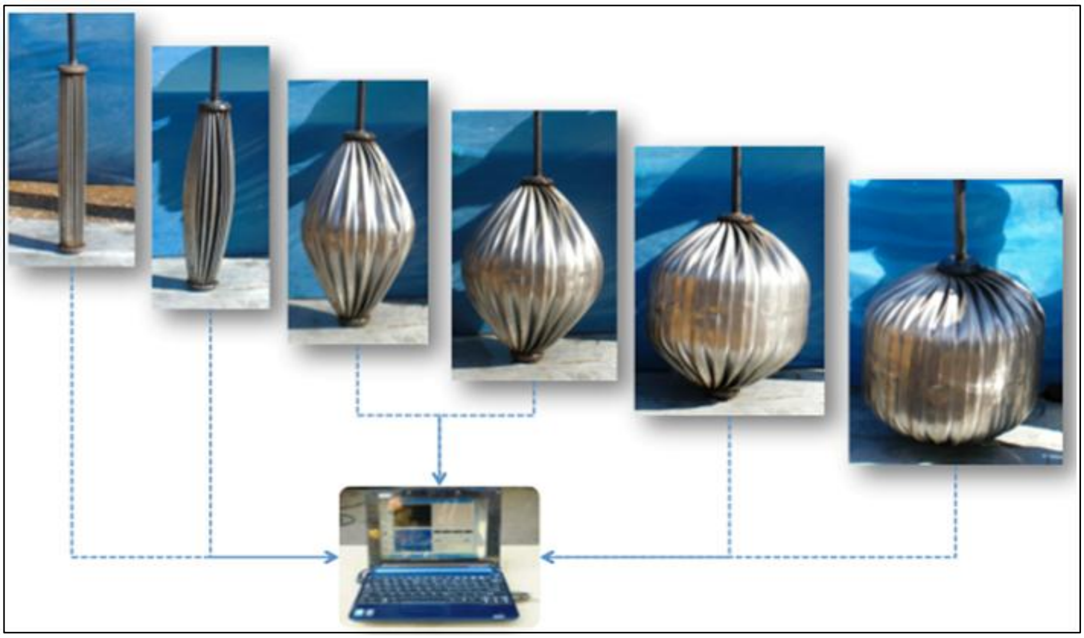

Fig. 3 Procedure of expanding the EB (from Terceros 2013)

The full displacement pile, FDP, an alternative bored pile, was introduced in 2012. The FDP consists of a 360-mm to 450 mm O.D. displacement body with a 25-mm wall attached to an auger length. Rotating the auger pulls down the pipe and displacement body and no soils removed (but for nearest the ground surface on starting the pile). When the desired depth had been reached, concrete is pumped through the displacement body and out through the auger tip during gradual withdrawal of the system. Thereafter, a reinforcement cage is lowered into the concrete to the pile toe. Figure 4 shows a photograph of the FDP equipment ready to construct a pile.

The compact sandy soils in and around Santa Cruz have shown to be very suitable for the FDP pile. Since its introduction, close to 2,000 FDP piles have been installed. No practice has yet been established for considering the significant increase of capacity for the FDP pile as opposed to the standard bored pile. However, several static loading tests as well as dynamic tests (PDA and CAPWAP analysis) have shown that the FDP pile develops at least twice the unit shaft resistance of the standard pile and a stiffer and more consistent toe resistance. When increase of toe resistance is required, the FDP pile is equipped with an Expander Base.

4. DESIGN OF PILED FOUNDATIONS IN BOLIVIA

Figure 5 shows the load-movement response of static loading tests on six standard type bored piles of diameters ranging from 350 mm through 450 mm and lengths ranging from 10 through 18 m. The SPT N-indices from the site indicate a compact soil (low-range of compactness; 10 through 15 bl/0.3m). All are bored piles drilled under bentonite. The curves show clearly that the pile response to the applied load is mostly through shaft resistance. Moreover, by most definitions of ultimate resistance, the tests have been brought to full mobilization of the pile capacity.

Fig. 4 The FDP pile construction unit

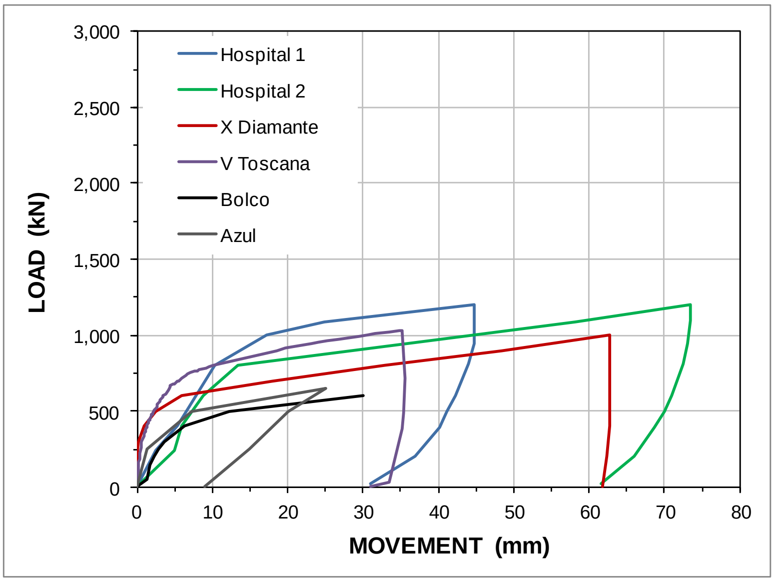

Fig. 5 Load-movement curves for static loading tests on six standard bored piles

The response from FDP piles with Expander Base is shown in Figure 6. The piles have the same range of diameter and length as the standard bored piles. In contrast to the response of the bored piles, the pile capacity has not been mobilized for the piles despite the maximum applied loads are much larger than those shown for the standard type piles.

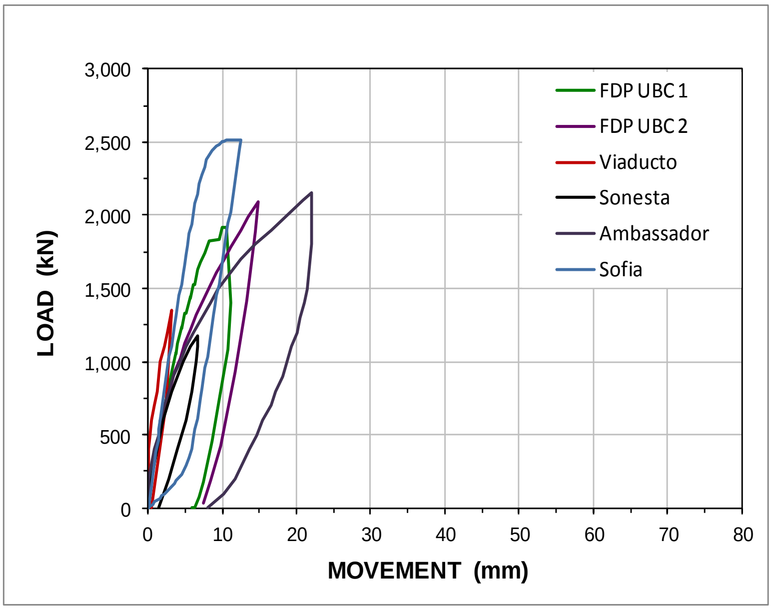

Fig. 6 Load-movement curves for static loading tests on six FDP bored piles

In April 2013, four strain-gage instrumented piles—two bored piles and two FDP piles—were constructed and subjected to static loading tests with the objective of comparing the load movement response and the load distributions for the piles. One of each pile type was equipped with an Expander Base (EB) at the pile toe. The bored pile with EB was tested using the bidirectional-cell and regular head-down tests were used to test the other three. The results of the test—presented to this conference by Fellenius and Terceros (2014)—show that the shaft resistance for the FDP piles was more than twice that of the bored piles and that the addition of the EB increased stiffness of the pile toe much beyond that of the pile without the EB.

6. CONCLUSIONS

The recent increase of the Santa Cruz, as well as the overall Bolivian, economy due to the expansion of the hydrocarbon industry, has created a demand for new residential as well as office and industrial buildings, which mostly consist of multi-storey or high-rise buildings with significantly larger foundation loads. Foundation piles have become larger and longer, the load on individual piles has increased, and the limits placed on acceptable differential settlement have become stricter. The development has resulted in a demand for higher capacity piles and use of more sophisticated design and construction methods, as well as a more rigorous approach to verifying the quality of the construction processes and results

The demands are being met by the Expander Body, which provides an assured stiff pile toe response, and by the introduction of the FDP pile, which offers a substantial increase of pile shaft capacity as well as a higher quality pile. The demand for more sophisticated analysis and testing method is being met by the introduction of high-capacity SCPTU equipment for use in site investigations, static pile loading tests performed on instrumented piles, and applying pile dynamics methods for integrity testing and capacity determination.

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