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 resist loads that we could describe as light. These loads are usually transmitted by driving short metal piles into the ground. In order to determine the ground bearing capacity, real-scale load tests are used after analyzing and characterizing the ground using geotechnical fields and laboratory tests.

The importance of these tests in the foundation design requires a proper design of the test procedures that must include 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.

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1. INTRODUCTION

This article 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 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 that total more than 40 GW built, 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 a wide range of foundations that allow piles to be driven into low or high compact soil. In cases when high ground strength is discovered prior to ramming, either a narrower predrilling of the ground can be performed or a wider predrilling of the ground to place the pile into the hole and fill it with a hydraulic conglomerate under pressure.

When the plants are equipped with trackers, generally the foundations are made with rolled or cold-formed steel piles with edges of 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 an isolated short pile.

For its design 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 rigor.

The described foundation type—short metallic piles subjected to what could be classified as moderate loads—allows sizing from full-scale static load tests.

This differs from other types of structures for civil works or building infrastructures, in which ground characteristic strength is usually determined from analytical expressions based on soil and rock mechanics and intrinsic geotechnical parameters (density, cohesion, undrained shear strength, friction angle, etc.),

and ultimate strength (shaft and toe resistance), obtained from field tests (standard penetration tests, pressure metric tests, etc.) and laboratory tests.

2. PREVIOUS GROUND STUDIES

Ramming and full-scale load tests should never replace the prior execution of geological-geotechnical study, or be an argument for minimizing the scope of the geotechnical study.

On the other hand, the success of a static load test depends mostly on a proper design based on a comprehensive geotechnical study that provides accurate and useful data. Additionally, it is important to remember the formal or administrative requirement for conducting a geological-geotechnical study mandated by 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", and "Technical specifications for the request for a geophysical study for a photovoltaic power plant" www.orbisterrarum.es).

the features that the geological-geotechnical study must include for the technical and economic evaluation of the subsequent static load test campaign are:

- Zoning diverse types of ground depending on the geology (geological mapping). This includes detecting areas with anthropic landfills, low bearing capacity soils, and cut and fill areas affecting future photovoltaic panels.
- Assessing the feasibility of pile driving through penetration tests and trial pits in order to determine the need to carry out complementary works such as pre-drilling, drilling diameters, installation of micropiles, etc.
- Detecting geological risks that may affect the foundations, including: seismic effects, swelling, collapse, flooding, erodible areas, and other features that could affect the foundation materials such as corrosivity or aggressiveness to concrete.
- Evaluating the ground corrosiveness of buried foundation elements.
- Evaluating the value of the permanent, variable, or accidental actions that the structures must support, originating in the ground (overloads, ground pressure, expansiveness, freezing, earthquake, etc.).
- Provide an estimation of the shaft resistance for establishing a preliminary pile embedment length.

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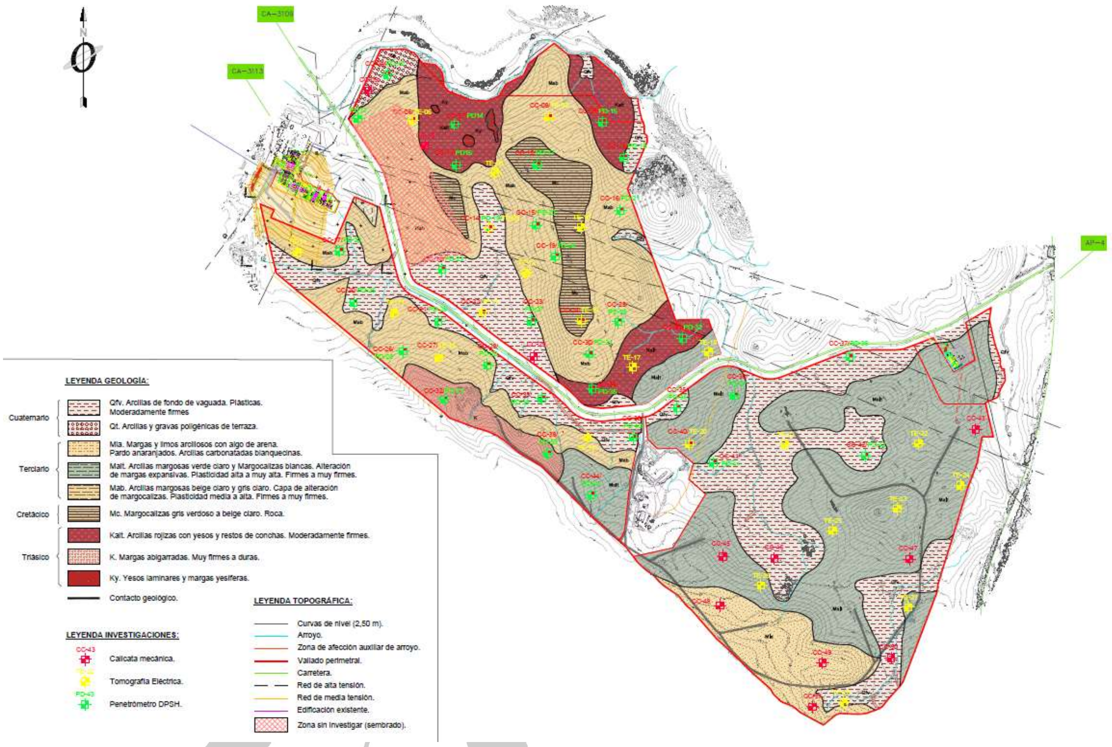

Fig. 1: Example of detailed geological mapping for geotechnical study of a photovoltaic plant

Fig. 2: Zoning of the pile driving feasibility for the same project of figure 1

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When planning a campaign of static load tests, in addition to initial information about the ground behavior provided by the geotechnical study, it is critical to have knowledge of the order of magnitude of the forces that the structure transmits to the ground.

The combined information from a geotechnical study and a load study on the ground significantly aids in evaluating the number of tests required, estimating the initial embedment length, understanding the needs for ground preparation prior to driving, and establishing the load increments to be applied during the tests.

3. CRITERIA FOR ESTABLISHING THE NUMBER OF TESTS

Currently, there are no specific regulations that establish the number of test points required for this type of construction to be carried out on a plot. According to ORBIS TERRARUM, the two fundamental factors that establish the number of test points are surface and existing lithological heterogeneity in the plot.

The various technical specifications provided to ORBIS TERRARUM by this type of campaigns, already show the lack of common quantitative and/or qualitative criteria that establishes the number of load tests.The most common practice is to determine the number of test points based on the installed power (possibly influenced more by economic considerations than technical ones, attempting to limit the cost of the study based on the expected investment, i.e., the installed power in MW) or to leave it to the discretion of the bidder.

In the absence of specific regulations, ORBIS TERRARUM has analyzed the general market trend based on test campaigns carried out over recent years. Considering the campaigns that fall within an acceptable range of variation, and discarding those with an insufficient or illogical number of tests, the following expression is proposed to determine the number of posts to be tested based on the plant surface area:

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

Where:

$N =$ *Number of posts to be tested*

$S =$ *Plot surface (Ha)*

This proposal is intended for plot surfaces greater than 0.5 Ha. For smaller plots, a minimum of 3 piles is recommended for testing.

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

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

Factors such as greater or lesser lithological variability or fluctuation in thickness and/or strength, make it necessary to increase or decrease the number of test points. These factors must be taken into account for the quantitative design of the static load test campaign, highlighting the importance of using the data provided by the prior geotechnical study to design the campaign.

Emphasis must be placed on the quality of the tests execution. It is crucial to avoid falling into the routine of executing tests without analyzing the results in parallel, to avoid adjusting campaign decisions. The extensive surface area of the plots leads to many tests that must be executed. Having a smaller number of correctly executed tests is prioritized over a larger number of tests with doubtful quality and difficult interpretation.

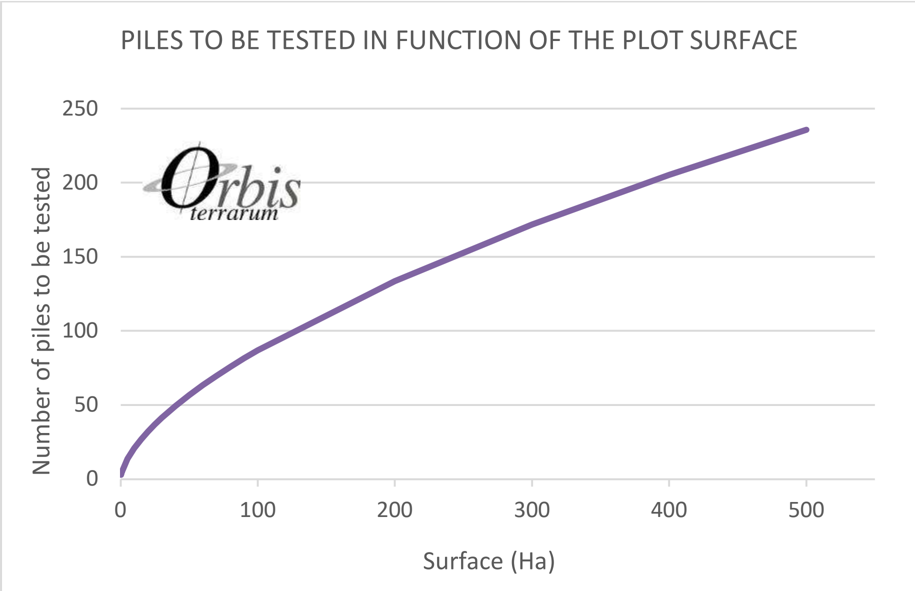

Fig.3: Number of piles to be tested depending on the surface of the plant in Ha

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Table 1: 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

Finally, the performance of tests 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

Before carrying out a campaign of static load tests it is essential to determine whether the piles can be driven directly into the ground or if preliminary work (such as pre-drilling) is required to facilitate driving. Therefore, during the preliminary feasibility study phase, the geotechnical study will test the capacity of the ground to admit a foundation solution. This can be done by driving piles through continuous dynamic penetration tests, or a preliminary ramming campaign that can also obtain preliminary data about the ground behavior against axial and lateral forces.

Subsequently, it is crucial to carry out the ramming and static load test campaign during the project phase using piles with a similar cross-section to those designed for the project. This helps determine the areas in which direct ramming is feasible, project the embedment length of the piles, determine the ultimate strength parameters of the ground, and estimate the displacement of the structures for the viable foundation solutions.

While the fundamental objective of a feasibility study is to evaluate the most appropriate construction method and pre-size the embedment length from initial data, the project phase requires more detailed information to draft a test procedure. It is important to know the approximate order of magnitude of the factored reactions of the structure in the foundation (tensile, compression, lateral load and bending) in order to size an embedment length and check its validity for all possible reactions, considering both the ultimate limit state and the service limit states (e.g., allowable displacements). Generally, the loads are applied in load-unload steps until a maximum value is reached, emphasizing the static nature of the applied loads. Although load-unload cycles are performed, the loads are applied during a time period that allows stabilization displacement and must be considered static.

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For the dimensioning and verification of a foundation with isolated metallic piles,permanent, variable, and accidental loads are considered static and must be treated in the calculation according to current regulations, similar to other building structure foundations and civil works.Effects such as the loss of long-term strength due to dynamic loads are outside the scope of this type of test.

In soils more sensitive to strength variation with moisture content, it is common to simulate saturation conditions around the pile by flooding.

4.1 Testing equipment

The necessary machinery and measuring equipment for these tests include:

- Driving equipment and percussion rotary drilling equipment, with an energy capacity to drill at least 800-1.000 J. It is desirable for the drilling equipment to be capable of drilling holes up to a maximum diameter of 150-200 mm in case of high ground hardness.
- Digital dynamometer with a calibration certificate and minimum capacity to measure up to 50,0 kN in any direction .
- Load cell with a calibration certificate and minimum capacity to measure up to 50,0 kN in the axial direction of the profile.
- Digital or analog 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 in case pre-drilling was necessary

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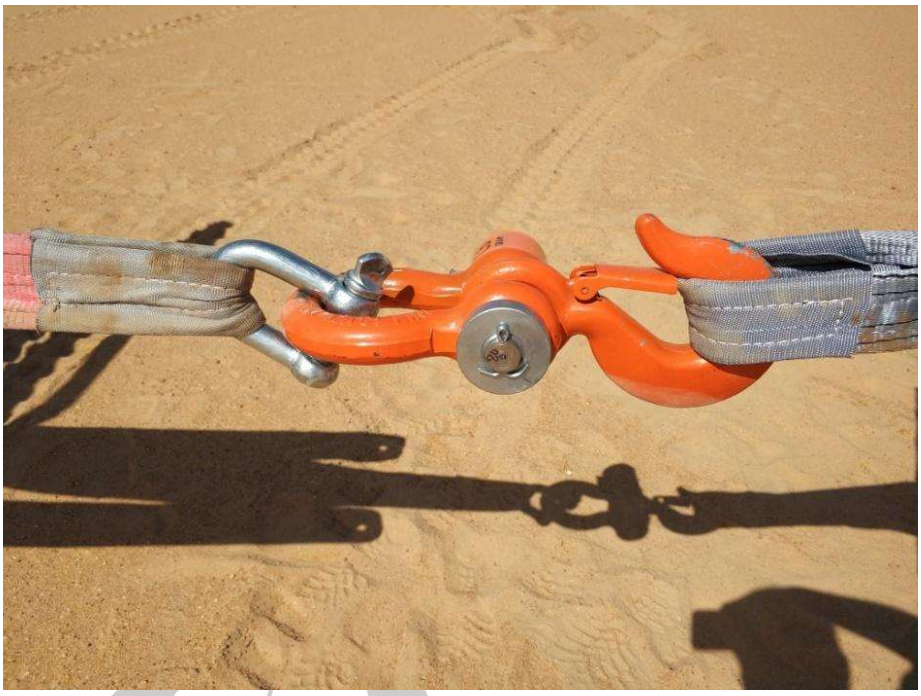

Photo 2: Dynamometer for measuring load applied assembled for lateral load test

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. The load can be applied with a level or chain hoist for axial tensile load tests and lateral load tests, or with a hydraulic jack for compression tests. When the loading steps are not small it is common to apply the load with the hydraulic system of the machinery (excavator, backhoe loader…).

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

4.2 Testing method

The method of conducting load tests on driven piles, including: the number of load steps, duration of load application, and timing of displacement measurements, allows us to obtain conclusions about the ultimate ground strength, and the foundation´s behavior based on the measured absolute and residual displacements.

Extrapolating 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 is not reached due to soil failure, the maximum load applied in the test must be adopted as the ultimate load.

It is recommended to perform a test per driven pile, either a lateral load test or an axial load test, aiming to achieve 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 common practice is to use the driven pile to carry out the two tests[1]. This practice is considered acceptable, with the recommendation that the lateral load test be performed first. Once it is verified that the pile has not sustained considerable deformations and is suitable for a second test, the vertical load test can be conducted. This guideline, while not a general rule,may also depend on the value of the reactions in the foundation or the pile-ground behavior in the first tests. It follows the recommendations indicated in Eurocode 7, particularly in sections 7.5.2, “Static load tests” and 7.7.2, “Resistance to lateral loads obtained from pile load tests” which 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.

[1] 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.

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4.2.1 Pile tests

During the pile driving, the driving time by segments must be registered. This is necessary to determine the driving speed and estimate ramming production. Additionally, it will provide qualitative data that together with other test results from the geotechnical study, will help to more precisely delineate areas with different behaviors in terms of ground strength.

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

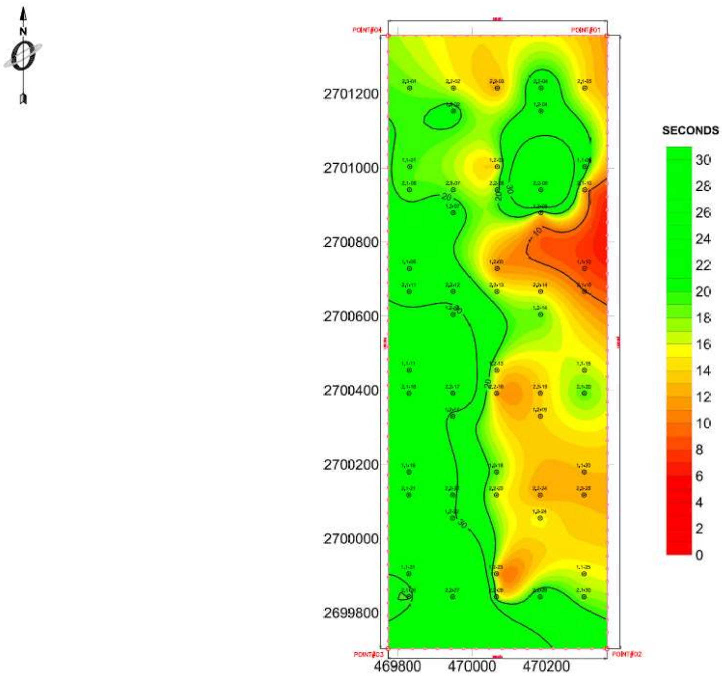

Fig. 4: Example of driving time isoline map

4.2.2 Pile testing under under lateral load

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

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

Where:

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

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

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

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The maximum load that the test must reach shouldbe applied by load-unload steps, measuring for each load step the absolute relative displacement between the base of the pile and the ground, and for each unload step, the remnant displacement. Displacements will be measured using a micrometer, and the measurements should be taken as close as possible to ground level.

It is recommended for the maximum load applied to be at least 120% of the lateral load, $F_{l,d}$,value.

As an example, figure 5 includes a lateral load test carried out in accordance with the guidelines indicated.

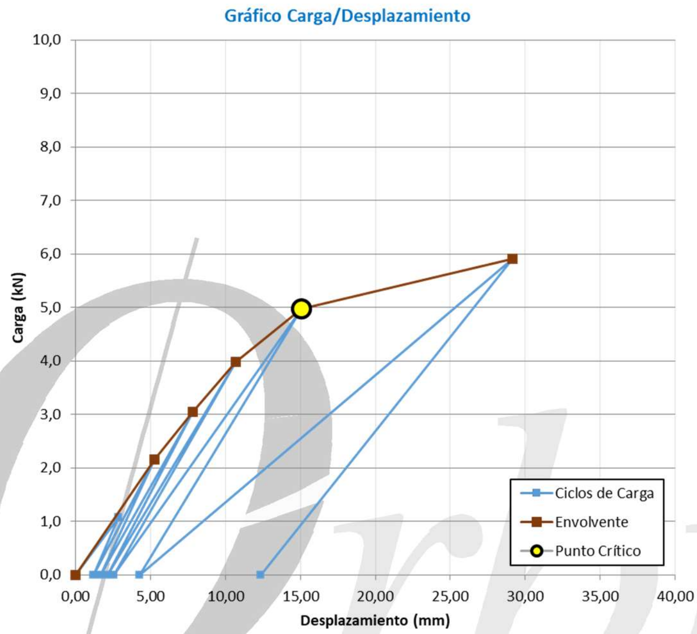

Fig. 5: Example of load-displacement curve in lateral load test

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

It is important to remember that the objective of the test is to verify the ultimate limit state of the foundation to horizontal forces and ensure that the absolute and remanent displacements that occur in the foundation during the structure's service life are allowable. In any case, the test can always provide, through back-analysis calculation, an equivalent horizontal subgrade reaction modulus of the ground for the considered embedment length. This can be used to check the foundation using specific software for any other combination of bending and shear moment actions transmitted to the ground (as long as it is for the same embedment length considered in the tests and calculations), or another type of cross-section but of similar dimensions.

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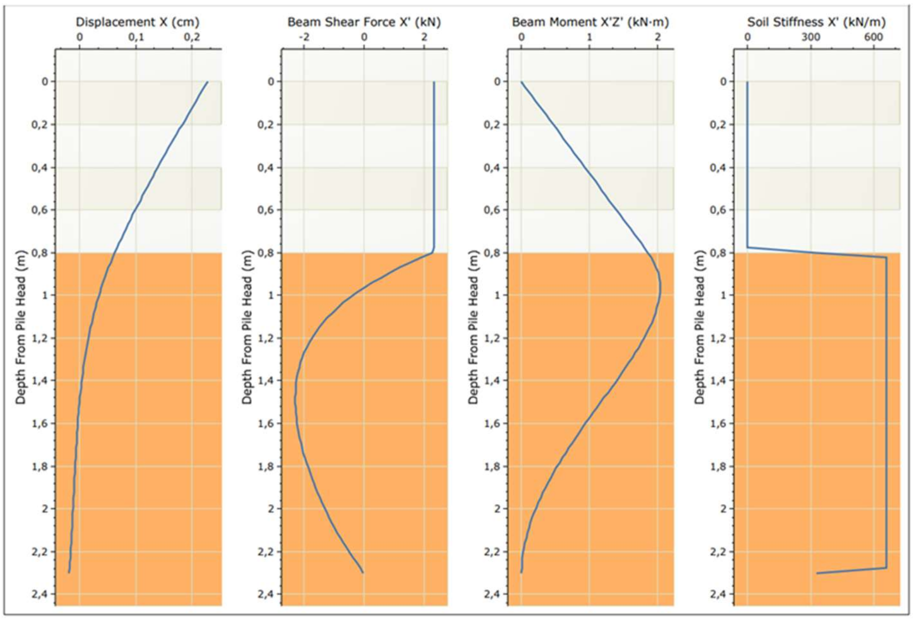

Fig. 6: Example of bending moment, shear and displacements graphs in back analysis calculation to determine the horizontal subgrade reaction modulus of the ground from the tests

As for the values of allowable horizontal displacements of the foundation, they will be defined by the structural engineer and depend on the type of structure, modulation, loads, etc. Common values observed in 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 influential in this type of structure, although this should not be taken as a general rule.

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, ensuring that 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 subjected to a vertical tensile and compression load.

The values $R_{t,d}$ and $R_{c,d}$ are derived 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 to the top of the driven pile, and the displacements obtained in each load step must be measured to study the service limit state of allowable displacements of the structure. Figure 7 includes an example of a vertical tensile load test conducted according to the guidelines indicated.

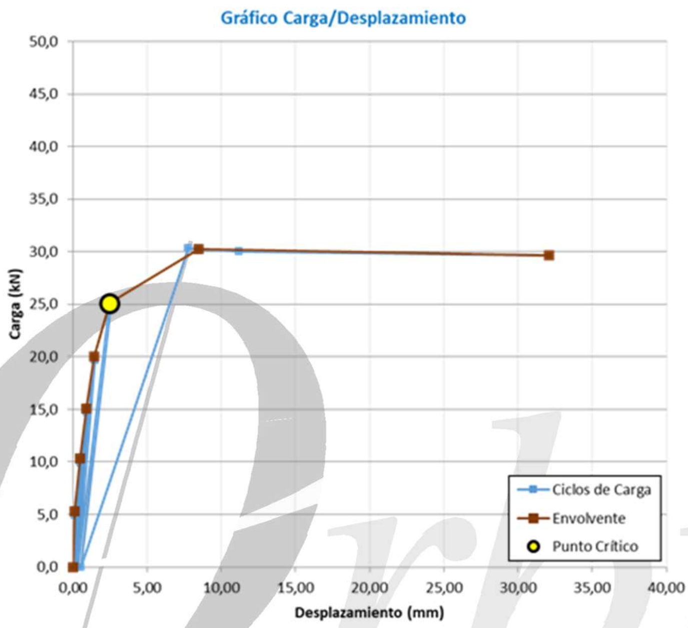

Fig. 7: Example of load-displacement curve for an axial tensile test

It is recommended to apply the load until the pile is removed in uplift tests in order to determine the ultimate 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 to consider only axial tensile load tests in the campaigns because they are usually more limiting for the dimensioning of the structure. Additionally, both in technical bibliography and in various foundation standards and guides, it is common to find the relationship between the resistance per shaft for tensile and compression forces:

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

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4. REPORT

The scope of a report of this type must be set between the technical test team and their client and can vary greatly, from a simple report summarizing the obtained results ("factual report") to a much more comprehensive report analyzing the results in-depth and pre-sizing the foundation ("engineering report"). The scope of the report must be defined in the conditions of the agreement.

The factual report must include, at least, the following 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 pile driving machine, loading devices, reaction system and measuring equipment.
- Data of the pile driving such 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 to include 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.
- Analysis 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, it is important to emphasize that the testing areas must be representative of the plant construction, taking particular care in areas with landfills.

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