TECHNICAL SPECIFICATIONS FOR CARRYING OUT RAMMING AND STATIC LOAD TESTS FOR THE DESIGN OF FOUNDATIONS WITH METALLIC PILES IN PHOTOVOLTAIC POWER PLANTS

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Summary: Foundations projected for photovoltaic plants will resist light loads. These loads are usually transmitted to the ground by driving short metal piles. In order to determine the ground bearing capacity, the most usual is to use real-scale load tests after analyzing and characterizing the ground using geotechnical field and laboratory tests. The importance of these tests in the foundation design requires a correct design of the test procedure that includes the number of tests to be performed, their location, load to be applied, etc. This article provides recommendations based on the extensive experience of ORBIS TERRARUM in static load tests or pull-out tests for photovoltaic plants in several countries around the world.

Fig. 1: Lateral load

1. INTRODUCTION

This paper includes a series of recommendations for the planning of ramming and static load tests campaigns that allow establishing the ground characteristics for the design of the foundations of photovoltaic power plants by driven piles. These are based on the experience of ORBIS TERRARUM after undertaking geotechnical studies of more than 500 plants in several countries of the world, having participated in all type of geotechnical works in the different construction or project phases: geological-geotechnical feasibility or detailed studies, geophysical studies, ramming and static load tests campaigns, studies of the ground and environmental aggressiveness to the metallic structures that support the photovoltaic panels, technical advisory to designers or builders, etc.

The vast majority of the structures that support the solar panels and trackers that make up these plants are founded using metallic piles driven into the ground, seeking to optimize costs and execution times, compatible with the structural safety of the construction. This article refers to these type of foundations, viable in general in a very wide range of types of ground, from the point of view of its strength, either by piles simply driven into soils of low to high compactness or consistency or, when the ground strength is very high, with actions prior to ramming, such as the pre-drilling with a diameter lower than the dimensions of the cross section that facilitates its ramming later, or greater, which allows the placement of the metallic pile inside, and filling it later with a hydraulic conglomerate.

When the power plants are equipped with solar trackers, the foundations are usually made with hot rolled or cold-formed steel piles with edges about 150-200 mm and an embedment depth greater than 1,50 m. In the case of fixed photovoltaic plants, the metallic piles that are being used are cold-formed steel with a significantly lower edge, around 80-150 mm. In both cases, the width/length ratio of the foundation responds to a typology that could be classified as isolated short pile.

It will be necessary to follow the standards, guides and codes applicable in each country, as well as any useful technical bibliographic reference usually accepted by the geotechnical community that tends to enrich the conclusions of the report. It is necessary to emphasize the treatment that is given to the analysis of this type of tests in the "Eurocode 7: Geotechnical Project. Part 1: General Rules", as well as in other available official publications that deal with this type of foundation with technical accuracy.

The type of foundation described: short metallic piles subjected to loads that we could qualify as moderate, makes possible to size it from static load tests on a full scale, unlike other types of structures for civil works or building infrastructures, in which the usual way is to determine the ground characteristic strength from analytical expressions of guides and recommendations based on the science of soil and rock mechanic, and using intrinsic representative geotechnical parameters (density, cohesion, undrained shear strength, friction angle, etc.) and of ultimate strength (shaft and toe resistance), obtained from field tests (standard penetration tests, pressureometric tests, etc.) and laboratory tests.

2. PREVIOUS GROUND STUDIES

The ramming tests and full-scale load tests can never replace the prior accomplishment of a geological-geotechnical study. They also can never be an argument for minimizing the scope of the geotechnical study.

The success of a load tests campaign depends mostly on a proper design that must be based on a good geotechnical study with a correct scope that provides useful and real data. In addition, do not forget the formal or administrative need for the realization of the geological-geotechnical study derived from current legislation.

The scope of this type of study for photovoltaic power plants and the basic guidelines for its planning have already been the subject of other papers by ORBIS TERRARUM (see "Technical specifications for the request for a geological-geotechnical study for a photovoltaic power plant"[1], and "Technical specifications for the request for a geophysical study for a photovoltaic power plant"[2],. Among the features that the geological-geotechnical study must include for the technical and economic evaluation of the subsequent campaign of static load tests, should be highlighted:

- Zoning diverse types of ground areas depending on the geology (geological mapping). In particular, detection of existing areas of anthropic landfills or of low bearing capacity soils and cut and fill areas affecting future photovoltaic panels.

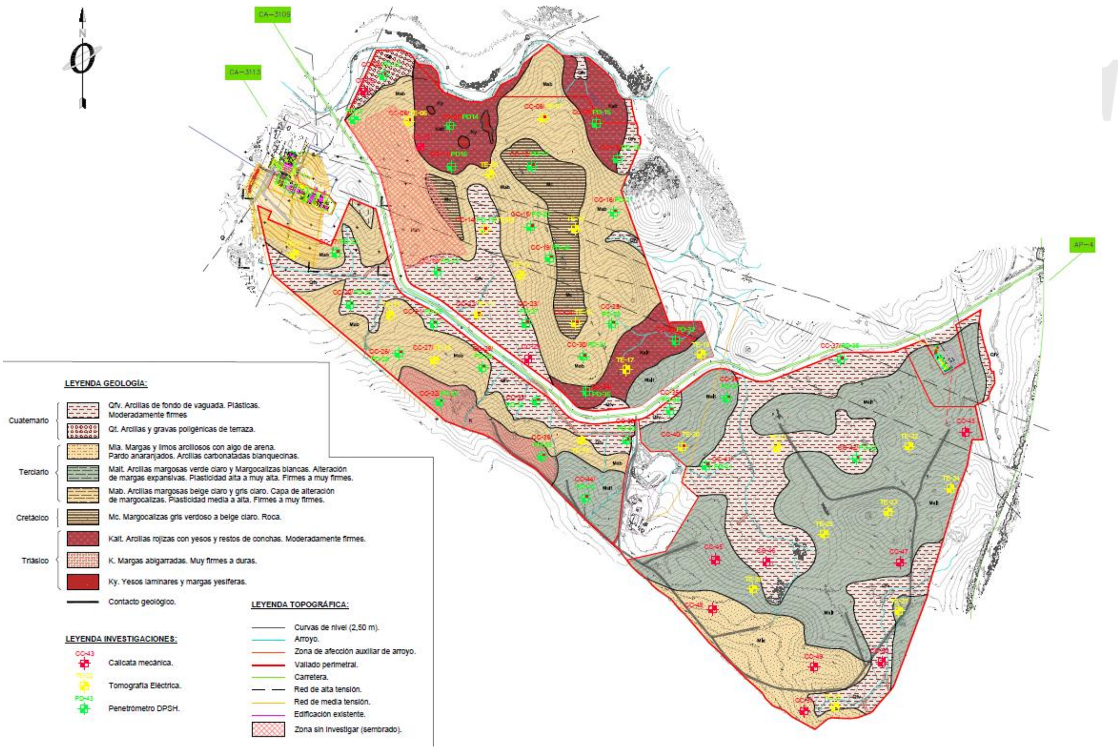

Fig. 2: Example of detailed geological mapping for geotechnical study of a photovoltaic plant in Spain

[1] https://www.orbisterrarum.es/wp-content/uploads/2021/07/Orbis-technical-specification-of-geotechnical-studies-for-PV-plants.Rev04-1.pdf

[2] https://www.orbisterrarum.es/wp-content/uploads/2022/09/Technical-Specifications-on-Electrical-Methods-for-new-PVPs-2.pdf

- Set the feasibility of pile driving through penetration tests and trial pits in order to foresee the need to carry out complementary works such as pre-drilling, drilling diameters, installation of micropiles, etc.

Fig. 3: Zoning of the pile driving feasibility for the same project of figure 2

- Detecting geological risks that may affect the foundations: seismic effects, swelling, collapse, flooding, erodible areas, etc., as well as other features that could affect the foundation soils such as corrosivity or aggressiveness to concrete.
- Evaluate the ground corrosiveness to buried foundation elements.
- Evaluate the value of the permanent, variable or accidental efforts that the structures had to support whose origin is in the ground (overloads, ground pressure, expansiveness, freezing, earthquake, etc.).
- A first estimation of the shaft resistance for establishing a preliminary pile embedment length.

In addition to initial information about the ground behavior provided by the geotechnical study, the other important part when planning a campaign of static load tests should be the knowledge of the order of magnitude of the forces that the structure transmits to the ground.

The double information available, a geotechnical study and a study of loads on the ground, helps appreciably to evaluate the number of tests to be carried out, estimate the initial embedment length, know the needs of preparation of the ground prior to driving, establishing the load increments to be carried out during the tests, etc.

3. CRITERIA FOR ESTABLISHING THE NUMBER OF TESTS

At the moment there is no specific regulation that establishes for this type of construction the number of test points to be carried out on a plot. From the point of view of ORBIS TERRARUM, there are two fundamental factors to establish the number of test points: surface and existing lithological heterogeneity in the plot.

The various technical specifications of campaigns of this type that were supplied to ORBIS TERRARUM already show the lack of common quantitative and/or qualitative criteria in order to establish the number of load tests, being the most extended the one in which the number of test points depends on the installed power (perhaps motivated more by economic issues than by technical ones, trying to delimit the cost of the study based on the expected investment, that is, based on the power in MW installed), or the one in which they simply leave it to the discretion of the bidder.

In the absence of specific regulations, ORBIS TERRARUM has tried to analyze the general trend of the market from the test campaigns carried out over the last few years, which number can be considered quite significant. Considering all those campaigns that fall within an acceptable range of variation, and therefore discarding those in which the proposed number of tests is no significant or logical, the following expression is proposed to determine the number of posts to be tested based on plant surface:

$$N = 5{,}0\ x\ S^{0{,}62}$$

Where:

N = *Number of piles to be tested*

S = *Plot surface (Ha)*

Proposal that is made for a plot surface greater than 0,5 Ha. For smaller plots, a minimum number of piles to be tested of 3 is proposed.

The proposed expression is deduced from the trend of the "Surface-Number of posts tested" curve obtained from the cloud of points of all the considered campaigns.

Figure 4 and Table 1 show the graphic and numerical results for the proposed equation. Although the graph shown in figure 3 has been limited to a maximum area of 500 Ha, for the adjustment of the trend curve, data of up to a maximum of 2.000 Ha have been used (e.g. PFV Al-Dhafra, in Abu Dhabi).

There are factors such as greater or lesser lithological variability or fluctuation in thickness and/or strength that these lithologies have both in plan and in depth that may make it necessary to increase or decrease the number of test points, and these are factors that must take into account for the quantitative design of the static load test campaign, hence the importance of being able to count on the data provided by the geotechnical study prior for the design of the campaign.

It is emphasize about the quality in the execution of the tests. As can be supposed, the proposed expression leads to a large number of tests in large areas to investigate. It should not fall into the inertia of a routine execution, without analysis of results in parallel to its execution that allows take changing decisions as the campaign progresses. It is considered a priority to have a number of correctly executed tests against many tests of doubtful quality and difficult interpretation.

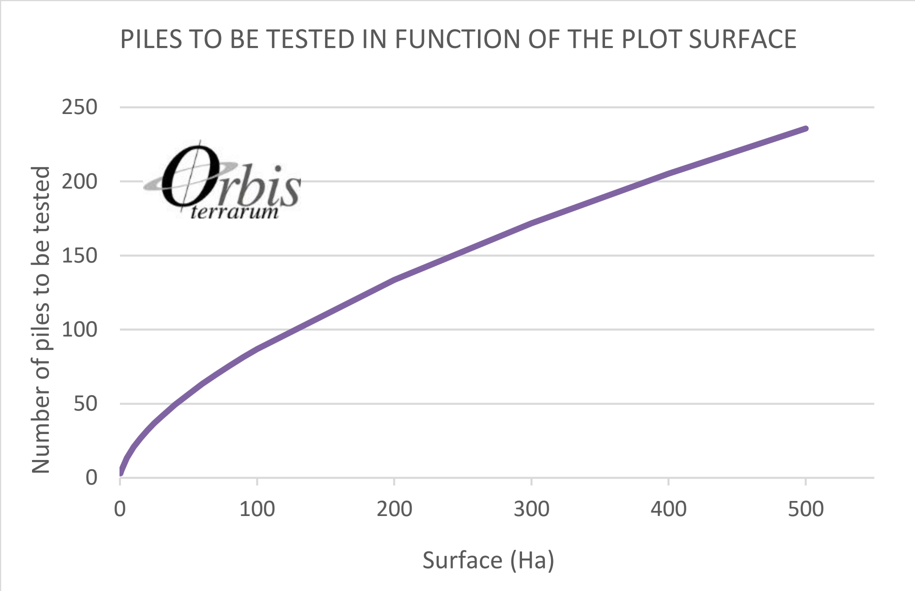

Fig.4: Number of piles to be tested depending on the surface of the plant in Ha

Plot surface (Ha)	Minimum number of piles to be tested
≤ 0,5	3
1	5
5	14
10	21
50	57
100	87
250	153
500	236

Table 1: Number of piles to be tested depending on the surface of the plant in Ha

Finally, the tests performance per day is very variable and depends on the test procedure in terms of loading steps, preparation of the pile (with pre-drilling or not), time necessary for displacement stabilization, etc.

4. METHODOLOGY

It is a prerequisite before carrying out a campaign of static load tests to know if the driving of the piles is feasible or if it is necessary to carry out some type of previous work to facilitate its driving (generally pre-drilling). For this reason, in the phase of preliminary feasibility studies, this issue must be investigated, determining in the geotechnical study the capacity of the ground to admit a foundation solution by driven piles through continuous dynamic penetration tests, or through a previous campaign of ramming piles that, in addition, could be used to obtain preliminary data about the ground behavior against axial and lateral forces.

Subsequently, is essential to carry out the ramming and static load test campaign in the project phase with piles of cross section similar to those designed to delimit more precisely the areas in which direct ramming is feasible and in which it is not, project the embedment length of the piles, determine the ultimate strength parameters of the ground as closely as possible, and estimate the displacements of the structures for the viable foundation solutions.

While, for a feasibility study the fundamental objective is to evaluate which is the most appropriate construction method and pre-sizing the embedment length from a few start data, in the project phase it is necessary to have more information to draft a test procedure, so, it is desirable to know a fairly approximate order of magnitude of the factored reactions of the structure in the foundation (tensile, compression, lateral load and bending), in order to be able to size an embedment length and check its validity for all possible reactions both from the point of view of the ground strength (ultimate limit state), as well as for the service limit states that the project must keep in mind (for example, allowable displacements by the structures).

In general, the loads are applied by load-unload steps until a maximum value is reached. It´s emphasize about the static nature of the applied loads. Although load-unload cycles are carried out, the loads are applied during a time that allows the stabilization of the displacements and must be considered as static. In the case that concerns us: dimensioning and verification of a foundation by isolated metallic pile, the permanent, variable, and accidental loads, are considered static and they must be treated in the calculation according to current regulations and equal to another foundations of building structures, civil works, etc.

Effects such as the loss of long-term strength due to dynamic loads are outside the scope of this type of test.

In some soils, more sensitive to strength variation with moisture content, it is usual to simulate situations of saturation in the ground around the pile by flooding.

4.1 Testing equipment

The machinery and measuring equipment necessary for these tests are basically:

- Driving equipment and percussion rotatory drilling equipment, with an energy capacity to drill of not less than 800-1.000 J. It is desirable that the drilling equipment is prepared to drill holes up to a maximum diameter of 150-200 mm in case it is necessary for the high hardness of the ground.
- Digital dynamometer with calibration certificate and minimum capacity to measure in any direction up to 50,0 kN.
- Load cell with calibration certificate and minimum capacity to measure up to 50,0 kN in the axial direction of the profile.
- Digital or analogic micrometer for displacement measurement with enough range to measure the maximum expected displacement and precision of 0,01 mm.

- Auxiliary elements: slings, pile-loading fixing devices, hoists, etc.

Photo 1: Equipment owned by ORBIS TERRARUM for driving piles and drilling with bottom-hammer in case pre-drilling was necessary

Photo 2: Dynamometer for measuring load applied assembled for lateral load test

Photo 3: Digital micrometer installed for vertical tensile load test

The application of the load to the pile can be carried out either through the construction of a loading frame, or by employing heavy machinery as a reaction, applying the load with a level or chain hoist in the case of axial tensile load tests and lateral load tests, or with a hydraulic jack. It is also usual to apply the load with the hydraulic system of the machinery (excavator, backhoe loader…) when the loading steps are not small.

It is recommended that the heavy machinery that is used as reaction in the tests weighs at least 2-3 times the value of the maximum load to be applied

4.2 Testing method

The method of carrying out the load tests on driven piles into the ground, number of load steps, duration of the load application, and moment of measurement of the displacements, etc., must allow obtain conclusions about the ultimate ground strength if it could reach, and the foundation behavior for the absolute and remanent displacements measured.

The extrapolation of the load-displacement graph based on the results of other tests is not admissible for obtaining the critical load or ultimate load of the elastic phase. If the final load of a test is not reached because of soil failure, the maximum load applied in the test must adopt as the ultimate load.

It is recommended to perform a test by driven pile, either the lateral load test, or an axial load test, trying to achieve in each case the ultimate ground strength, the maximum load of the load device, or the maximum load allowable by the pile before depleting its resistant capacity.

However, the most extended practice is to take advantage of the driven pile to carry out the two tests[3]. This practice is considered correct, and it is recommended that the lateral load test be carried out first and, later, once it is verified that the pile has not considerable deformations and is suitable for a second test, the vertical load test. This guideline, although it should not be taken as a general rule, since it may also depend on the value of the reactions in the foundation or the pile-ground behavior in the first tests, would follow the recommendations indicated in Eurocode 7, in which in its sections 7.5.2, "Static load tests" and 7.7.2, "Resistance to lateral loads obtained from pile load tests" states:

7.5.2.1 (4) Pile load tests for the purpose of designing a tensile pile foundation should be carried out to failure. Extrapolation of the load-displacement graph for tension tests should not be used.

7.7.2 (2) Contrary to the load test procedure described in 7.5, tests on transversely loaded piles need not normally be continued to a state of failure. The magnitude and line of action of the test load should simulate the design loading of the pile.

4.2.1 Pile tests

During the pile driving, the driving time by segments must be registered. This will be necessary for determining the driving speed and estimating ramming production. In addition, it will be an additional qualitative data that, together with other test results of the geotechnical study, will serve to delimit with higher precision the areas of different behavior in terms of ground strength.

Next figure shows an isoline map of pile driving times for a static load campaign carried out in Egypt.

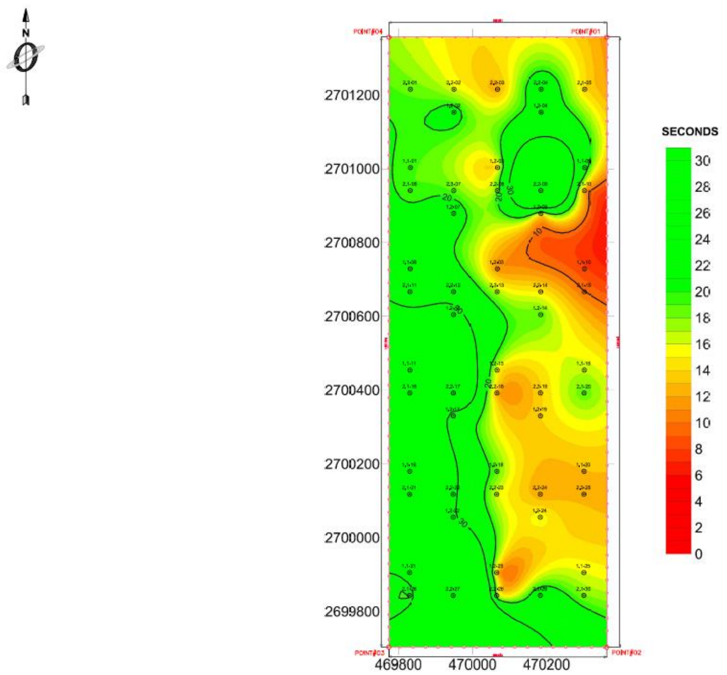

Fig. 5: Example of driving time isoline map

[3] In the case to carry out a test per pile, the number of poles to be tested deduced from the equation proposed in section 3 should be doubled.

4.2.2 Pile testing under under lateral load

For the checking of the ultimate limit state of ground strength ground and the service limit state for allowable displacements of the structures, the lateral load tests will be carried out with several embedment lengths, Li, to determine the project embedment necessary to support the design lateral load with adequate safety against ground-breaking, that is, to satisfy for all the load combinations that:

$$F_{l,d} \leq R_{l,d}$$

Where:

$F_{l,d}$ = Factored lateral load that the pile transmits to the ground.

$R_{l,d}$ = Factored ground strength when is subjected to a lateral load.

The value of $R_{l,d}$ is the one deducted from the test with the corresponding reduction factor, and the value of $F_{l,d}$ will be provided by the structural engineer.

The maximum load that the test has to reach must be applied by load-unload steps, measuring for each load step the absolute relative displacement that occurs between the base of the pole and the ground, and for each unload step, the remanent displacement. Displacements will be measured using a micrometer, and the measures should be taken at a point as close as possible to ground level.

As an example, figure 6 includes a lateral load test carried out in accordance with the guidelines indicated.

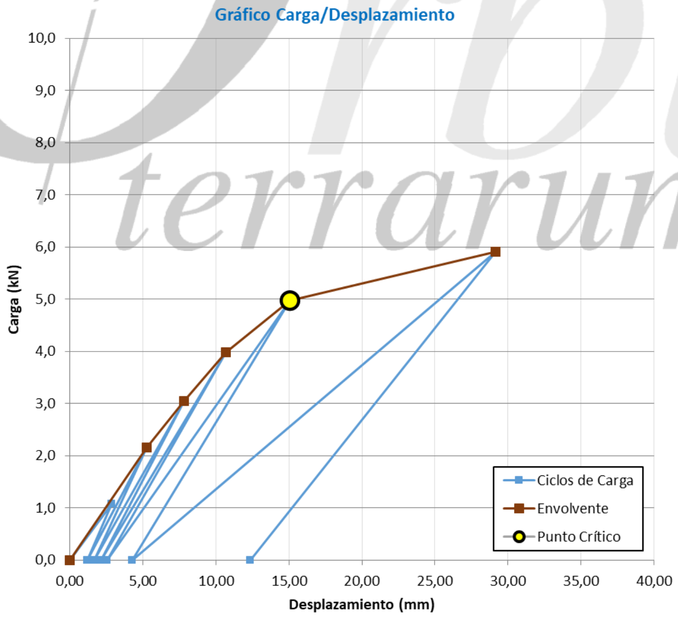

Fig. 6: Example of load-displacement curve in lateral load test

Regarding the height of application of the load, it should be such that, for the maximum lateral load, $F_{l,d}$, at the base of the pile the bending moment concomitant with the lateral load considered is originated, M_d. In the absence of this datum, it is recommended that the height of application of the load would be about 1,0 m, and no higher than 1,5 m in piles that are not made of rolled steel or does not have section symmetric transverse.

It should not be forgotten that the objective of the test is the verification of the ultimate limit state of the foundation to horizontal forces and that the absolute and remanent displacements that occur in the foundation during the useful life of the structures are allowable. In any case, the test can always provide, by a back-analysis calculation, an equivalent horizontal subgrade reaction module of the ground for the considered embedment length, that can be used for checking the foundation by means of specific software for any other combination of bending and shear moment actions to be transmitted to the ground (as long as it will be for the same embedment length considered in the tests and calculations), or another type of cross section but of the same order of magnitude in terms of its dimensions.

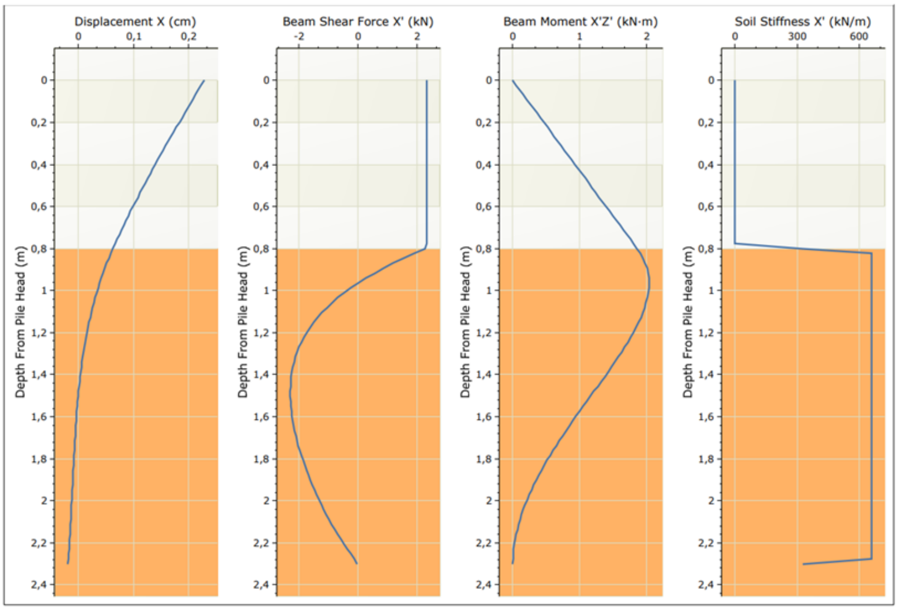

Fig. 7: Example of bending moment, shear and displacements graphs in back analysis calculation to determine the horizontal subgrade reaction modulus of the ground from the tests

As for the values of horizontal displacements allowable by the foundation, they will be defined by the structural engineer and depend on the type of structure, modulation, loads, etc. As an example, some the most usual values observed in the different test procedures are in the order of 20-30 mm for absolute displacements and 10 mm for remaining displacements.

Horizontal loads are generally higher and therefore more limiting in the design of structures with solar trackers. When PV plants are designed with fixed type panels, the lateral load is less limiting and the number of this type of tests could be reduced.

4.2.3 Pile testing under axial load

To check the ultimate limit state of the ground strength for both tensile and compressive vertical loads, the test procedure is similar. Axial tensile force is usually more influent in this type of structures, although this should not be taken as a general rule.

As in the case of a pile subjected to lateral loading, the tests will be carried out with different embedment lengths, L_i, in order to determine the optimum embedment to support the vertical loads with an adequate safety factor against pile-ground contact breaking, that is, to satisfy for all load combinations:

$$F_{t,d} \leq R_{t,d} \qquad and \qquad F_{c,d} \leq R_{c,d}$$

Where:

$F_{t,d}$ y $F_{c,d}$ = Factored tensile and compression loads that the pile transmits to the ground.

$R_{t,d}$ y $R_{c,d}$ = Factored ground strength when is subjected to a vertical tensile and compression load.

The values $R_{t,d}$ and $R_{c,d}$ are deduced from the tests and the values of $F_{t,d}$ and $F_{c,d}$ will have to be provided by the structural engineer.

Tensile or compressive forces are applied on the top of the driven pile the displacements that are obtained in each load step must be measured for also studying the service limit state of allowable displacements of the structure. Figure 8 includes an example of a vertical tensile load test in accordance with the guidelines indicated.

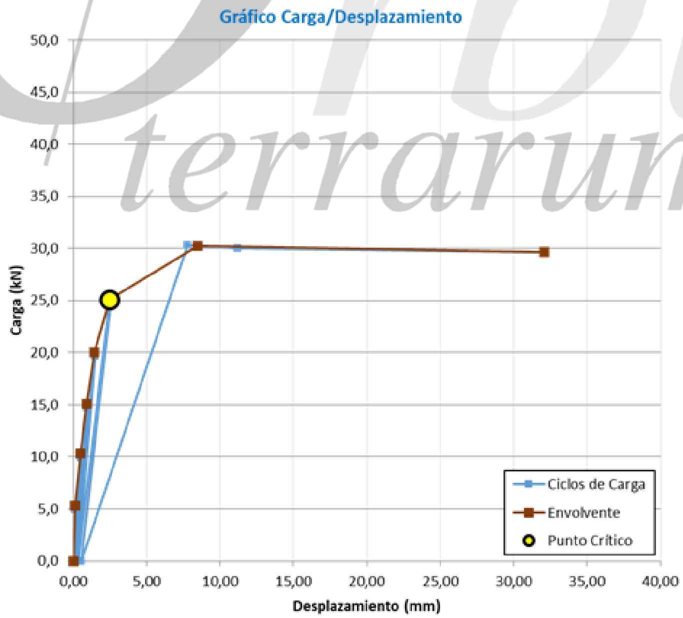

Fig. 8: Example of load-displacement curve for an axial tensile test

It is recommended to apply the load until the pole is removed in uplift tests in order to be able to determine the ultimate value of the ground strength for the tensile reaction. If this is not achieved, the tests will be carried out until reaching the maximum load capacity that the reaction or the measurement equipment can provide.

It is usual practice to consider only axial tensile load test in the campaigns because is usually more limiting for the dimensioning of the structure and, furthermore, both in technical bibliography, as in the different foundation standards and guides, it is common to find the relationship between the shaft resistance for tensile and compression forces:

$$R_{tensile} = (0{,}60\ to\ 0{,}70) \times R_{compression}$$

4. REPORT

The scope of a report of this type must be set between the technical test team and his client, and can be very variable, from a simple report that summarizes the obtained results ("factual report") to a much complete report where the results are analyzed in-depth and pre-sizing the foundation ("engineering report"). The limit of the scope of the report must be defined in the conditions of the agreement.

It is considered that the factual report must include, at least, the next information:

- Background, scope of the report, location of the studied area, site description, technical bibliography and any other available information useful for carrying out the works.
- Site description and ground conditions.
- Geometry and resistant characteristics of the piles used.
- Description of the driving pile machine, loading devices, reaction system and measuring equipment.
- Data of the pile driving as: embedment length, driving time by representative sections, auxiliary works done for pile driving (pre-drilling, material used for filling the pre-drilling hole, etc.).
- Results of the tests, both numerical (time, loads and displacements) and graphical representations (load-displacement curves).

In the case of engineering report its content should be expanded at least:

- Analysis and calculation of the characteristic parameters that govern the ground behavior for axial and lateral loads.
- Setting the ultimate ground strength for the most unfavorable load combinations.
- Analyses of the serviceability limit state for the allowable foundation displacements.
- Zoning the site based on the statistical analysis of the test results.
- Pre-sizing the foundation for each identified area.
- Estimation of performance of the driving works.

Finally, is important to remark that the testing areas must be representative for the plant construction, taking particular care in areas with landfills.