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PROGETTO DEFINITIVO DI UN IMPIANTO DI PRODUZIONE DI ENERGIA ELETTRICA DA FONTE FOTOVOLTAICA DI POTENZA COMPLESSIVA PARI A 16,6 MWp E DELLE RELATIVE OPERE DI CONNESSIONE DA REALIZZARSI NEL COMUNE DI MATERA (MT), DENOMINATO "CSPV MATERA"

JOSE ANTONIO VALLE FERNANDEZ
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A.7 Relazione preliminare sulle strutture

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PVH | OPTIMIZED SOLAR SOLUTIONS

GENERAL TECHNICAL DESCRIPTION

GEOGRAPHIC SITUATION: MATERA (ITALY)

AXONE DUO Single-Axis Tracker

Document No.: **PVH_ITALY_GeneralTechnicalDescription_MATERA_Rev00**

Rev.: 00 Date: 27th October 2021

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00	27/10/2021	All document	Issued	Enrique Miñano	Iván Leiva	Eduardo Chillarón

Contents

1. INTRODUCTION

The object of this document is to carry out a brief description of the main technical solutions adopted by PVH for the projects.

Methodologies used by the PVH engineering team to develop all the products are shown in the following chapters.

The core of the PVH team is composed by engineers with more than 10 years of experience in solar and in other sectors like aeronautics, automotive, oil and gas, wind energy…

The knowledge and the know-how of all those industrial sectors has been applied to develop PVH products.

2. REFERENCES

2.1 Applicable Standards

The solar array shall be designed to the normal and expected base set of requirements established by:

[I] EN 1993-1-1 2010: Design of steel structures. Part 1-1: General rules and rules for buildings

[II] EN 1991 1-4 2010: Eurocode 1 – Actions on structures, Part 1-4: General actions, Wind actions

[III] EN 1991 1-3 2009: Eurocode 1 – Actions on structures, Part 1-3: General actions, Snow Loads

[IV] Modello di pericolosità sismica MPS04-S1

[V] CPP14149_PVHTracker_REP_SOLSTADYN_R02

[VI] PVH_AxoneDuo_DAMPING_FACTOR_ANALYSIS

[VII] CPP13360_PVHardwareAxone_REP_SOL_R02

2.2 Computational Analysis

- Ansys V19
- Abaqus/CAE v17
- ConSteel 14

3. GEOGRAPHIC SITUATION

This document corresponds to the study made for the project that will be located close to the town of Matera in the province of Basilicata (Italy).

Figure 1. ***Situation of the Solar Array***

4. STRUCTURE DESCRIPTION

The structures used in the offer is an AXONDE DUO.

Figure 2. ***AXONE DUO 120 modules***

Solar panels are established in a portrait orientation:

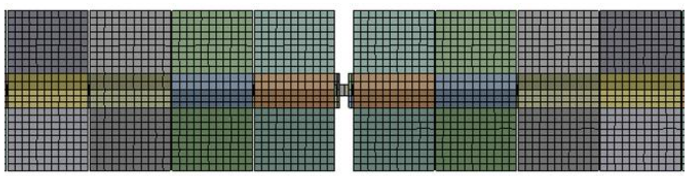


Figure 3. ***AXONE DUO One panel in a portrait position per Columns***

The arrays are divided into different zones. External zones, where the rows are more exposed to wind and as consequence the structure is more robust. Then, internal zones, where the rows are less exposed to the wind.

PVH have further experience in other tracker products such as ML3H, ML2V and Anywind.

4.1 Main Components

Each structure of 1 axis solar array is composed by the following components: Posts, Rotation Beam, Panel Rail (Omega profile), solar Modules and a central electrical motor. The distribution and its location in the structure are shown in the next figure:

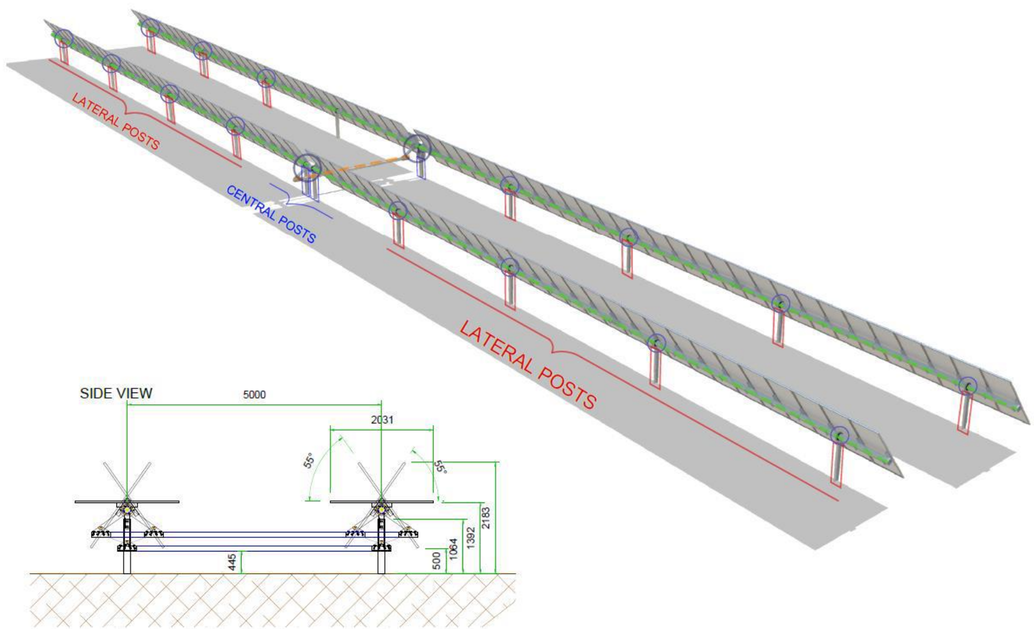


Figure 4. ***Main Components in a Row (AXONE DUO)***

4.2 Main joints

- <u>Joint between rotation beams</u>: The rotation beam is the element that allows rotation of the tracker. In order to ease it shipping it is divided in several parts. Each part is joint by a clamp. The thickness of these clamps and diameter of bolt are calculated depending on the applied loads

Figure 5. ***Joint between rotation beams***

- Joint between post and rotation beam: Between the rotation beam and the post is situated a steel post head with an internal plastic bearing which allows the rotation. This post head is made by stamping. This element has been optimized regarding with Detailed finite element models and correlating with tests.

Figure 6. ***Joint between rotation beam and post***

- Joint between panel rail and rotation beam: this joint is made by mean of two U-bolts, and it permits move the solar panels simultaneously with the rotation beam.

Figure 7. ***Joint between Panel rail and rotation beam***

5. MATERIALS AND STRENGH REQUIREMENTS

All the solar array structure is made of S275JR and S355JR steel; the next tables show physical and mechanical properties.

MATERIAL (en 1993-1-1:2005)	ELASTIC MODULUS (MPa)	POISSON RATION	DENSITY (Kg/m³)
S275JR	210000	0.3	7850
S355JR			

Table 1. ***Material Physical Properties***

MATERIAL (EN 1993-1-1:2005)	THICKNESS [mm]	MECHANICAL PROPERTIES	
		YIELD STRESS [MPa]	ULTIMATE STRENGTH [MPa]
S275JR	T≤16	275	410
	16<T≤40	265	
S355JR	T≤16	355	470
	16<T≤40	345	

Table 2. ***Material Mechanical Properties***

The material properties are linear elastic for the global model.

A safety coefficient has been applied to the yield stress of each material. This value is shown in the following table related to equation (reference [I]):

$$\sigma_{final} = \frac{\sigma_y}{SC}$$

Strength requirements are function to design criteria used. The next table shows the safety coefficient values for each material.

MATERIAL	YIELD STRESS (MPa)	SAFETY COEFICIENTΦ (-)	ALLOWABLE STRESS (MPa)
S275JR	275	1.05	261.9
S355JR	355	1.05	338.0
Magnelis 350 GD	350	1.05	333.3

Table 3. ***Safety coefficient Value***

6. METODOLOGY

The first step for the structural calculations of the tracker is to define a suitable stow position for the tracker. Solar trackers and other structures of similar characteristics are susceptible to aeroelastic instabilities, which can result in catastrophic failures. To prevent these type of failures, extensive wind tunnel testing has been performed to our tracker design. These aeroelastic studies of our tracker have been done by CPP, Ref. [VI]. From the results and conclusions obtained from these tests, a stow position is chosen for our trackers. In the case of the Axone Duo model, the best stow position is with the external trackers nose down at 30 degrees and internal trackers nose down at 5 or 15 degrees (Depending on the length and chord of the tracker). With these stow position we can ensure that the critical speed at which instabilities occurs is higher than the maximum wind speed expected in the location.

The next step for the calculations is a structural analysis using the corresponding wind loads, snow loads and seismic loads. The loads and combinations used for calculations are obtained from local codes, which can be found in section 2.1.

For the wind loads, shape coefficients and dynamic amplification factors have been obtained from another wind tunnel test of our tracker at different angles and locations at the array.

Taking into account all previous considerations, we proceed to estimate the section profiles needed for our tracker and reaction forces to be use for foundations analysis.

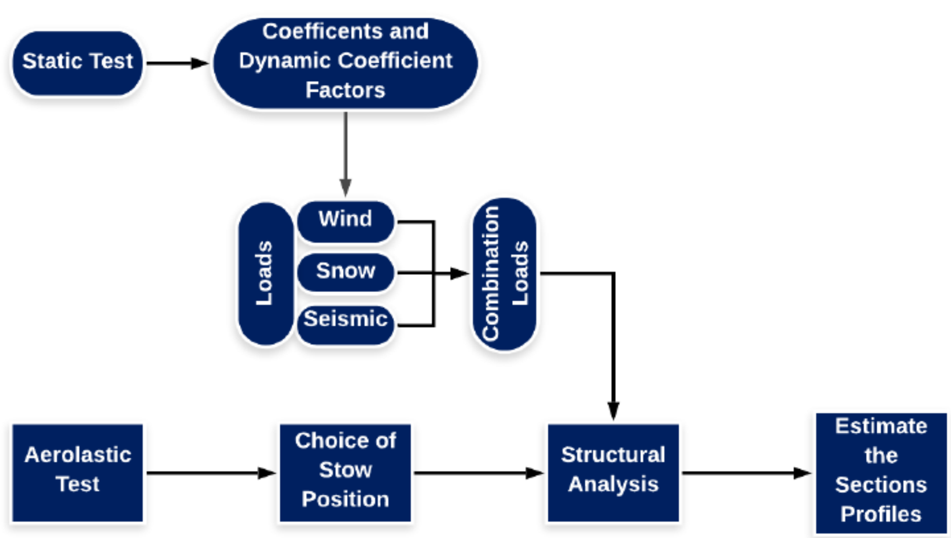


Figure 6. ***Methodology Scheme***

7. MODELLING

7.1 General Finite element model

To simulate the Axone Duo Single-Axis Tracker, only one row has been modelled for each zone in order to simplify the analysis, applying the corresponding boundary conditions. So, each row has been analyzed isolated with their properties and loads.

The finite element model consists of mid-surfaces.

Mesh is mainly based on "**Beam elements**" except the solar modules, which are defined with "**Shell elements"** using quadrilaterals.

In case of bolted joints, "**Joints**" elements are used to simulate the bolt and to join locally the different parts (Zone I and Zone II respectively).

The following types of elements have been used in the finite element model:

- **Shell elements**: has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. As it was mentioned above, two different components were modelled with Shell.

- **Beam elements**: is a uniaxial element with tension-compression, torsion, and bending capabilities. The element has six degrees of freedom at two nodes: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. This element includes stress stiffening; large deflection capabilities and simplifications due to its symmetry and standard pipe geometry are included. Depending on the element represented, different profiles has been utilized.

- **Connector elements**: is suitable for analyzing bolted joints. This element adds an additional equation to the solution which constraint the degrees of freedom between two points corresponding to each joint.

These include translations in the x, y, and z directions and rotations about the x, y, and z directions. Depending on the joint different restrictions will be carried out.

- **Rotation joint**: to simulate the bearing joint between the rotation beam and the posts a special connector which only allow the rotation in the X global axis has been defined (Blue circles)

- The lower nodes of every post constraint the translations and the rotations in all directions.

7.2 Detailed Finite Element Model

- For specific parts, with some singularity or with difficulties to do a hand calculation, a detailed model has been done.
- In these models, geometrical non-linearity and contacts are defined, performing a refined mesh.

In the following pictures, several examples are shown:

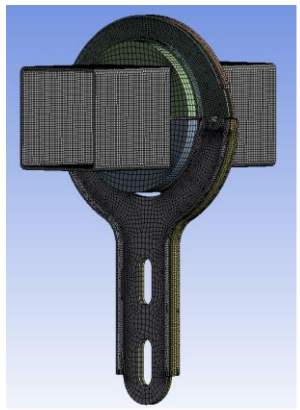


Figure 8. ***Stamping post head DFEM***

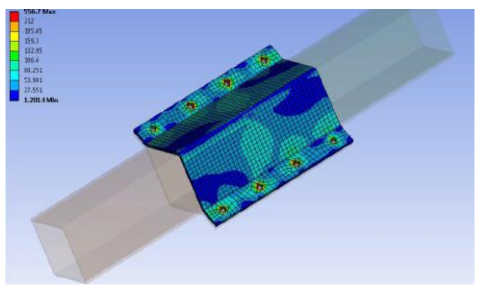


Figure 9. ***Clamp DFEM***

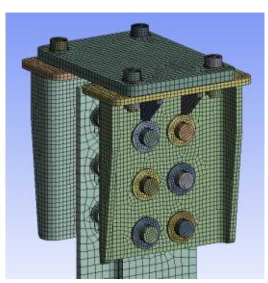


Figure 10. ***Joint to Central motor DFEM***

7.3 Cold formed profiles calculation

The cold formed manufactured profiles have to be checked by mean of a special analysis in order to check possible local buckling and to take into account residual stresses and imperfections generated during the manufacturing process. In this chapter this analysis and results are shown.

These are the steps followed to perform the analysis:

1- Buckling analysis: in this step a linear buckling analysis with the real conditions is carried out.

2- Nonlinear geometrical analysis: in this step a non-linear analysis is done applying an initial imperfection in the same direction than the first buckle mode.

The value of this imperfection is defined by the standards as analysis a conservative value of L/100 have been used.

Panel rails are checked by this methodology.

A shell FEM with section has been done, applying all the boundary conditions and constraining the pertinent DOF and applying the forces.

- Buckling analysis: applying shear and compression force
- Non- linear geometrical analysis: the forces and boundary conditions are the same than for the previous analysis. It is applied an initial deformation in the direction of the first buckle mode shown previously.

8. LOADS DEFINITION AND STANDARDS

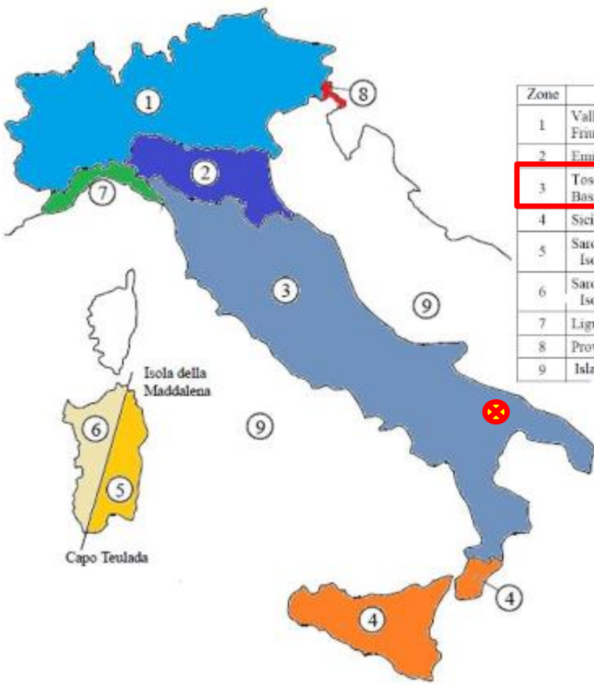
PVH defines the basis design criteria considering the following points:

- Wind loads definition is usually the most important issue in the trackers design (fully explained in following chapters).
- Seismic loads
- Snow loads
- Thermal loads
- Standard: Used to apply the load combinations and safety factors.
- Stress and deformation checks
- Dynamic checks (Natural frequency, structural damping…)

9. WIND LOADS DEFINITION

In the given location the basic wind load considered is taken according to the following figure:

Basic Wind Speed: $V_{b,0}$ = 27 m/s, considered that the structure is located in the Zone 3 (reference [II]). This value has been measured as a 10-minute average wind.



$$v_b = v_{b,0} \qquad \text{per } a_s \leq a_0$$
$$v_b = v_{b,0} + k_a\,(a_s - a_0) \qquad \text{per } a_0 < a_s \leq 1500 \text{ m}$$

Zone	Description	$v_{b,0}$ [m/s]	a_0 [m]	k_a [1/s]
1	Valle d'Aosta, Piemonte, Lombardia, Trentino Alto Adige, Veneto, Friuli Venezia Giulia except the province of Trieste	25	1000	0,010
2	Emilia Romagna	25	750	0,015
3	Toscana, Marche, Umbria, Lazio, Abruzzo, Molise, Puglia, Campania, Basilicata, Calabria	27	500	0,020
4	Sicilia e province of Reggio Calabria	28	500	0,020
5	Sardegna (zone east of the line connecting Capo Teulada with Isola di Maddalena)	28	750	0,015
6	Sardegna (zone west of the line connecting Capo Teulada with Isola di Maddalena)	28	500	0,020
7	Liguria	28	1000	0,015
8	Province of Trieste	30	1500	0,010
9	Islands (except Sicilia and Sardegna) and open sea	31	500	0,020

Figure 1. ***Basic value of velocity in the location***

$V_b = C_{dir} \times C_{seas} \times V_{b,0}$

Where:

C_{dir} is the wind directionality factor to be considered as 1

C_{seas} is the seasonal factor which was also considered as 1

For normal operations, the trackers are design for a maximum wind speed of 20 m/s (72 Km/h) measure as 3 sec gust.

Therefore:

	Stow Position	Working Position
$V_{b,0}$ (m/s, 10 min mean)	27.00	13.33
Cdir	1.00	1.00
Cseas	1.00	1.00
V_b (m/s, 10 min mean)	27.00	13.33

Table 4. ***Wind Speed***

The dynamic pressure is defined by the following equations:

$$q_b = \frac{1}{2} \cdot \rho \cdot v_b^2$$

And

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) = c_e(z) \cdot q_b$$

δ=1.25 kg/m^3 is the air density

C_e (Z) is the exposure factor.

For the external rows the exposure factor used is the one corresponding for a terrain category II, and for the internal rows the exposure factor used is the one corresponding to a terrain category II.

Exposure factors have been obtained from the following figure.

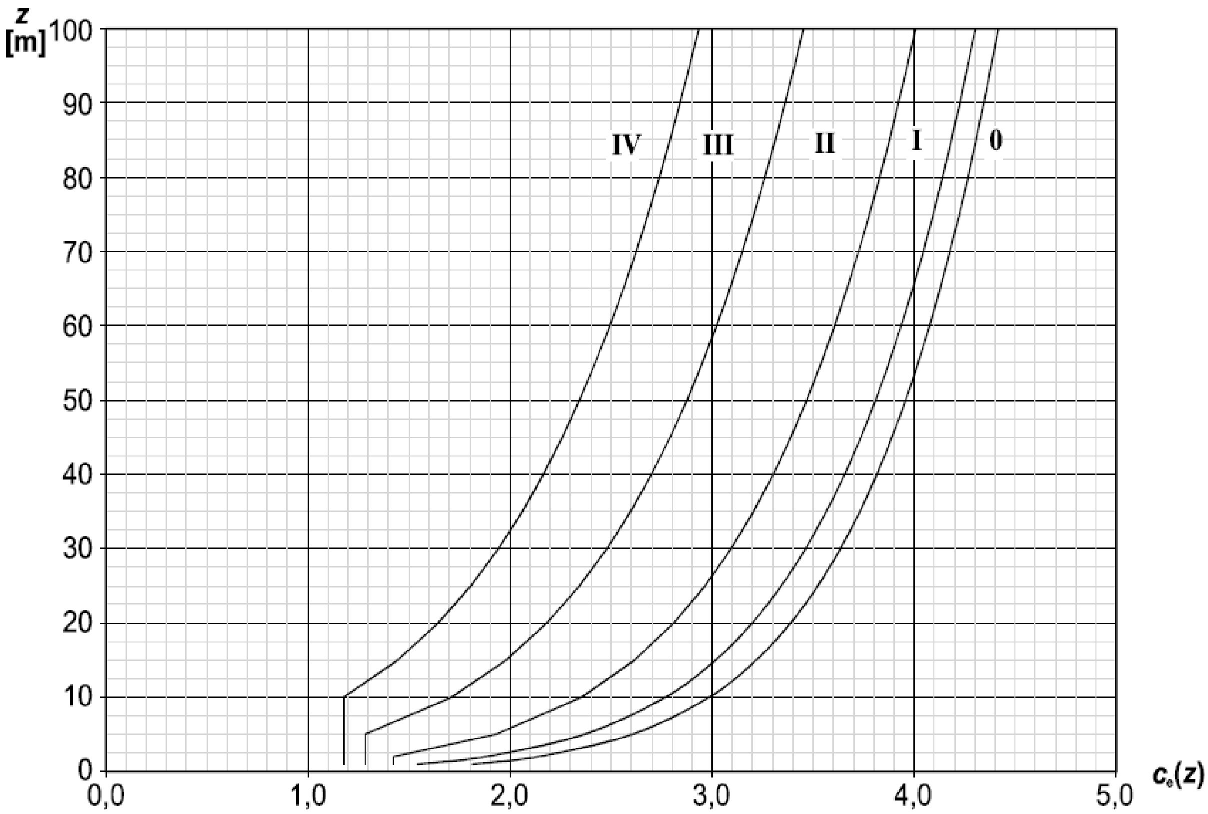


Figure 2. ***Exposure factor***

	Stow Position	Working Position
Ce	2.35	2.35
qb	455.625	111.11
qp	1070.72	261.11

Table 5***. Dynamic pressures***

WIND TUNNEL TEST

PVH for the study of its trackers has made a tunnel wind test with CPP, see Ref. [I], where several design loads have been examined by weighting the pressure taps on the modules by the appropriate area to produce peak normal force. The coefficients are given for each specific component (panel rail, tube, post…).

The load cases studied are listed below.

- $GC_{M\text{-}HalfTrakers}$: Peak half tracker (torque tube); for the design of the torque tube, drive system and associated components.
- $GC_{N\text{-}Post}$: Peak normal force on the post tributary area; for design of the post an associated components.
- $GC_{M\text{-}Module:}$ Peak moment on a module about the torque tube; for the design of the module clamps/purlins attaching modules to the torque tube.
- $GM_{M\text{-}Cantilever}$: Peak moment on row-end cantilever; for design of the cantilever.

Uplift and downforce cases are provided for all load effects.

The load distribution on the trackers is represented in the next figure:

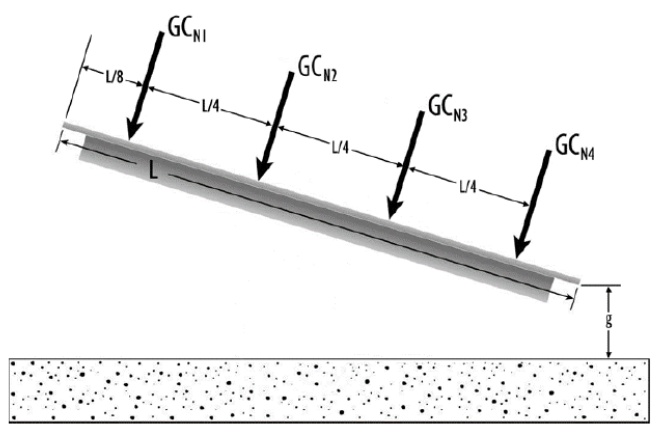


Figure 3. ***Load distribution schematic***

The result obtained have been simplified into zones of similar value or steps along a gradient. The zone map for the results presented in the next figures:

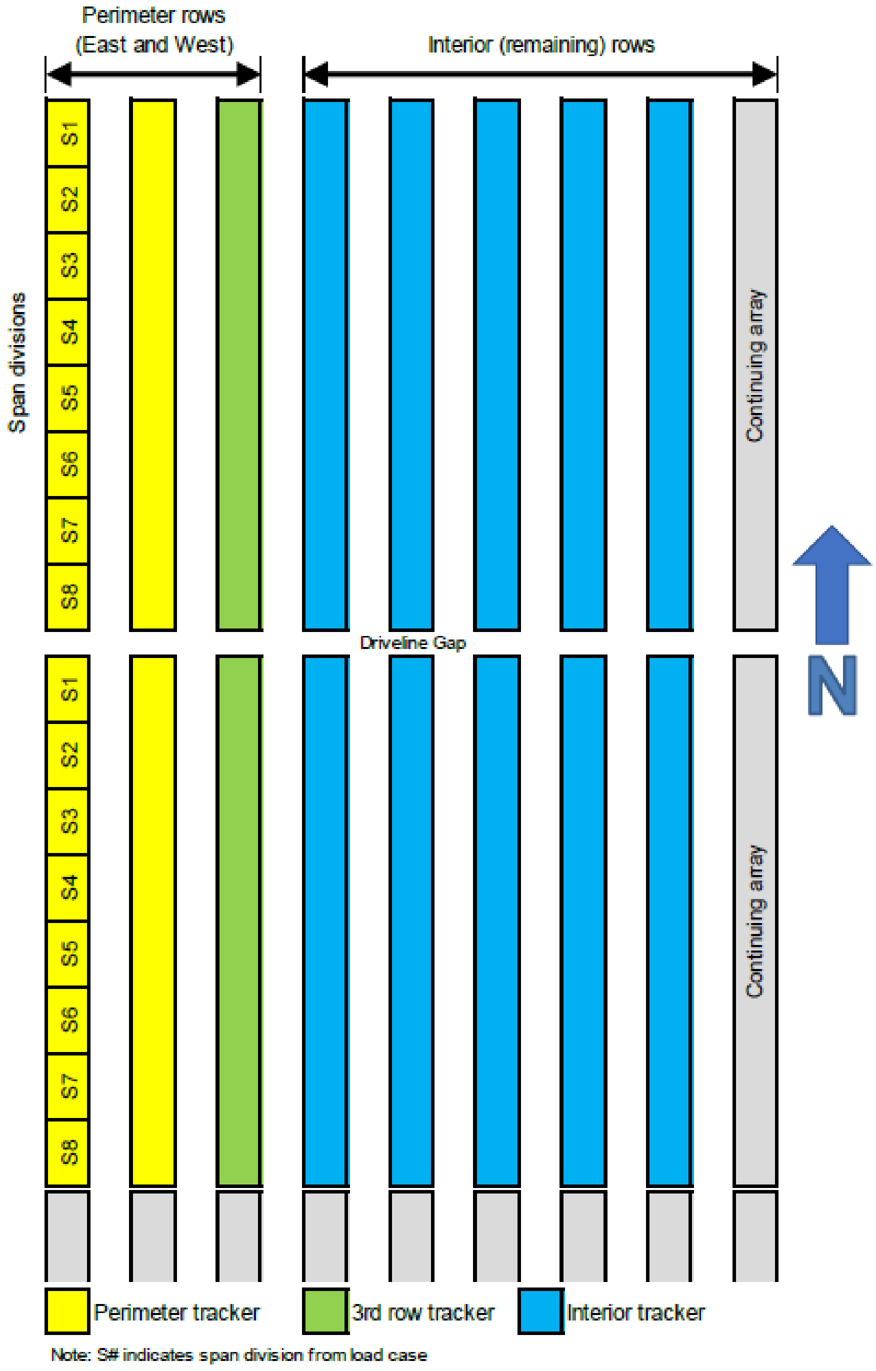


Figure 4. ***Load distribution schematic for torque tubes***

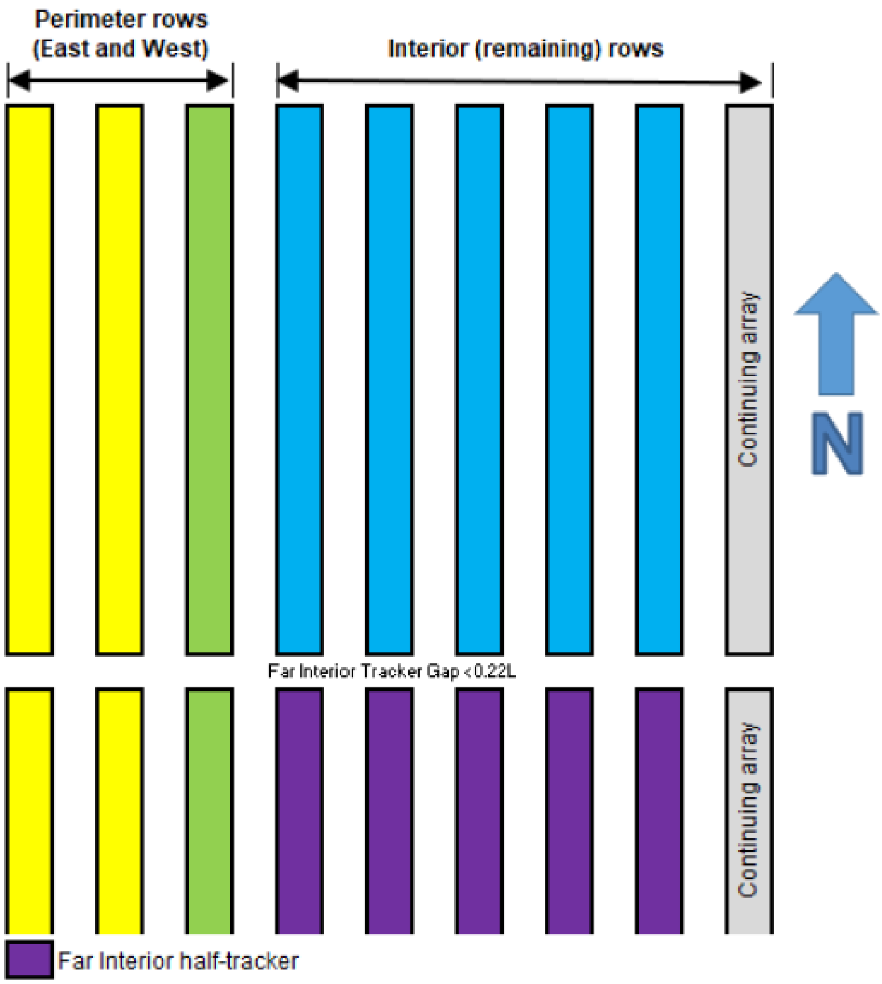


Figure 5. ***Row distribution schematic for torque tubes***

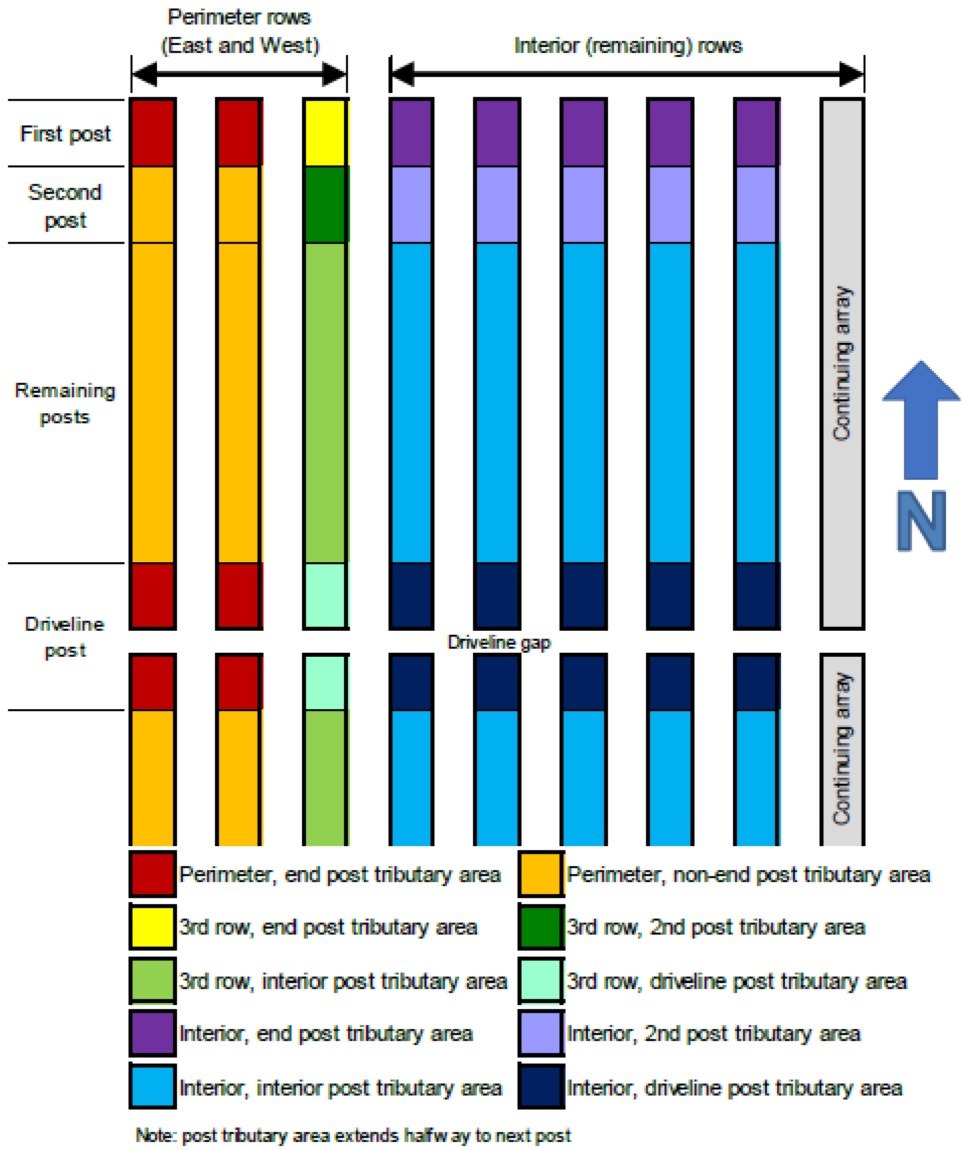


Figure 6. ***Load distribution schematic for Post and panel rails***

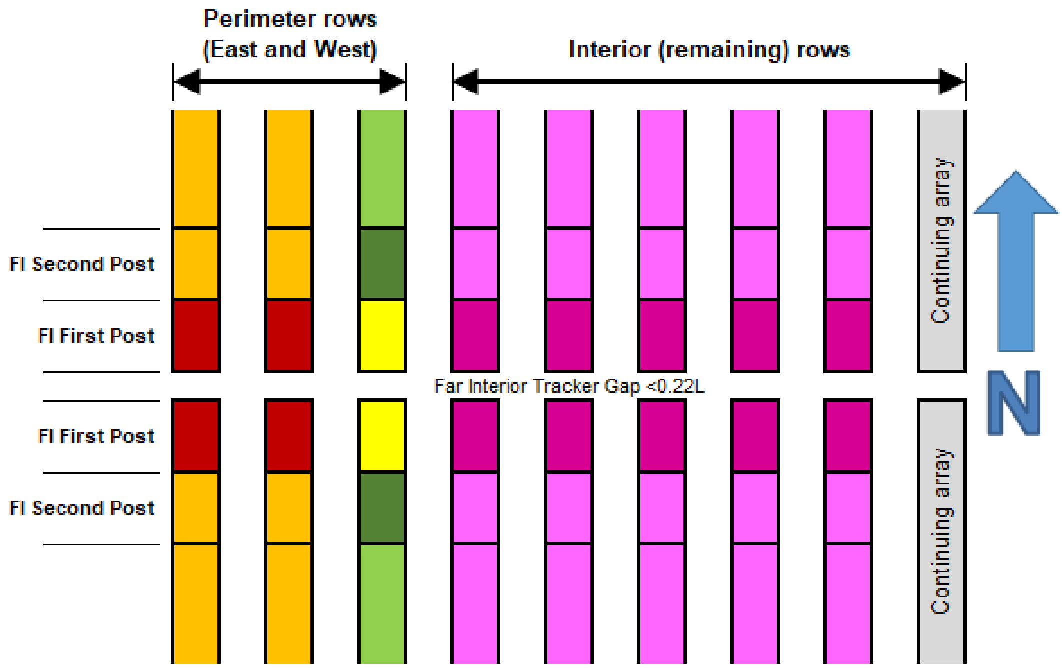


Figure 7. ***Load distribution schematic for post and panel rail of far interior rows***

10. EARTHQUAKE LOAD

Seismic loads are considered according to [I]. As can be seen in the map the reference, the plants are located in low seismicity areas. The plants have a PGA of 0.1g with a 10% probability of exceedance in 50years and this value is negligible compared with wind and snow loads.

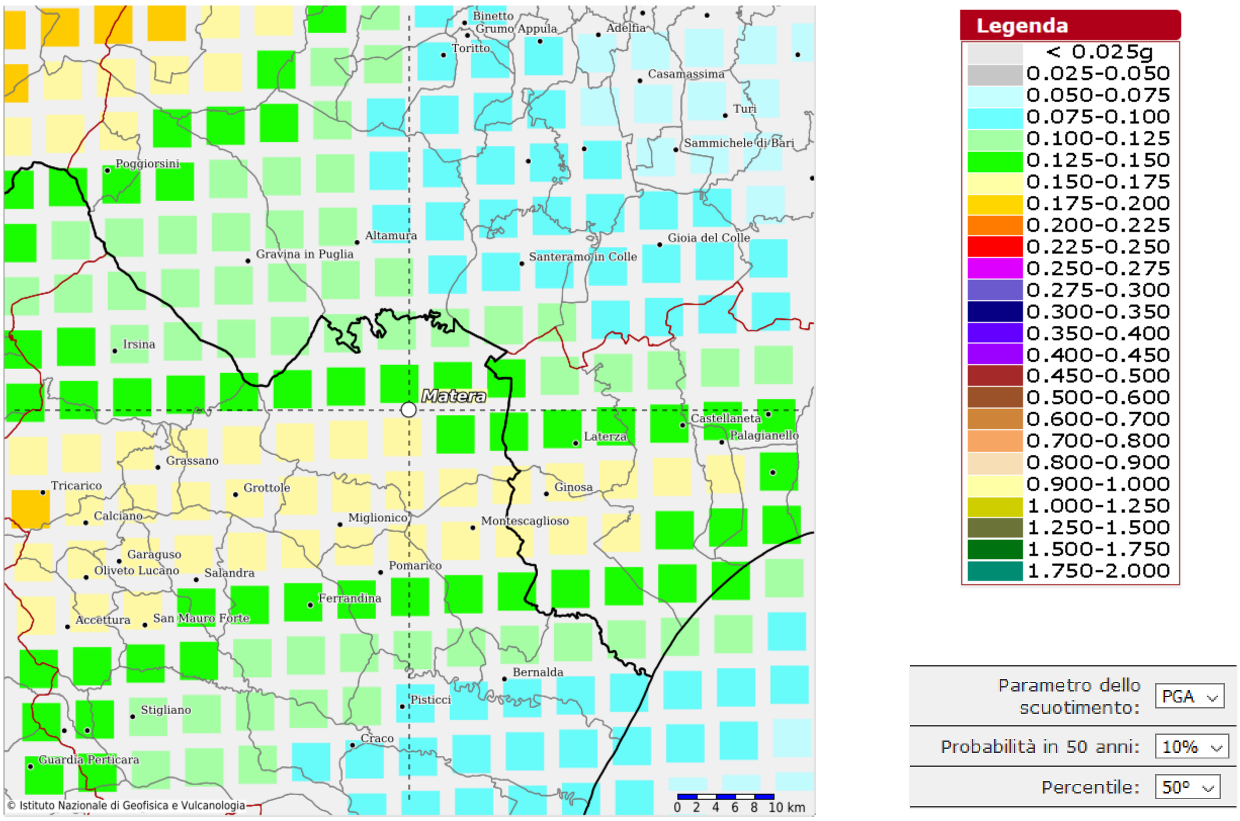


Figure 8. ***Seismic map of Italy***

11. SNOW LOADS DEFINITION

Snow loads are considered in the analysis according to reference [III].

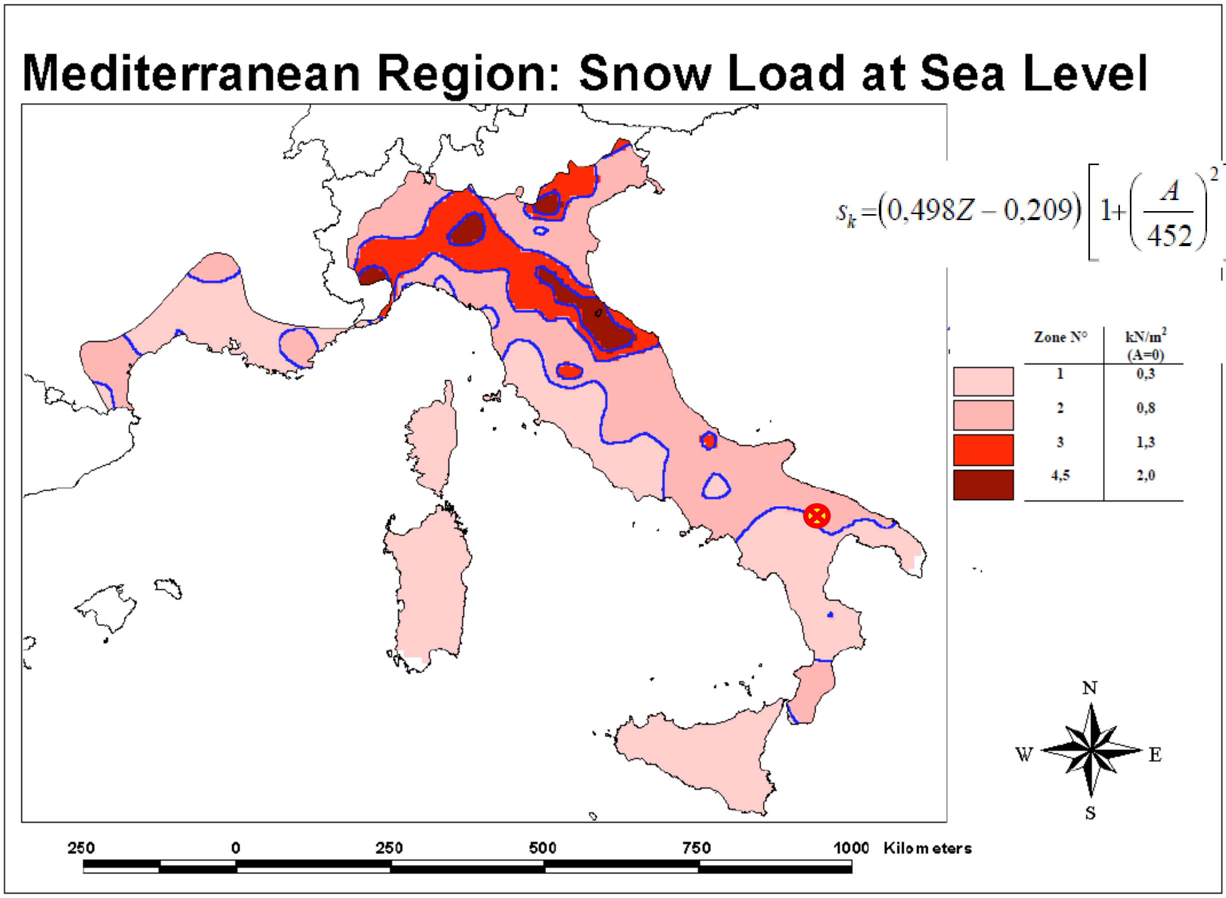


Table 6*. **Snow Load map considered for the locations***

The snow load is considered as $q_n = \mu * S_k$

Where:

- μ= 0.8 is the shape coefficient

Plant	Zone	Altitude	S_k	q_n
		m a.s.l.	[N/m²]	[N/m²]
Matera	2	380	1340	1072

Table 7*. **Snow load for each plant***

12. LOAD COMBINATION

Following the specifications in reference [I], the load combinations are also function to design criteria used in this reference:

Load combinations following are described below.

CASE	LIMIT STATE	WEIGHT	WIND PRES	WIND SUCT	SNOW
1	ULS	1.35	1.5	-	0.75
2	ULS	0.9	-	1.5	-
3	ULS	1.35	0.75	-	1.5
12	SLS	1.0	1.0	-	0.5
13	SLS	0.9	-	1.0	-
14	SLS	1.0	0.6	-	1.0

Table 8. Coefficients of each load case

These coefficients have been considered for multiple inclination angles of the tracker.

13. AEROLASTIC WIND TUNNEL TESTS

Apart of the static wind tunnel tests to calculate the forces and the dynamic amplification factors in the tracker also aeroelastic wind tunnel test to check dynamic instabilities like torsional galloping have been done.

An aeroelastic wind tunnel test is a test where the model inside the wind tunnel is not rigid, it has the same properties (stiffness, natural frequency, mass, damping…) than the real tracker but, of course, scaled.

Two kind of wind tunnels tests like this can be performed, a sectional test or a test with several complete rows. PVH has carried out both tests reaching to the conclusion that a sectional test does not reproduce well the behaviour of the solar trackers and can give wrong results.

Figure 25. ***Sectional wind tunnel test***

All this information can be checked in reference [VII].

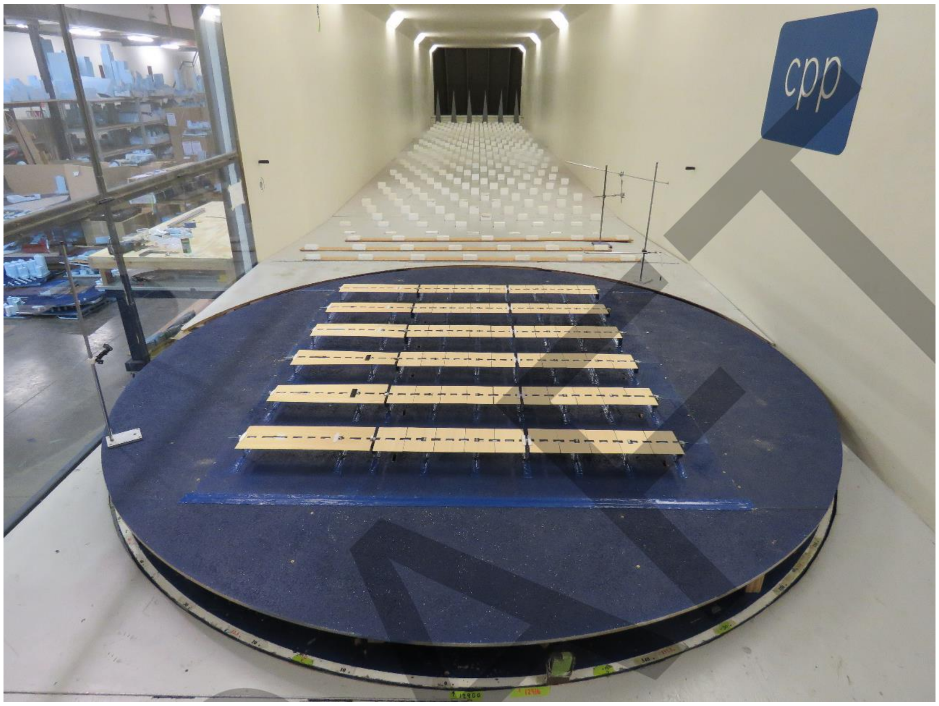


Figure 26. ***Several complete rows wind tunnel test***

The aeroelastic wind tunnel test with the complete rows has been done with CPP, American engineering specialized in solar trackers. The results of these tests show like a position of 30° for exterior rows and 15° for the interior ones is safe:

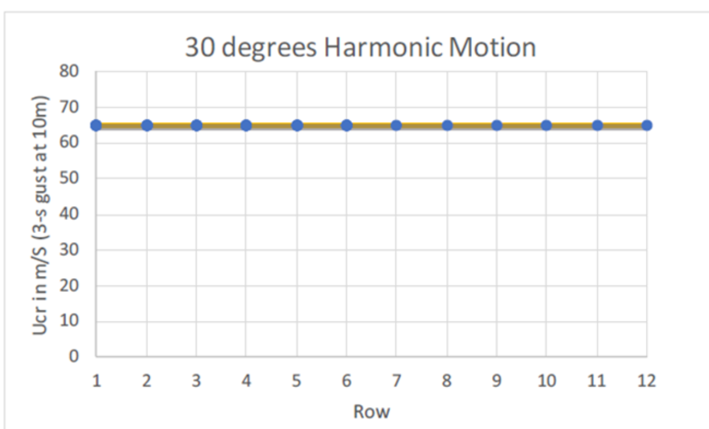


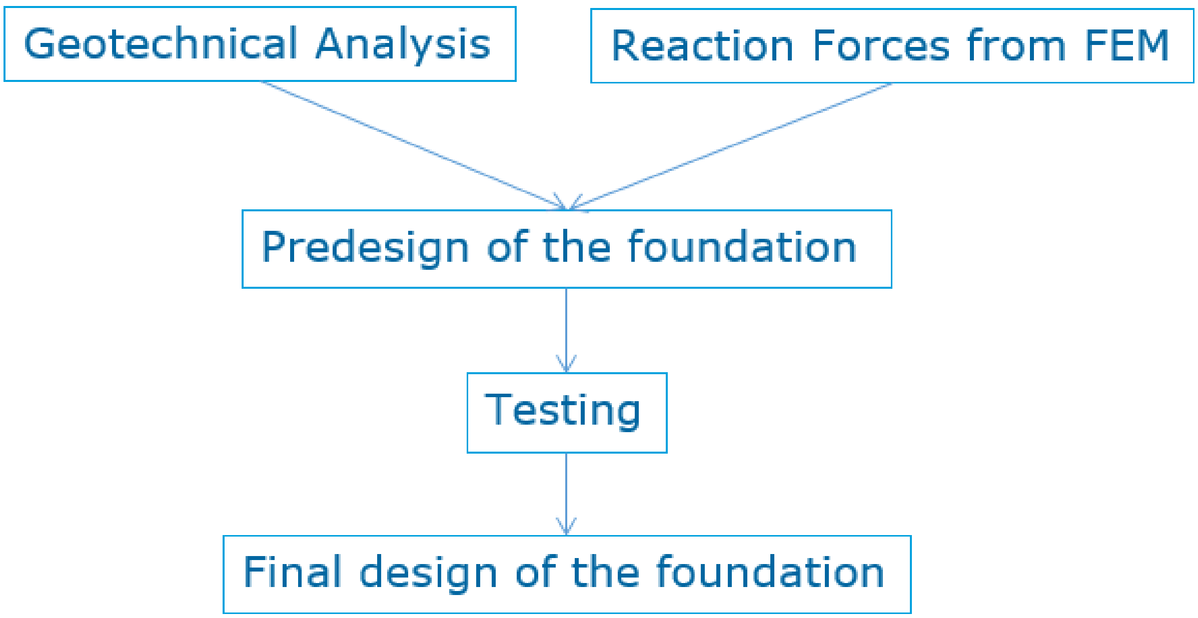
Figure 20: *U_{cr} of all rows at 10m height, 3-second gust, for 30° harmonic motion for all rows at damping=15%. Nominal initial tilt is -30° for first row, -15° (nose down into the wind) for all other rows.*

Figure 97. ***CPP wind tunnel test results AXONE DUO***

14. FOUNDATION

Regarding the foundation analysis, from PVH we work with Javier Alvarez, University Professor specialist in pile foundations calculation with more than 20 years of experience.

The next steps are followed in the foundation analysis



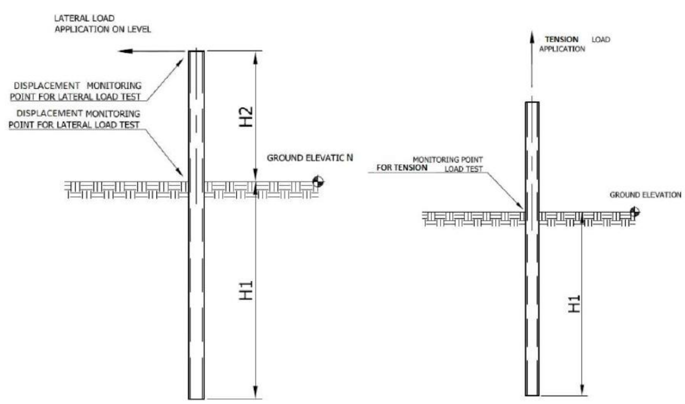


Figure 28. Pile length

15. CONCLUSIONS

- PVH company has large proven experience in the field of design and construction of tracking solar systems.
- Structures are defined according to:
    1) Location of solar plants
    2) Standard of calculation
    3) Loads definition
- Results for the dimensioning of components and joints are based on General and Detailed FEM modelling correlated with tests.
- A deep geotechnical analysis with pull out tests on the field are made in all the project which provides the most optimized pile solutions.
- Additionally, PVH is able to provide the client a maintenance and monitoring services after construction