TECHNICAL SPECIFICATIONS FOR THE REALIZATION OF STATIC LOAD TESTS FOR THE FOUNDATION OF PHOTOVOLTAIC PLANTS

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Summary: Foundations projected for photovoltaic plants resists loads that we could describe as light. These loads are usually transmitted to the ground by driving short metal piles. In order to determine the ground bearing capacity, real-scale load tests are used 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.

1. INTRODUCTION

This article includes a series of recommendations for the planning of static load test that allow estimating the ground characteristics for the design of foundations of photovoltaic plants by means of driven piles. These are based on the experience of ORBIS TERRARUM after taking part in the geotechnical research of more than a hundred plants in several countries of the world that total more than 5,500 Mw built. ORBIS TERRARUM has participated in all types of geotechnical works in the different construction or project phases: geological-geotechnical feasibility or detail studies, driven pile campaigns and static load tests, technical advisory to designers or builders, etc.

The vast majority of the structures that support solar panels and trackers that make up these plants are based on metallic piles driven into the ground, seeking an optimization of cost and execution times, compatible with the structural safety of the construction. This article refers to these type of foundations, generally feasible in a very wide range of grounds, either by piles simply driven into soils of low to high compactness or consistency, or with actions prior to the piling as the pre-drilling and improvement of the filling material of the drill hole with granular material, cement mortar and even concrete (micropiles).

These foundations are executed with metallic piles with a section lower than 200-250 mm and with an embedment in the ground greater than 1,50 m, responding generally to a short isolated pile typology. 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”, although there are other official publications that deal with this type of foundation with technical rigor.

These type of foundations - short metallic piles subjected to loads that we could qualify as moderate – can be dimensioned from simple static load tests on a real scale. In other major civil works, it is more usual to determine the soil strength features from analytical expressions, using representative geotechnical parameters (density, cohesion, undrained shear strength, friction angle, etc.) and of ultimate strength (shaft and toe resistances) obtained from field tests (standard penetration tests, Pressuremeter tests, etc.) and laboratory tests.

2. PREVIOUS GROUND STUDIES

Static load tests can never replace the realization of a good geological-geotechnical study. They also can never be an argument for minimizing the scope of the geotechnical study.

On the contrary, the success of a static load tests 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. Do not forget, in addition, 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 plants and the basic guidelines for its planning have already been the subject of another paper by ORBIS TERRARUM (see "Technical specifications for the

application of a geological-geotechnical study in photovoltaic plants"[1], INFOEMPRESAS, September of 2016 and web update of 2018). Among the aspects that the geotechnical study must gather for the technical and economic evaluation of the subsequent static load test campaign, three of them should be highlighted:

- Zoning different types of ground 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.

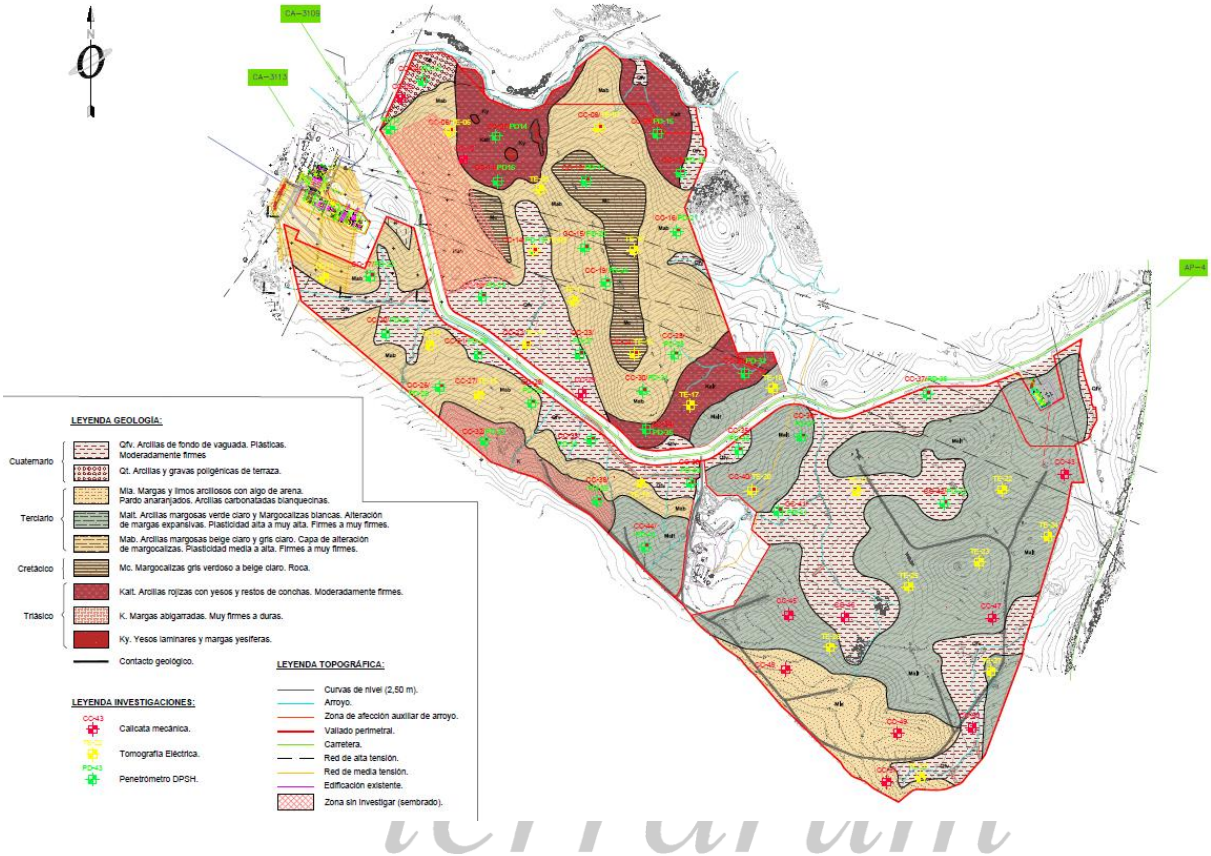

Fig. 1: Example of detailed geological mapping for geotechnical study of a photovoltaic plant

[1] http://www.orbisterrarum.es/en/technical-specifications-ramming-pullout-photovoltaic-plants/

Set the feasibility of pile driving through penetration tests and trial pits in order to foresee the need to carry out complementary works in the load test campaign as pre-drilling, drilling improvement, etc.

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

- 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 materials such as corrosivity or aggressiveness to concrete.
- A first estimation of the shaft resistance for establishing a preliminary pile embedment length.

In addition to the knowledge of the ground obtained with the geotechnical study, the other important part when planning and conducting a static load test campaign will be, logically, the knowledge of the forces that the structure transmits to the ground.

These two documents, geotechnical study and study of loads in the field, will allow evaluating both the number of tests to be carried out, forecast of embedding of the profiles in the ground, preparation of the ground prior to the pile if necessary, load increases to perform during rehearsals, etc. Knowledge what will mainly allow to establish the density of test points.

3. CRITERIA FOR ESTABLISHING THE NUMBER OF TESTS

For this type of construction there is no specific regulation that establishes the number of tests to be carried out in a plot. The quantity of tests to be carried out would be subjected to two main factors: plot surface and lithological heterogeneity.

The technical specifications for this type of campaigns reviewed by ORBIS TERRARUM already show the lack of common quantitative and / or qualitative criteria among several petitioners of this type of works when establishing the number of load tests for a project. Some of these criteria depend on the installed capacity (perhaps motivated more by economic issues trying to limit the cost of the study) but, in many cases, the design of the campaign is entrusted to the bidder.

For the determination of the number of tests ORBIS TERRARUM proposes the surface area occupied by the panels as the basic starting data. After studying and analyzing a significant number of campaigns (carried out by ORBIS TERRARUM or other companies) the following expression is proposed in order to determine the number of trials:

$$N = 13{,}5\ x\ S^{0{,}45}$$

Where:

N = Total number of tests to be performed (traction, compression and lateral load)

S = Plot area (Ha)

This expression is derived from the average curve (red line) shown in Figure 3 "Plot area vs Number of tests per Ha". This curve represents the average trend line that best fits the series of static load tests campaigns from which information has been provided.

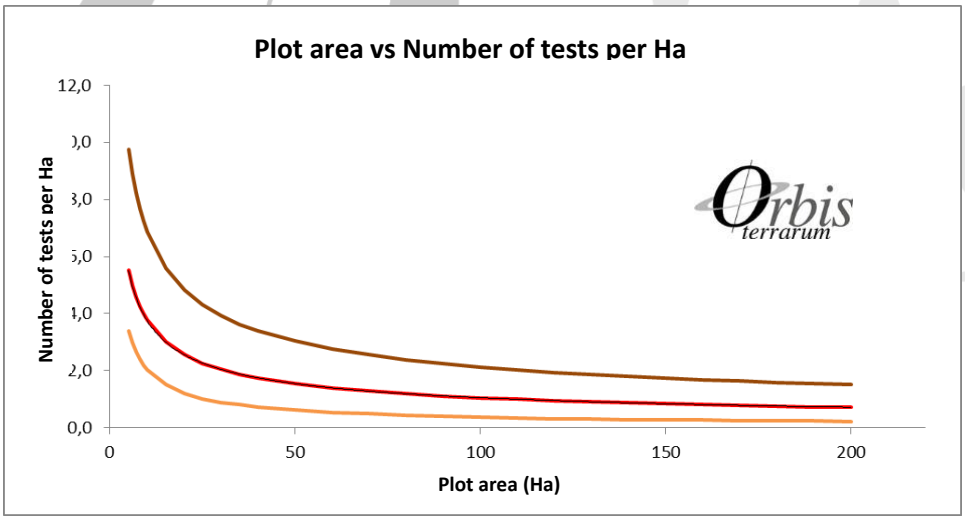

Fig. 3: Number of tests per Ha recommended according to the panel occupation surface

As already mentioned, there are factors such as the lithological variability and the variation in thickness and / or strength of these lithologies in surface or in depth that may make necessary to increase or decrease the number of test points. In this sense, the data of the campaigns that have been analyzed have also served to establish two envelopes that would reflect the lithological and resistant variability with respect to the proposed average curve. Figure 3 also shows an upper envelope (brown curve) that could serve as a reference for complex plots in terms of their geology, with great variability both in geological units and in their strength features, and a lower curve (orange curve), representative of study areas with a homogeneity in lithology and strength.

It is important to note the quality in the execution of the tests. As it can be observed, the proposed expression leads to a large number of tests in big areas. It is not recommended to carry out a test campaign without performing simultaneously an analysis of the results. Not doing this only leads to perform one test after another with any value for the foundation design.

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. It is considered that, if heavy machinery is employed as reaction, the average number of tests could be around 15 test/day with a maximum of 18 test/day.

It should always be a priority having well performed tests than having many tests of doubtful quality and interpretation.

4. METHODOLOGY

It is a prior condition, before carrying out a campaign of static load tests, to know if pile driving is feasible or to know if it is necessary to carry out some kind of previous work in order to facilitate the driving (pre-drilling, for example). That is why, in the feasibility studies phase, it is essential to determine the capacity of the ground to admit a foundation by driving piles, either as a part of the geotechnical study based in dynamic penetration tests, or by designing and performing a previous driving campaign, which, in addition, would allow to obtain preliminary data about the ground behavior under axial and lateral loads.

Performing the static load test campaign in the design phase with piles of shape and dimensions similar to those planned is fundamental for obtaining the embedment length of the piles and for determining as closely as possible the parameters of ultimate strength of the ground and estimation of the displacements of the structures.

While for a feasibility study the fundamental objective are to evaluate if this constructive method is adequate and to pre-dimension the embedment length, the test procedure in the design phase should obtain a maximum load similar to that of the calculation of the structure. For this reason, calculation values of actions (major loads) as traction, compression and lateral load transmitted to the ground by the pile must be known before performing the tests or, at least, very approximate values.

It is important to remark the static character of the applied loads. Even if load-unload cycles are carried out, the loads are applied for a certain time that allows the stabilization of the displacements so they can be considered as static. In this case, transient or variable actions as seismic, wind or snow loads are considered according to the current regulations in the calculation of foundations for building structures, civil works, etc.

Regarding the effect of possible ground strength loss during the pile driving (dynamic loads), it is assumed that developing the tests immediately after the driving includes already the effect derived from the possible ground strength loss by a punctual action originated by the dynamic load during the driving, although it is difficult to set a unique criterion.

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

Other effects of long-term strength loss such as liquefaction, swelling-retraction of the ground, heladicity, etc. are beyond the scope of these tests, also the soils sensitive to repetitive loads.

4.1 Testing equipment

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

- Pile Driving equipment.

Photo 1.- Pile driving equipment

- Drilling machine capable of drilling up to a maximum diameter of 200-250 mm.
- Loading device with a minimum capacity of 50 kN that allows to apply the load on the pile in any direction, preferable being operated by a intermediate hoist.
- Stiff frame for compression tests.
- Digital dynamometer to measure in any direction with a minimum capacity up to 50 kN.
- Digital or analogic micrometer for displacement measurement with enough range to measure the maximum expected displacement and with an accuracy of 0,01 mm.
- Auxiliary elements: slings, pile load cap, etc.

Photo 2.- Drilling machine with compressor

Photo 3. - Micrometer installed for displacement measurement during lateral load test

Photo 4: Dynamometer measuring the lateral load applied

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 pulley system or hoist in the case of axial tensile load tests and lateral load tests, or with a hydraulic jack in the case of compression tests. It is also usual to apply the load with the hydraulic system of the machinery (excavator, backhoe loader…).

4.2 Testing method

The execution of load tests on driven piles and in particular in terms of the number of loading steps, their duration and times of measurement, must be good enough for obtaining conclusions about absolute displacements and residual or non-recoverable displacements. The loads must be applied in such a way that allow estimating the ultimate ground strength, especially in the axial tensile load test, as this is usually the most restrictive action for ground bearing capacity in this type of facilities.

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.

However, the most widespread practice is to use the driven pile to perform the two main tests (see next chapters for a description of these tests). This practice is considered valid, although, in general, the correct procedure is to perform firstly the lateral load test and, subsequently, after checking that the pile has not suffered serious deformations and that is suitable for the second test, perform the

vertical load test. This guideline should not be taken as a general rule and will depend on the behavior of the ground and the pile in the first tests.

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.

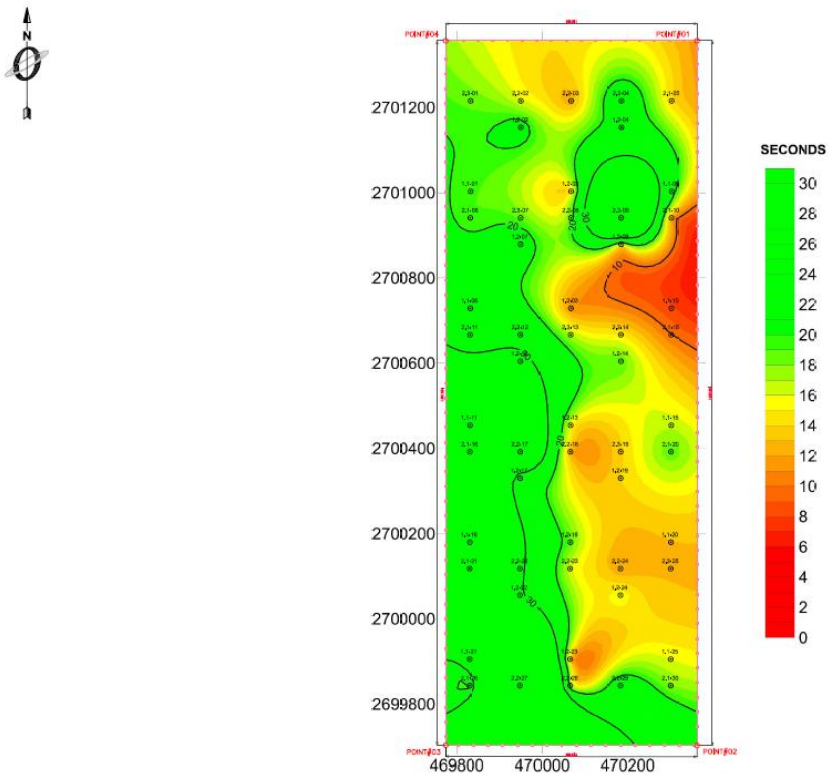

Fig. 4: Example of driving time isoline map

4.2.2 Pile testing under under lateral load

To check the ultimate ground strength lateral load tests will be carried out with different embedment depths (L_i) in order to determine the optimum embedment for resisting the design lateral load with an adequate safety against yielding of soil, that is, to satisfy all load combinations that match next expression:

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

Where:

$F_{tr,d}$ = Calculation value of the lateral load on the pile that is transmitted to the ground.

$R_{tr,d}$ = Calculation value of ground strength with transversely loaded pile.

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

With the additional objective of obtaining data of absolute and remaining displacements for the maximum load and for various load levels and also for studying the compliance with the limit state service of allowable horizontal displacements, the maximum load has to be applied in four or five loading-unloading steps. Each step must be a percentage of the maximum load $F_{tr,d}$. Displacements will be measured at a point of the segment that is cantilevered from the pile with the micrometer, at a point as close as possible to the ground level.

It is recommended that the maximum load applied will be at least 120% of the lateral load $F_{tr,d}$ calculation value.

As an example, the load and displacement measurement steps that could be obtained in a lateral load test procedure could respond to the next scheme:

- Application of 40% of the lateral load, $F_{tr,d}$, calculation value and measuring of the displacement when the load is applied, and after a time "t".
- Once the time "t" has passed and the displacement has been measured, proceed to unload and measure the remaining displacement when it remains stable.
- Repetition of the two previous steps for 60%, 80%, 100% and 120% of the lateral load $F_{tr,\ d}$.

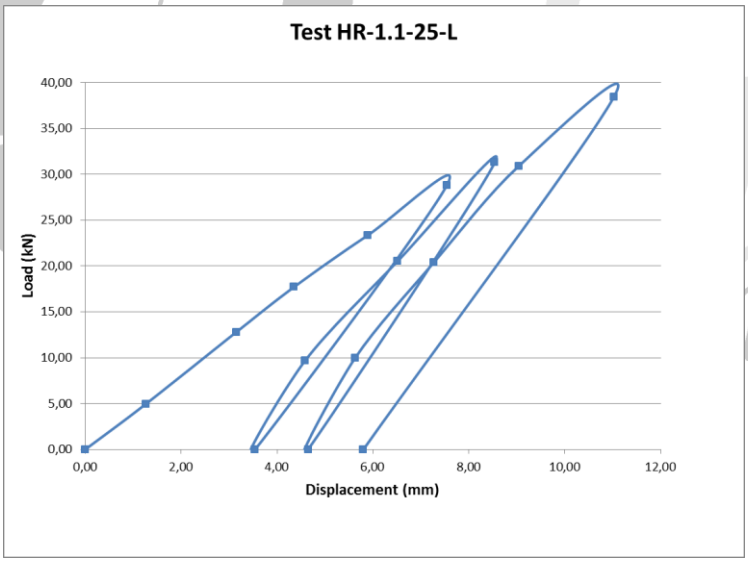

Fig. 5: Example of load-displacement curve for a lateral load test

As for the height of load application, it should be such that for the maximum load, $F_{tr,d}$, a moment similar to the reaction determined in the structural design (M_d) will be generated at the pile base. In any case, for the types of piles that are being used in the foundations of photovoltaic plants, it is recommended that the height of load application will be in order of 1,0 m and in no case exceeding 1,5 m.

It should not be forgotten that the objective of the test is the verification of the ultimate limit state of the foundation to horizontal stresses and that the absolute and remaining displacements that occur in the foundation during the useful life of the structures are allowable. In any case, the test can

always provide, by means of a back-analysis calculation, an equivalent horizontal reaction module of the ground for the considered embedment length (or equivalent horizontal subgrade reaction modulus) 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).

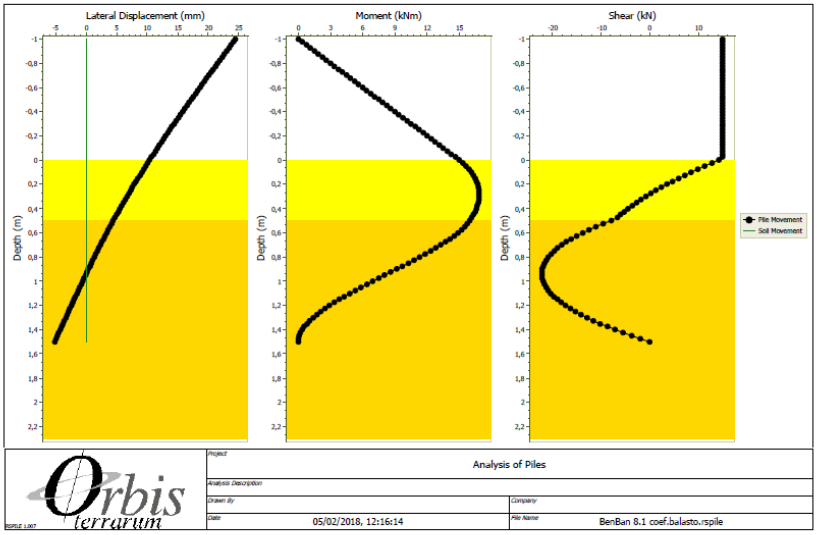

Fig. 6: Example of bending moment, shear and displacement in back-analysis to determine the horizontal reaction modulus of the ground from field tests

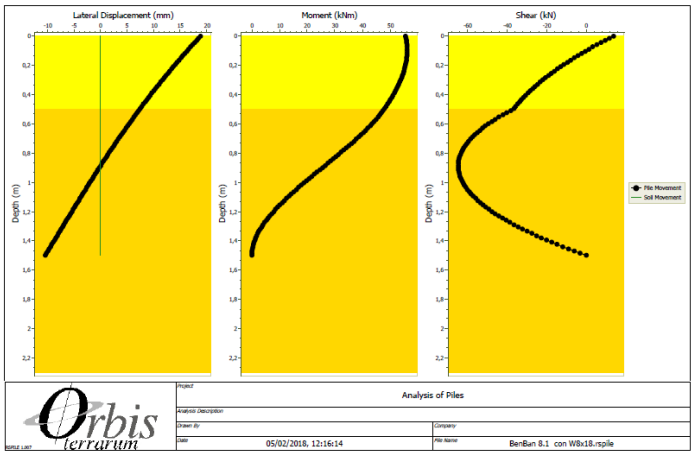

Fig. 7: Bending moment, shear and displacement in the same project of figure 8 for bad combination of shear and bending moment in head of foundation

As for the values of horizontal displacements allowable by the foundation, they must 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 usually 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.

When conducting double horizontal load tests, the reaction equipment will need to be duplicated. This reduces the shear stress and maintains the bending moment at the base.

4.2.3 Pile testing under axial load

For checking the ultimate limit state of the ground strength for both tensile and compressive vertical loads, the test procedure is similar. Axial tensile stress is usually more influent in this type of structure, 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 security factor against soil yielding, i.e., to satisfy all load combinations that comply next expressions:

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

Where:

$F_{t,d}$ y $F_{c,d}$ = Calculation values (increased) of the tensile and compression axial load respectively that the pile transmits to the ground.

$R_{t,d}$ y $R_{c,d}$ = Calculation values of ground tensile strength and compression respectively for an isolated pile in the ultimate limit state.

The values $R_{t,\,d}$ and $R_{c,\,d}$ must be 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 stress can be applied to the driven pile head and the displacements that are obtained in each load step must be measured for also studying the ultimate limit state of service of vertical movements of the structure foundation.

As an example, the load and displacement measurement steps that could be obtained in a vertical load test procedure could respond to the next scheme:

- Application of 40% of the axial load, F, calculation value and measuring of the displacement when the load is applied, and after a time "t".
- Once the time "t" has passed and the displacement has been measured, proceed to unload and measure the remaining displacement when it remains stable.
- Repetition of the two previous steps for 60%, 80%, 100% and 120% of the axial loads, F.
- Application of new load increments of 5,0 kN and measurement of the absolute displacement obtained until the maximum ground strength or the maximum load capacity is obtained.

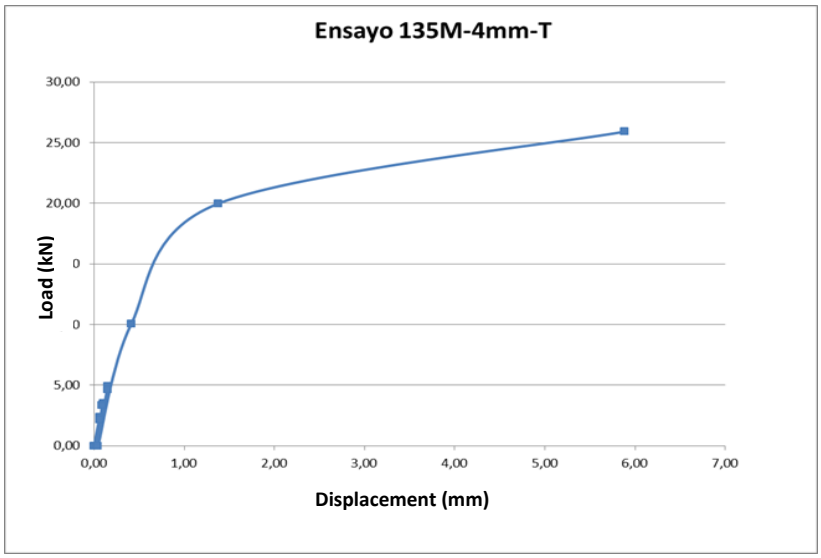

Fig. 8: Example of load-displacement curve for an axial traction test

It is usual to design the campaigns only with tests of traction load (in addition to the tests of lateral load), forgetting the compression in case the maximum pull out load is bigger than foreseen for compression. Many times traction loads are more limitative for the structure design. In addition, in technical literature usually accepted as in different standards and foundation guides, it is common to find a relation between shaft resistance for tensile and compression stresses:

$$R_t = (0{,}60\ a\ 0{,}70) \times R_c$$

4. REPORT

The content and scope of a report of this type must be set by the testing technician and his client, and can be from a simple report that summarizes the obtained results ("factual report") to a much complete report where the results are analyzed. The minimum content of the report must be defined in the contract conditions.

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 segments, 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 or interpretative report its content must be, at least:

- Calculation an analysis of the ground representative parameters for axial and lateral loads.
- Setting the ultimate ground strength for the different 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.
- Dimensioning of the foundation for each identified area.
- Estimation of pile driving production.

Finally, is important to remark that the testing areas must be representative for the plant construction, being careful in those areas with artificial or man-made ground.