

Dynamic Pile Load Testing Experiences in Costa Rica. Three Case Studies: Moin Oil Terminal, Caldera Grain Pier, and Chucas Bridge.

**Mauricio Coto,¹ Luis Ángel Vargas,² and
Luis Millán Solórzano³**

¹MVM Instrumentación; San José, Costa Rica, e-mail: mcoto@myv-sg.com

²MVM Instrumentación; San José, Costa Rica, e-mail: lvargas@myv-sg.com

³MVM Instrumentación; San José, Costa Rica; e-mail: luis@millaning.com

ABSTRACT

The present paper discusses dynamic pile load testing (DLT) experiences in Costa Rica, specifically the results from three case studies, performed by the authors. These cases are the Caldera Grain Pier, the Moin Oil Terminal and a bridge over Tarcoles river at Chucas hydroelectric project. In every case, DLT was relevant to define criteria, follow-up driving conditions, estimate set-up, and confirm pile capacity. On two of those projects, static pile load tests (SLT) were also carried out, in parallel, thus allowing comparisons between DLT and SLT results. For every case study, results are presented and compared, furthermore conclusions and lessons learned are drawn. The final perception is that DLT is a unique technique that can accurately predict the capacity of a pile, if used properly. Comparison with SLT results was key to draw the latter conclusion given the good correlation between SLT and DLT results.

INTRODUCTION

The primary test that can accurately predict pile capacity and pile response, for both driven and bored piles, is the Static Load Test (SLT), either in compression or in tension. Nevertheless, a Static Load Test (SLT) is seldom performed, due to the cost, time and, complex setup that a single SLT involves.

In general, SLTs can be economically justified only on large-scale projects, and even in such cases, the variability of the geotechnical conditions may be such that the a few tests may not be enough to understand the whole picture of the piles behavior across the project site.

The truth is that in many pile projects, nothing is done to verify on-site pile capacity. Due to the uncertainty, high safety factors must be applied to avoid the catastrophic consequences of a deep foundation failure. In this context, DLT presents as a good alternative to solve most problems stated above (including pile capacity determination), due to its simplicity and robust theoretical framework.

OBJECTIVE

The purpose of this article is to describe the development of the dynamic tests in Costa Rica, with a discussion of the results obtained in three (3) case studies, for specific local projects: two (2) of them are for driven piles and the third one is for bored piles. These projects are:

Case 1: Caldera Grain Pier.

Case 2: Moín Oil Terminal.

Case 3: Chucas Bridge.

Following, a description of the findings for each case is presented:

CASE 1: CALDERA GRAIN PIER

The Caldera Grain pier was built between years 2013 and 2014. The project included the installation of 365 steel tubular piles, 914 mm in diameter and, 16-19 mm in thickness, lengths varying from 30 to 50 meters. These piles support three different structures: an access bridge, a berthing platform and, a mooring dolphin. All piles were installed vertical, except for the 12 piles in the dolphin that are battered. A photo of the construction process of the pier is shown in Figure 1.

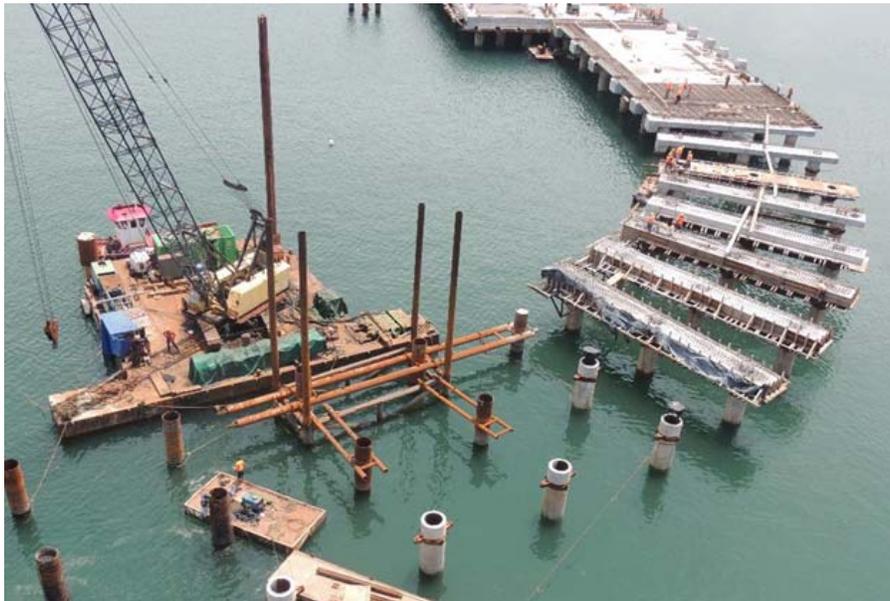


Figure 1.- Overview of the construction process for the Caldera Grain Pier, Costa Rica.

The soils profile for Case 1 is presented in the following table:

Table 1. Summary of Typical Soil Properties for Case 1.

Soil Layer	Elevation (m)	Raw Field SPT N-Value (average)	Estimated N60 (Average)
Loose Sand	0 to -12	10	7
Dense Sand	-12 to -21,5	40	28
Firm to Stiff Fat Clay	-21,5 to -36,5	15 to 20	10 to 15
Hard Clay	-36,5 to -44,5	70	50
Conglomerate	> -44,5	Refusal	---

Regarding pile driving environments, three very different zones can be identified: Zone 1, Zone 2, and Zone 3, being the latter the furthest from the coast. In this zone, no pile refusal was expected on hard soil, behaving predominantly as friction piles. In the case of Zone 2, the piles were driven to refusal in bedrock. Lastly, in Zone 1, a pre-drilling process into the rock was required to drive the piles.

For pile installation, firstly, a vibratory hammer was used to drive each pile through softer upper layers. After this process was finished, the pile driving was completed to final depth with a Delmag 62-22, which is a single acting diesel impact hammer, with a ram weight of 61 kN, total weight of 216 kN and, delivered energy, according to manufacturer, of 107-224 KN-m.

For this project, thirty-five (35) dynamic load tests were carried out as part of the quality control. Most of the tests were done on restrike, after a resting time between the pile driving process and the corresponding test. This allows considering potential variations in capacity with time (typically, increase in capacity or “set-up”). Table 1 shows a summary of the test results for each group considering geotechnical area and structure.

Table 2. Summary of Dynamic Load Testing for Caldera Grain Pier.

Zone	Value description	Mobilized capacity (kN)		
		Shaft	Toe	Total
Zone 1	Minimum	4579	568	5503
	Average	7190	1232	8422
	Maximum	9700	1788	10833
Zone 2	Minimum	5157	726	5883
	Average	6860	942	7802
	Maximum	9075	1181	10152
Zone 3	Minimum	4424	516	4963
	Average	6172	881	6481
	Maximum	7846	1128	8001

As can be seen in the previous table and as expected, piles in Zone 1 give the higher mobilized capacities (piles with socket in bedrock), piles in Zone 2 give intermediate mobilized capacities (piles with refusal in bedrock) and, piles in Zone 3 (friction piles) give the lower mobilized capacities. Therefore, DLT results for many test piles are totally in agreement with the driving environment for each Zone.

The dynamic stresses in the tested piles cause by driving were deemed to be allowable and, the actual capacity of each tested pile was deemed to be higher than its corresponding design capacity. Some of the tests were performed during installation of the piles. The results showed that the dynamic stresses caused by driving were allowable. In all DLT tests performed, the estimated capacity is higher than the design capacity.

As part of the quality control, three static tests (SLT) were carried out on piles located outside definitive positions: one of the tests reached 3,500 kN of vertical load, whereas the other two reached around 5,000 kN. By applying a safety factor of two (2), the allowable compression capacity for Zone 3 is between 1,500 to 1,750 kN, whereas for zones 1 and 2, the allowable pile capacity is 2,500 kN. Nevertheless, due do the limitations of the reaction load frame and jack, of the three SL tests; none of them was able to reach the geotechnical failure condition.

Given the impossibility to achieve geotechnical failure of the SLT piles, a direct comparison of DLT and SLT estimated pile capacities was not possible. Nevertheless, the DLT and SLT estimated stiffness could be compared, as shown in Figure 2, with very similar results in the load-displacement pile response for both tests.

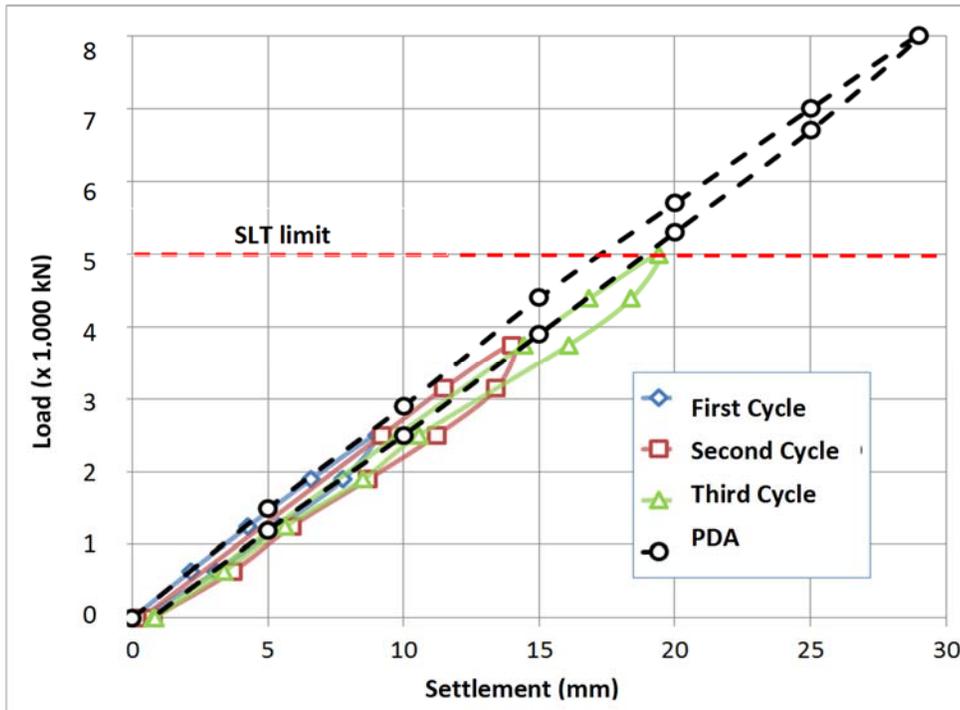


Figure 2.- Load-displacement response for both static and dynamic load tests.

DLTs in this project were key to demonstrate that the actual capacity of the tested piles is well over the design capacity.

The required axial capacities from design were as follows:

Zone 1 and Zone 2 = 2500 kN.

Zone 3 = 1500 kN.

The latter fact was overseen by the SLT given that the piles could not be loaded higher than 5,000 kN, due to limitations with the reaction load frame and hydraulic jack.

Caldera is the first project in Costa Rica, in which Dynamic Load Testing was performed on piles. DLT results showed good agreement with SLT results, which demonstrate their accuracy in estimating pile capacity and stiffness.

CASE 2: MOIN OIL TERMINAL

The new RECOPE Moin Oil Terminal is located North of the current Moin oil port. The structures on piles include: an access bridge, load-unload platforms and, Dolphins for mooring and bearthing. The project includes 109 steel tubular piles, 914 mm in diameter, 16 mm in thickness and, lengths ranging from 33 to 42 meters.

The geotechnical profile for the project of interest is summarized in the following table:

Table 3. Summary of Typical Soil Properties for Case 2.

Soil Layer	Elevation (m)	Raw Field SPT N-Value (average)
Medium Dense Sand w/clayey silt	0 to -7,5	13 to 24
Firm Fat Clay (CH)	-7,5 to -8,9	9
Hard Lean Clay (CL)	-8,9 to -40,0	35 to 60

Pile driving started by the end of 2014 and finished beginning 2015. Currently, the construction of the port is completed (see Figure 3).

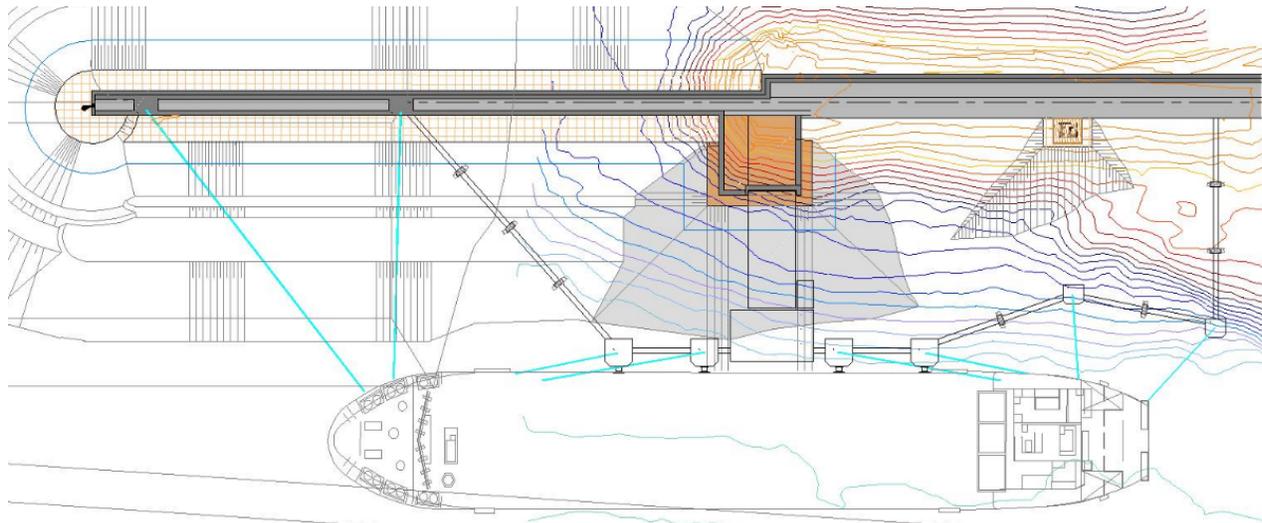


Figure 3.- Plan view of the new Moín oil port.

Based on the required pile forces from the structural analysis and, depending on load combinations and design pile depth, three (3) pile groups were defined and they are described in Table 4.

Table 4.- Pile groups with similar requirements.

Structures Group	Maximum Compression Loads (kN)			Toe elevation (m LLWL)
	Service	Force	Extreme	
Load platform, Storage platform, Bridge, Mooring dolphins DA5 and DA6, Berthing Dolphins DA1 to DA4	1,153	1,778	2,358	-23,1 to -29,9
Berthing Dolphins DA1-DA4	2,225	3,774	4,300	-38,3 to -41,3
Catwalks supports	219	314	242	-11,2 to -30,0

The quality control program included Wave Equation Analysis prior to the pile driving, as well as SLTs and DLTs. Dynamic tests were used as a basis to define the driving criteria, and also, to control de installation process, thus avoiding damages on the driven pile. In the case study 1, Caldera Port, the dynamic tests were used for the latter only.

The prior analysis of wave propagation allowed to define driving criteria well before the load tests. The predictions thus obtained were highly accurate. For example, for the hammer Berminghammer 6505-B, a driving criteria of 28 blows/10 cm penetration for a 160 cm drop height was estimated by means of WEA (Wave Equation Analysis), for those piles in Group #1. After the pile tests, both dynamic and static ones, the adopted driving criteria was 25 blows/10 cm penetration, which is pretty close to the WEA-estimated criteria.

In this project, twelve (12) dynamic load tests were performed, including both the SLT piles and some production piles. Primary purpose of DLTs was to verify pile vertical capacity. A signal matching was carried out to fine-tune the estimated pile capacities.

As an example, Figure 4 shows both signals of force and velocity versus time, for pile #58, located below one of the Dolphins (Group #2). In addition, Table 3 shows the corresponding results for Group #1. In this case, the phenomenon of increased pile capacity versus time was also observed given that some DLTs were performed during initial driving, as well as, during restrike, for the same piles. This phenomenon is very important at those sites where clayey soils are predominant.

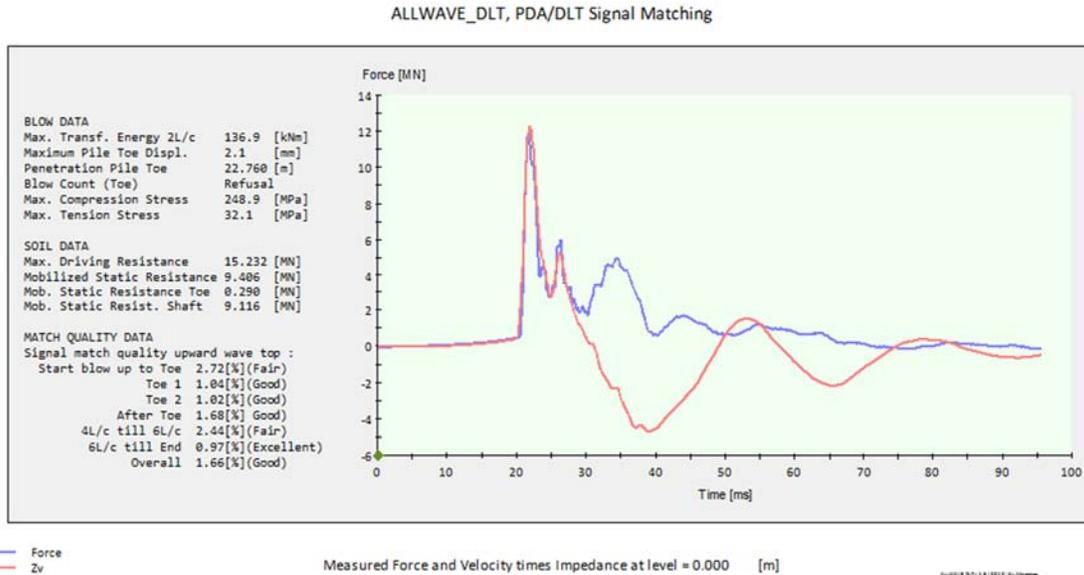


Figure 4.- Force-velocity plots versus time for a PDA test in pile #58.

On the other hand, three (3) SLT tests were performed for acceptance loads up to 3 MN (Group #1) and up to 7 MN (Group #2 and Group #3). For every SLT, three load cycles were applied, being the idea not to produce failure in the test piles for the first and second cycle, and induce failure during the third cycle. Unfortunately, geotechnical failure was only achieved in the first SLT.

The results obtained from DLTs are in good agreement with the SLT results. For instance, for SLT #1, a ultimate vertical capacity of 3.7 MN was obtained, whereas for the corresponding DLT, a ultimate capacity of 3.3 MN was calculated, being the test performed for the smaller resting time. A higher resting interval would have allowed the pile capacity to increase to values closer to the SLT result.

Table 5.- DLT results for Pile Group #1.

Test Pile	Resting time (days)	Estimated Capacity (kN)	Required Capacity (kN)	Test Type
SLT #1	0	2,813	3,232	Initial Driving
	1	3,424	3,232	Restrike
12	0	2,544	1,780	Initial Driving
16	0	2,606	2,686	Initial Driving
	6	3,613	2,686	Restrike
19	10	3,441	2,686	Restrike
69	0	3,875	3,232	Initial Driving

Important Remark:

With a resting time of 1 day, the increase of capacity during restrike was around 22%. With 6 days of resting time, the estimated increase was 38%. Understanding the behavior of the pile versus time is key and the most direct response is given by the PDA – DLT test.

SLTs #2 and #3 estimated pile capacities were relatively high, in good agreement with the DLT results. DLT estimated pile capacities were in the order of 9 MN, with the limitation of not mobilizing full capacity during driving, whereas SLT #3 reached 11 MN, but not exhibiting geotechnical failure.

CASE 3: CHUCAS BRIDGE

As part of Chucás Hydroelectric Project, a 255-meters long access bridge was built over the Tárcoles River. The bridge is composed of two abutments and four piers. Three (3) out of the four (4) piers and one (1) of the abutments required a piled foundation. The piles are concrete bored piles, 120 cm in diameter, that were poured using a tremie pipe.

Following, the typical geotechnical profile around the test pile is presented:

Table 6. Summary of Typical Soil Properties for Case 3.

Soil Layer	Elevation (m)	% Recovery	% RQD
Coluvium (boulders in sandy Matrix)	0 to -17	20 to 40	0 to 30
Weathered Andesite (Transition)	-17 to -23	83 to 96	0
Fissured Andesite (Bedrock)	-23 to -27	83 to 93	20 to 30

A DLT test was performed for a selected pile of every pier on piled foundation, totaling three (3) DLTs. To perform such tests, a dynamic source was required to generate the stress wave in each pile. CODOCSA, the bridge contractor, machined a system with a 155 kN falling weight mass and, adjustable drop height. The original system is shown in Figure 5.

Besides, a crane was also provided to move the mass from test site to test site, as well as the guide frame. The crane was also helpful to position the mass on the frame.



Figure 5.- Falling Mass and Guide Frame for the execution of DLT tests on bored piles.

Prior to the DLT tests, CSL (Crosshole Sonic Logging Tests) were performed to verify pile integrity in the test piles. Figure 6 shows a CSL analysis for a given test pile. In this case, some anomalies were found in the upper first meter of pile. This zone was demolished in order to connect the pile with the pier footing.

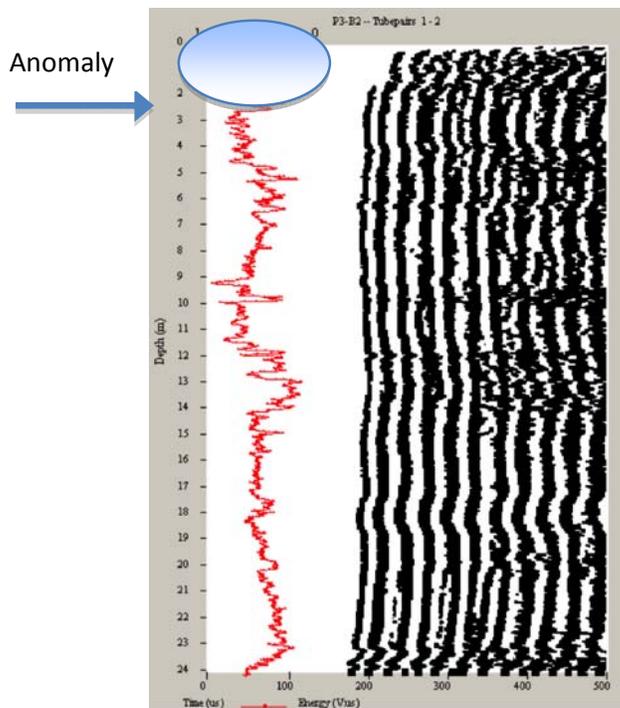


Figure 6.- “Waterfall” Diagram to analyze the integrity of a given test pile by means of CSL (Crosshole Sonic Logging)

On the other hand, the modulus of Elasticity of the concrete (E_c) was estimated from data of tested concrete cylinders.

Prior to DLT tests execution, a WEA was performed in order to predict the behavior of the pile – falling weight system. By means of this analysis, the transferred amount of energy due to the impact was estimated, as well as the induced dynamic stresses due to the impact and, the expected theoretical capacity. The result of the WEA analysis is shown in Table 7.

During every DLT test, the mass was dropped from different heights, that were defined by means of the WEA analysis. The objective was to choose a maximum drop height that do not overstress the pile, either in tension or in compression.

The key challenge to be faced by the team in order to apply DLT to a bored pile was to define the pile geometry (variations in diameter with depth). In the case of driven piles, each pile comes from a factory and its diameter is almost constant with depth.

For the case of bored piles, given that the ground itself acts as a formwork for the concrete pouring, the diameter is highly irregular with depth. In order to draw a plot of diameter versus depth for each test pile, a PIT (Pile Integrity Test) was performed prior to the DLT test. This input allowed an easier and more accurate signal matching process.

In Figure 7, a PIT result is presented. Every arrow shows the location of a relevant increase in diameter. In addition, the contractor provided a plot of concrete consumption versus depth. With the help of both plots, a third plot was developed, pile diameter versus depth (see Figure 8).

Table 7.- WEA analysis prior to the DLT test.

Drop Height (m)	Potential Energy (kN-m)	Impact Energy (kN-m)	Transferred Energy (kN-m)	Compressive stress (MPa)	Tensile stress (MPa)
0,3	45,0	45,0	16,7	7,8	2,9
0,5	79,4	79,4	27,7	9,9	3,6
0,8	126,8	126,8	44,3	12,3	4,5
1,0	158,5	158,5	56,3	13,8	5,1
1,5	237,7	237,7	82,8	16,6	6,3

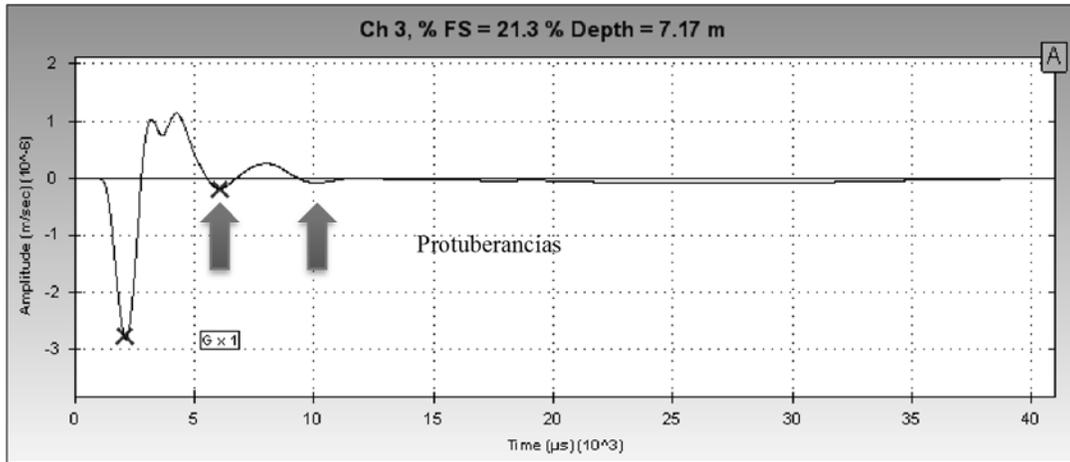


Figure 7.- PIT results for a given test pile.

As shown above, the derivation of the actual geometry of the pile (diameter versus pile depth) is of paramount importance for the correct interpretation of DLT tests performed on bored piles. This problem does not exist in the case of driven piles given the accuracy that can be achieved in fabricating the piles in factories. The signal matching process for a given test pile and with the maximum drop height allowed to estimate its vertical capacity, which is shown in Table 8.

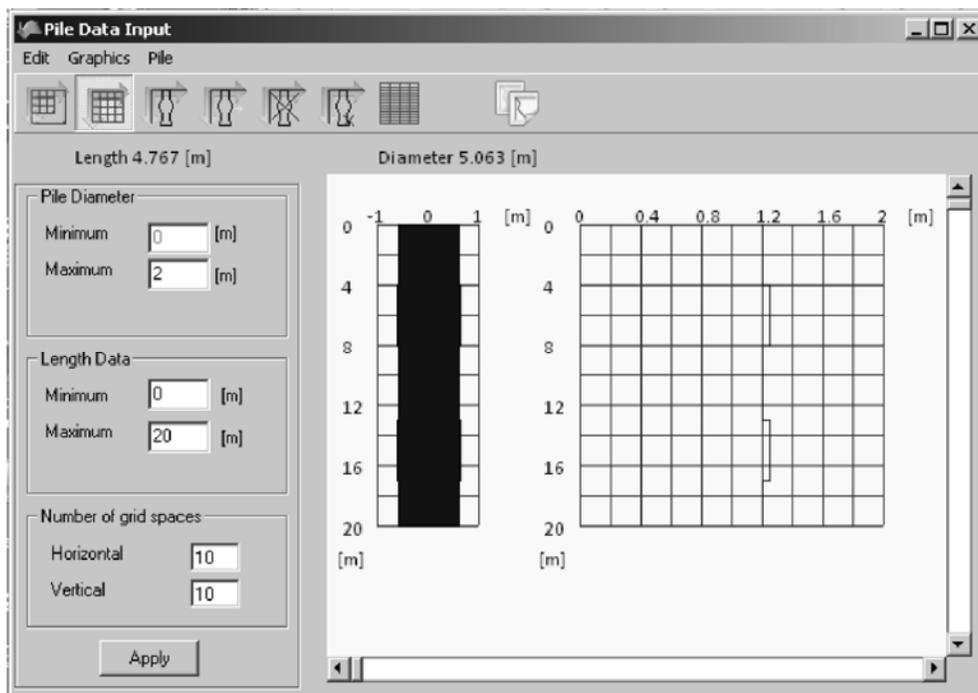


Figure 8.- Plot of pile diameter versus depth for a given test pile.

Table 8.- Results of a DLT test on a 120 cm DIA bored pile.

Energy (kN-m)			Mobilized Capacity (kN)			Tensile Stress (MPa)
Potential	On head	At tip	Total	Tip	Shaft	
174	136	38.5	9,470	440	9,030	3.0

Remark:

Due to the challenge that represented to mobilize capacity of the pile without damage, the criterium to stop the test was not to exceed the maximum tensile strength of the concrete. This criterium limited the mass drop height to a maximum of 1,50 meters. Given that the required design capacity was 6500 kN, the estimated safety factor is around 1,50. This approached is considered conservative given that the ultimate capacity of the pile was not mobilized by the drop mass.

CONCLUSIONS

Due to the geological variability, especially important in Costa Rica, a methodology is required to confirm design assumptions for a given pile project (capacity, etc.). Pile capacity is very susceptible to geological variations, both horizontal and vertical and therefore, the construction follow-up is key to achieve a proper cost-safety balance.

Typically, static load tests (SLT) are performed, nevertheless, those tests are expensive and time consuming, which discourage its use in middle to small projects. Even for large projects, the quantity of SLTs is well restricted and therefore, not statistically representative, which generates a void of information that complicates the decision-making process.

In this context, dynamic load tests (DLTs) constitute a very promising alternative for control and follow-up of pile projects. DLT tests allow estimating the pile capacity, with very low errors in the order of 10% to 15%. On the other hand, PDA tests (Pile Dynamic Analysis) allow a construction control of the driving process, for the case of driven piles.

Dynamic Tests were originally thought for driven piles, as an alternative to the indiscriminate use of dynamic equations. Nevertheless, successful trials for bored piles have been made, just like was shown for the case of PH Chucás (Case Study 3). There are two important differences between driven piles and bored piles in order to apply DLT tests and these are:

- For driven piles, the very same installation process of the piles (driving by hammer) allows the execution of the dynamic tests. For bored piles, a falling mass system must be designed and machine to provide the dynamic source.

- For driven piles, the diameter is reasonably constant with depth. For bored piles, due to their construction process, the diameter is irregular with depth and a plot must be obtained to input the actual geometry of the pile in the signal matching process. A good alternative to obtain proper geometry is by means of PITs (Pile Integrity Test).

The speed to perform a DLT makes it possible to perform a large quantity of such tests in a relatively short period of time, which allow a better statistically representation of the geotechnical conditions for a given pile project. In addition, the absence of a structure load frame, just like the one required for SLT tests, make dynamic tests approximately 10 times cheaper than static tests.

An additional important advantage of DLT tests is that they allow to understand the variation of pile capacity with time after the initial pile driving. This is of the utmost importance for the case of predominantly clayey saturated soil deposits, given that the radial dissipation of excess pore pressure after the initial driving, considerably increases the pile capacity. In Moín case study (Case Study #2), a resting time of one day and restrike was enough for an increase in capacity of 22%. A resting time of six days and restrike showed that the pile capacity increased in 38%.

Due to the latter and given the successful experiences in Costa Rica, as well as in other countries, the authors consider this methodology to verify piles during construction stage, very accurate and promising for any project, in spite of its size. In Costa Rica, the use of dynamic testing is of recent occurrence, but hopefully they are to be implemented in more projects, in the very near future.

REFERENCES

- Chen, Q., Haque, Md. N., Abu-Farsakh, M., and Fernandez, B. A. (2014). "Field investigation of pile setup in mixed soil." *Geotechnical Testing J.*, Vol. 37(2), pp. 268-281.
- Coto, M. y Vargas, L.A. (2015) *Informes de Pruebas de Carga Dinámica a pilotes Proyecto Puente P.H. Chucás*. Atenas, Costa Rica.
- Haque, Md. N., Abu-Farsakh, M. Y., Tsai, C., and Zhang, Z. (2016). Load testing program to evaluate pile set-up behavior for individual soil layers and correlation of set-up with soil properties. *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)*, Vol. 143(4), pp.1-19, DOI: 10.1061/(ASCE)GT.1943-5606.0001617.
- Haque, Md. N., Abu-Farsakh, M., Chen, Q., and Zhang, Z. (2014). "Case study on instrumenting and testing full scale test piles for evaluating setup phenomenon." *Journal of Transport Research Board No 2462*, pp. 37-47.
- Middendorp, P and van Delft, M.C.H. (2013). *Stress Wave Theory*. Allnamics, La Haige, Netherlands.
- Millan, L.O. (2013-2014) *Informes de Pruebas de Carga Dinámica y Estáticas a pilotes. Proyecto Muelle Granelero*. Caldera, Costa Rica.
- Millan, L.O. (2014-2015) *Informes de Pruebas de Carga Dinámica y Estáticas a pilotes. Proyecto Muelle Petrolero*. Moín, Costa Rica.