FEATURE ARTICLE

Pile Driving Between the Amazon and Xingu Rivers: Solution Found

The construction of the 1,800 km (1,125 mi) long Tucuruí-Macapá-Manaus High Voltage Power Line started in 2008, and the Brazilian National Electrical System Operator first powered it in July of 2013. At a total cost of US$1.2 billion, it encompasses more than 3,300 towers, some of them 300 m (980 ft) tall — the equivalent of a 100-floor building. The job was one of extreme technical complexity, crossing regions of major forests and rivers. The line now connects the northern Brazilian states of Amazonas, Amapá and Pará to the Brazilian National Electricity Grid, greatly improving the reliability of energy distribution in that region, and eliminating the need for diesel fuel thermal plants, with their larger environmental footprint. It also provides fiber optic network to the two state capitals, Macapá and Manaus.

The Spanish contractor Isolux Corsán won the tender to construct and operate a substantial part of the line, including the part between the Amazon and the Xingu Rivers. Work on this part started in 2012, and included about 100 transmission towers up to 150 m (490 ft) high, through a region known as "Alagados." This region has a 1.5 m (5 ft) water level during the rainy season, and soaked ground the rest of the year. Navigating regular vessels is impossible during the flood season, when dense and intricate vegetation called "bulhado" fills the riverbed, and vehicle traffic is impossible during the dry season,

Figure 1. The "bulhado" vegetation, which makes navigation difficult in the rainy season

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due to the extremely low surface soil resistance. The contractors responsible for installing the foundations for the towers faced great logistical and technical difficulties, and developed new systems for driving the piles, with the simultaneous use of 15 small piling rigs. Here we describe the methods used for determining the driving and acceptance criteria, using Dynamic Load Tests (DLT) corroborated by Static Load Tests (SLT).

The Geographical Challenge

The Alagados region lies inside an Environmental Extractive Reserve called "Verde para Sempre" (Forever Green), created in 2003. This is one of the largest environmental reserves in Brazil, with very strict environmental control parameters. No deep foundation had ever been executed before along this region. The main challenge faced on this job, however, was working in a place where self-propelling vessels or land vehicles and equipment could not be used. During the rainy season, the bulhado vegetation prevents the movement of outboard motor boats with propellers going deeper than 50 cm (20 in) (see Figure 1). In the dry season, the heavy mud prevents the movement of driving equipment (see Figure 2).

Initially, the foundation contractor tried to utilize large size equipment, based on previous experience on this same job, namely the crossing of the Amazon River. That part of the job had taken place on a shoal near the margins of the Amazon River, on waters with depths ranging from 25 m (82 ft) and 2 m (6.5 ft). Due to the size of the Amazon, it does not have the dense bulhado vegetation of the smaller rivers, so despite the relatively shallow waters in some regions, self-propelling vessels could still navigate. A Chinese contractor built Tower 238, later known as the "Chinese Tower," used in the crossing of the Amazon River.

Figure 3 shows the kind of equipment used in the foundations of Tower 238. Vibratory and diesel hammers were used, weighing about 100 KN (22 kips), activated by an 1,150 KN (260 kips) main crane and a 750 KN (170 kips) secondary crane, on a 1,000 m^2 (10,000 ft^2) barge. The draft of that barge was close to 1.5 m (5 ft) in the river.

This kind of equipment in the Alagados region failed. The barge could only get in the Alagados with extreme difficulty, and could cause environmental damages, with the opening of access paths larger than those permitted in the construction license.

The project called for the driving of open-ended steel pipe piles, with diameters between 400 and 600 mm (16 and 24 in), lengths between 15 and 60 m (50 and 200 ft), compressive design load from 600 to 1,100 KN (135 to 250 kips), and uplift loads varying from 400 to 700 KN (90 to 160 kips). The contractor sought a solution that would allow driving such piles in those adverse conditions. The factors affecting the choice of the construction process were:

- The pile installation had to be carried out in the rainy season, that is, from March to July. After that, the dry season would make it almost impossible for any equipment to access the driving locations.
- The axis of the transmission line was up to 15 km (10 mi) away from the existing access rivers, the Aiquiqui and the Uiuy, and the access would have to be through the flooded area, with water levels as low as 1 m (3 ft), even in the rainy season.

Figure 2. Heavy mud in the dry season makes equipment movement almost impossible

Figure 3. Equipment used for driving the foundations of Tower 238, the "Chinese Tower"

- The dense vegetation in the water, the bulhado, existed in all the access and construction areas, making it impossible to use self-propelling vessels to move the barges.
- The environmental regulations only allowed a 5 m (16 ft) wide opening inside the axis of the line. They did not allow deforestation of the access regions.

Solutions

1. Using very light driving equipment and splitting the auxiliary equipment between several barges: The solution adopted assumed that the driving equipment should be as light as possible, and distributed between more barges, with lighter weight on each. This lowered the draft of the barges, and resulted in lower penetration in the bulhado vegetation. The lightest possible driving equipment would be a gravity hammer, with the lightest ram that would still allow driving piles to the required depth. These devices weighed about 90 KN (20 kips), with 10 KN (2.2 kips) of auxiliary equipment. The total weight of this configuration was 100 KN (22 kips), compared to about 3,000 KN (670 kips) of the solution used in the "Chinese Tower."

Gravity hammers, however, have a much lower productivity than vibratory or diesel hammers. Driving a pile with vibratory or diesel hammers of equivalent energy can be up to 10 times faster, due to their much higher blow rate. Furthermore, the crane used by the first contractor had a tall boom, which allowed lifting up to 48 m (160 ft) long pieces. They could weld the pile segments all at once on the ground, greatly speeding up the installation process. The solution adopted precluded the use of such tall booms, making it necessary to weld each segment during driving, which slowed down the process even more.

Due to the much lower productivity of the system now used, a larger number of piling rigs had to be used in order to comply with the time constraints. Fifteen rigs were used, each one with its own barge. Additional barges were also required for navigation, for temporary living and resting quarters for the crew, and for transporting the piles to the driving site. Forty small barges were used in total, in place of the two large ones used in the crossing of the Amazon River. A crew of 150 people was required for the gravity hammers, instead of the 10 people required by the heavy equipment.

A solution that at first seemed more expensive and slower proved, however, to be up to the challenge. The more sophisticated original solution failed. Figure 4 shows the driving system used to drive the steel pipe piles.

Figure 4. Light gravity driving system, on a small barge

2. Use of excavators over barges to propel the driving systems and auxiliary equipment: Before 2003, when the Alagados area was declared an environmental reserve, there was a period of intense exploration of hardwood from large trees. The lumbermen transported logs weighing several tons, and they did that by means of a loader on a barge: they placed a reinforced wooden structure, 1.5 m (5 ft) wide and 4 m (13 ft) long, on the shell of the loader. This piece, moving close to the water surface by the loader shell, worked as a paddle.

The idea of the loggers was the basis of the solution adopted for propelling the barges, except that a 25 tonne (55 kips) hydraulic excavator now replaced the loader, for added maneuverability. The shell of the excavator worked as a paddle, and since it can move in several directions, so could the barge. The hydraulic excavator on a barge was the sole means of propulsion used. It acted the same way as an outboard motor tug, with the advantage of not having the motor underwater, thus eliminating the risk of the propeller tangling in the dense vegetation, as shown in Figure 5.

Navigating Traditional Paths & Trails

The riparian paths. The Aiquiqui and Uiuy Rivers were used to access the axis of the transmission line. Descendants of the native Indians have lived by the margins of those rivers for hundreds of years. They know the deepest spots in the Alagados region, so the contractor hired them as

Figure 5. Excavator-on-a-barge system used

guides for navigating the barges through the less favorable locations.

The buffalo trails. After the creation of the environmental reserve in 2003, the only major economic activity permitted in the region is raising buffalos. Those animals always follow the same path when returning to their stalls. Since the soil has very low resistance, the weight of the buffalos throughout the time deepened the terrain, allowing the use of the path for navigation. The buffalos also destroyed the native vegetation along that path, making it even easier to navigate, with no further environmental damage. The contractors could take advantage of those buffalo trails, through information given by locals, for navigating the barges through the Alagados.

Driving Criteria and Dynamic vs. Static Load Tests

The foundation designers sized the diameters and lengths of the piles utilizing semi-empirical methods widely used in Brazil. Those methods propose a correlation between the NSPT and the lateral adhesion factor and the end bearing of the piles. The designers established a minimum total number of hammer blows and a minimum penetration depth as field verification criteria. Early in the pile driving process, however, it became clear that the criteria defined in the project were not adequate. In several cases, the piles reached the required depth, but not the total number of blows; in other cases, the driving reached the total number of blows, but the driven length was not sufficient according to the project.

Even taking into account possible inaccuracies in the soil borings, the discrepancies between the predicted and actual behaviors were too great. This was attributed to the inadequacy of the semi-empirical methods used, which were developed based on correlations between NSPT and Static Load Tests (SLT) results carried out in the southern part of Brazil, where the geological formations are much different.

The contractor's option was to perform load tests to verify the real capacity of the piles. The conditions in the Alagados region made executing SLT difficult and expensive. Dynamic Load Tests using the Pile Driving Analyzer (PDA®) are faster and less costly, allowing the testing of a larger number of piles. To validate the DLT, the parties to the project deemed it necessary to carry out comparisons of SLT and PDA results on test piles. They decided to create an experimental test site at the city of Porto de Moz, Pará, in the southern edge of the job site. They drove five test piles in the site and submitted them to SLT and PDA tests.

The tests performed in this experimental test site indicated good agreement between the results of static load tests carried to failure with those obtained with the PDA combined with the CAPWAP® method. The tests also indicated an increase in the capacity due to the setup effect, between end of drive and a restrike performed ten days later.

The results from the experimental test site led to choosing the PDA test results as the pile acceptance criteria. The specifications called for testing at least one pile per tower, chosen mainly based on the pile position in relation to the barge, minimizing the time spent on the positioning of the barge.

Some end-of-drive PDA test results in the Alagados region indicated that the uplift capacities (calculated as the skin friction reduced by a factor of 0.8), and in some cases even the compressive capacities were not being reached, so the piles would have to be driven further. This would represent an increase in the cost of the job, in terms of labor and additional piles. Since the results obtained in the experimental test site showed that the soils in the region exhibited a substantial gain in skin friction with time, the parties involved determined that a new test would be carried out a few days after the first one, if the initial results were not satisfactory. Retesting the piles with the PDA at different times after initial driving showed that the setup effect increased the capacity of the piles to the levels required by the project, allowing great savings in time and cost.

Conclusions

Adequately sizing the equipment navigation in flooded regions similar to the Amazon is very important for economic and environmental reasons. The project's large and heavy driving equipment was not adequate for navigating the floodplains of the rivers in the Amazon region, but light driving rigs on low draft barges seemed to be the ideal solution. This project shows that traditional foundation design methods may not be adequate for this region. New geotechnical studies are necessary, aimed at establishing more reliable design methods. Intensive use of Dynamic Load Tests, confirmed by Static Load Tests performed in the same region, should be mandatory. This is the only methodology with which one can currently rely.