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Behaviour and performance analysis against gravitational loads of a non-traditional, precast, removable and reusable shallow foundation

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Abstract

This communication shows part of the investigation done by the author related to the operation of a superficial, non-traditional foundation typology, commercially known as PILOEDRE®, designed for lightweight structures and prefabricated, with manual assembly, removable, and reusable. Specifically, this article is focused on the operation of the foundation against vertical descendent (gravitational) loads. The strategy of the investigation presents this new foundation as a combination of traditional foundation typologies, where current and accepted analytical methodologies are utilized. The proper functioning of the new analytical method is verified with numerical models and several real scale tests. Finally, a strength verification method is presented. The investigation shows how a systematic methodology based on established scenarios, combined with numerical tools of modelling and experiments, allows the study and comprehension of a non-traditional element within the foundations field.

Keywords

Shallow foundation; Numerical modelling; Piloedre; Light structures

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1. Introduction

As our society has increased its complexity, new aspects of structure requirements have started to be considered, and nowadays the importance of these aspects are increasing, such as the environmental impact, facility of construction, industrialization, etc. These new requirements have produced changes in most of the structural elements, but small changes in the design of the foundation elements, most of them still following traditional criteria without nearly any significant change.

The first idea about the new foundation treated in this research was conceived in 2013 with one fundamental objective: searching for a solution that allows the construction of foundations for structures on Spanish beaches. The main motivation was the presence of regulations that limit the possibility of using traditional founding solutions like the Spanish coast law. That law forces businesses to dismantle most of the structures, including foundations installed during the summer season.

Therefore, knowing that the installation has to be done in the middle of the beach, it has to be simple and able to be built with manual tools without the usage of heavy machinery, as well as reusable in order to be installed the following summer. The design of the new foundation is based on a reinforced concrete piece that weighs approximately 30 kg with four steel bars diagonally inserted into the concrete piece. The bars are driven into the ground forming a 40º angle in relation of the vertical axis (see Figures 1a and 1b), the whole structure (concrete piece and bars) weighs approximately 50 kg.

The design of this new foundation allows industrialisation, to create a prefabricated element that is easily transported to the installation site. The ease of the assembly, as well as the capacity of being dismounted, recovered and reused make this foundation technology more attractive for installations where its special features are appreciated, among them, lowering the environmental impact. (see Figures 2 and 3).

As a result, this new foundation is used as a support element for more complex structures and structures that require a higher level of responsibility (see Figure 3). Therefore, it was necessary to have a formal approximation to the foundation function and the resistant mechanisms associated with the interaction of the foundation with the ground, as it was shown in a previous publication at 2017 Seoul Congress (Tarrago et al, 2017).

This article documents part of the research on the function of this non-traditional, shallow foundation, called PILOEDRE®. Specifically, the article focuses on the function of the foundation against descendent vertical loads.

2. Methodology

The non-traditional nature of the foundation involves the lack of an established theoretical framework which allows for an adequate analysis of the foundation. The strategy to achieve a deeper understanding of the behaviour of the foundation is raised on three levels that arrive at the object of the investigation. These levels are an analytical, numerical and experimental approach.

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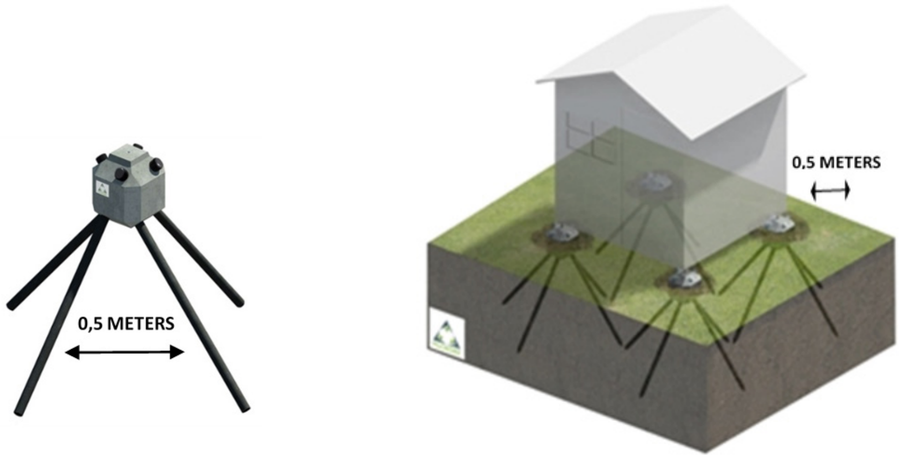

Figure 1a.
New foundation (left) and new supporting of a structure

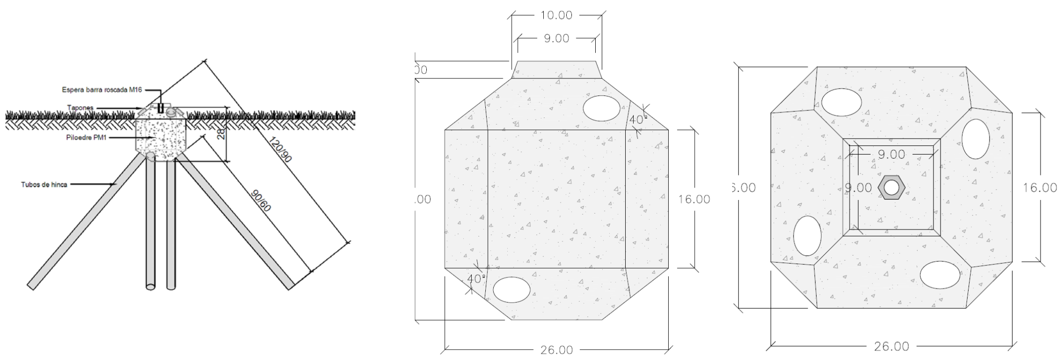

Figure 1b.
New foundation drawings (centimetres)

Figure 2.
Package with 4 and 8 foundations (above) and some elements of the new foundation holding up a modular structure (below)

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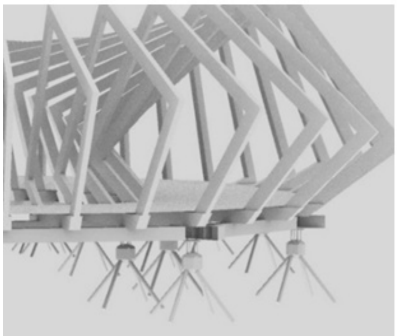

Figure 3.
Installation (2016) of the new foundation holding up the Möbius building in Oñate Square, Donosti (Spain). Installation done by students from Superior Architecture Technical School of UPV/EHU

3. Analytical approach

The analyzed foundation, due to its non-traditional quality, lacks a particular theoretical framework that allows for analysis of its performance, so was planned a new theoretical framework based on suitable traditional frameworks or combinations of some of them (see Figure 4) in order to have a tool that allows for the verification of the final capacity of the new foundation.

A first analysis allows us to reasonably consider that against the vertical loads transmitted by the structure. There are two kinds of foundation reactions: on one hand, the resistance to the subsidence of the concrete piece, a behaviour intuitively associated with a traditional shallow foundation (concrete footing), and on the other hand, the resistance to the vertical penetration into the ground of each of the four tubes of the foundation. It is important to realise, concerning the resistant mechanism related to the penetration by the tubes, that given the symmetry of the piece and the considered loads, the tubes will have a vertical movement rather than a longitudinal movement.
In conclusion, it is considered that the new foundation resistance can be analysed as the sum of the following resistance mechanisms (see Figure 5):

- Resistance mechanism related to the subsidence of a traditional superficial foundation with the same area as the concrete piece (aprox. 30 * 30 cm).

- Resistance mechanism related to the ground penetration by each of the tubes in a vertical direction, equivalent to a continuous deep foundation with a thickness of 43 mm (diameter of the tubes) and a variable depth.

This breakdown of the resistance mechanisms is consistent with the results and conclusions reached by the numerical models based on 3D finite elements (see chapter 4), corroborating that the prior hypothesis may be considered reasonable. Regarding the new foundation's total resistance , it is taken into consideration that the combination of the mechanisms implies the sum of the capacity of both mentioned resistance mechanisms. This hypothesis is coherent with a security standpoint based on Ultimate Limit States (Eurocode 7) and is traditionally accepted in other types of foundations, such as pile foundations, where its resistance mechanism is seen as the sum of the base and shaft resistance mechanisms.

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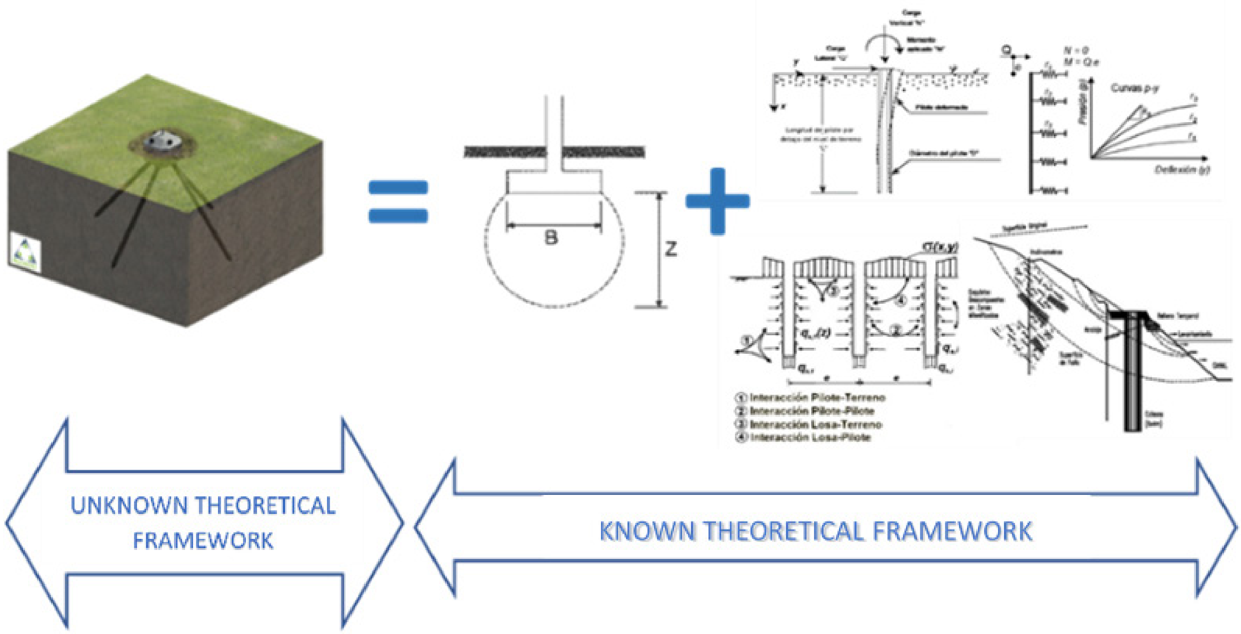

Figure 4.
Reinterpretation of the resistance mechanism of the non-traditional foundation as a union of traditional foundations resistance mechanisms

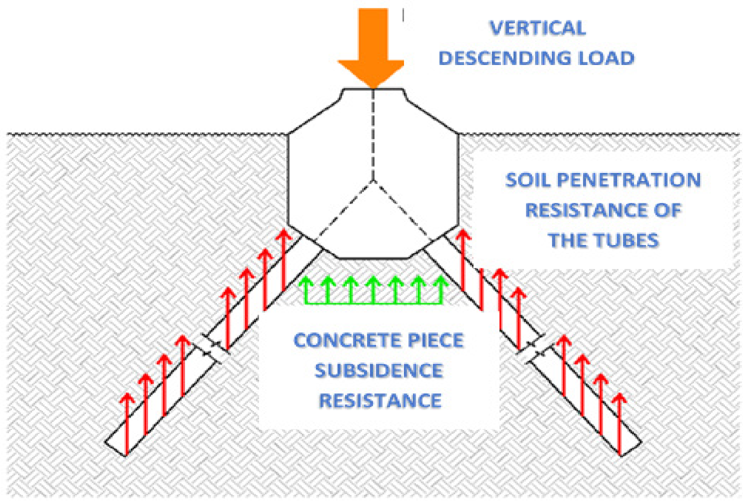

Figure 5.
Two opposing mechanisms against the foundation vertical load

Table 1.
Variation of the ultimate resistance with the soil parameters: cohesion and friction angle. An embedment of 20cm and homogeneous ground are assumed

		NEW FOUNDATION ULTIMATE RESISTANCE (kN)						
		INTERNAL FRICTION ANGLE (º)						
		0	15	20	25	30	35	40
SOIL COHESION (kPa)	0		6,8	11,2	18,9	33,1	60,7	118,9
	1	2,6	8,1	12,7	20,8	35,6	64,4	124,6
	5	6,1	13,2	18,9	28,6	46	79	147,1
	10	10,6	19,6	26,6	38,3	58,8	98,3	175,2
	25	24	38,9	49,8	67,4	97,5	152,2	259,7
	50	46,2	70,9	88,4	116	162	243,6	400,5

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For the resistance mechanism associated with the subsidence of both the concrete piece and the tubes in the ground, and after analyzing some theoretical frameworks, the methodology proposed by Brinch Hansen (1961) was selected. This methodology is based on the Terzaghi equation (Terzaghi, 1943), and some corrective parameters are applied that allow us to approximate the existing mechanisms in the studied foundation, as well as the consideration of drained or undrained situations (see below).

$$q_u = qN_q\, s_q d_q i_q + c\, N_c\, s_c d_c i_c + 0.5\, \gamma\, B\, N_\gamma\, s_\gamma d_\gamma i_\gamma$$

$$N_q = tan^2(45 + \frac{\phi}{2}) e^{\pi \cdot tan\phi}$$
$$N_c = (N_q - 1)cot\emptyset$$
$$N_\gamma = 2(N_q + 1)tan\emptyset$$

$s_q\, d_q\, i_q\, s_c\, d_c\, i_c\, s_\gamma\, d_\gamma\, i_\gamma$ corrective parameters

where:
$q_{u:}$ unit ultimate resistance.
c: cohesion.
γ: density.
q: Pressure on the base of the foundation (depends on the depth)
B: Width at base of the foundation
N_c,N_q,N_γ: capacity load factors (dimensionless)

The ultimate resistance of the foundation will be

$$Ru = \text{Rh} + 4 * \sum_{i=1}^{n} (\text{Rpi})$$

where:

Ru: Ultimate subsidence resistance of the foundation
Rh: Ultimate subsidence resistance of the concrete piece as an isolated piece.
n: Number of segments that the tubes are divided into. This allows for the consideration of the variation of the pressure (q) with the depth, as well as considering the existence of diverse kinds of ground or the water level if it exists.
Rpi: Ultimate subsidence resistance of the studied segment of the tube

The theoretical framework previously described allows for the evaluation of the maximum capacity of the new foundation for diverse types of soils, introducing the variables:
Φ : Internal soil friction angle
C: Cohesion
γ: Density.
H: Foundation embedment (depth of the inferior face of the concrete piece).

In the next table (table 1) the proposed method is applied, considering a foundation with 20 cm embedment , a soil density of 15 kN/m^3 and homogeneous ground with varying values of internal friction angle and soil cohesion.

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4. Numerical simulations

The interaction between the new foundation and the soil has been analysed using the numerical tool, PLAXIS 3D, a common software used for the analysis of the interaction of foundations with the soil. This analysis allows for the consideration of three dimensional resistance mechanisms as well as the introduction of the geotechnical features of the soil and strength-deformation characteristics of the concrete piece and the steel bars that form the foundations. The points highlighted in the model are:

- The geometry is generated based on a 5m×5m×2.5m prism, the piece and the four tubes that form the foundation inside the prism. The elements that form the discretization mesh have and average length of 0.03 meters (see Figure 6).
- The concrete piece of the foundation is modelled following an elastic linear model with non-rigid interactions on ground-piece interfaces.
- The tubes are modelled with elastic 'embedded pile' elements, commonly used to simulate piles.
- In order to simulate the soil geotechnical features a Mohr-Coulomb elasto-plastic model is used.

The model was calibrated with the data obtained in some load tests. The next figure 7 shows the adjustment of the model to the data of a load test, where four cycles of vertical increasing loads were applied on the foundation.

The numerical model provided several conclusions. Among them:

- It is reasonable to consider that the ultimate strength of the foundation against the vertical loads transmitted by the structure is the sum of the resistance to the subsidence of the concrete piece and the resistance to the vertical penetration in the ground of each of the four tubes of the foundation. In a comparative analysis, considering the presence and the absence of the tubes gave the new foundation an important added resistance and more stiffness (see Figures 8 and 9).
- The numerical modelling, once the relevant calibrations had been done, was good enough to predict the load/settlement relation observed in real essays.
- The numerical model can simulate the behaviour of diverse types of soil through the variation of its geotechnical parameters. Therefore, the model can estimate the maximum load capacity of the foundation, allowing for a comparison with the maximum load capacity obtained from the analytical analysis. This analysis shows that the capacity obtained with the analytical analysis was inferior to the capacity obtained from the numerical model (see Table 2).

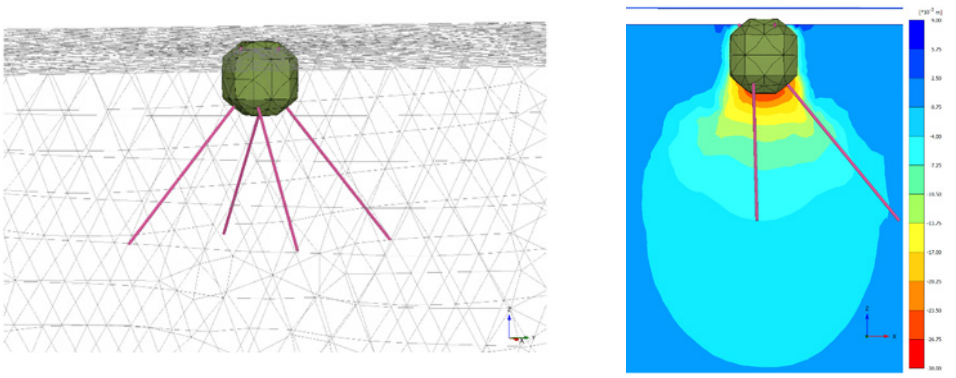

Figure 6.

Discretization mesh (left) and analysis where movements are represented (right)

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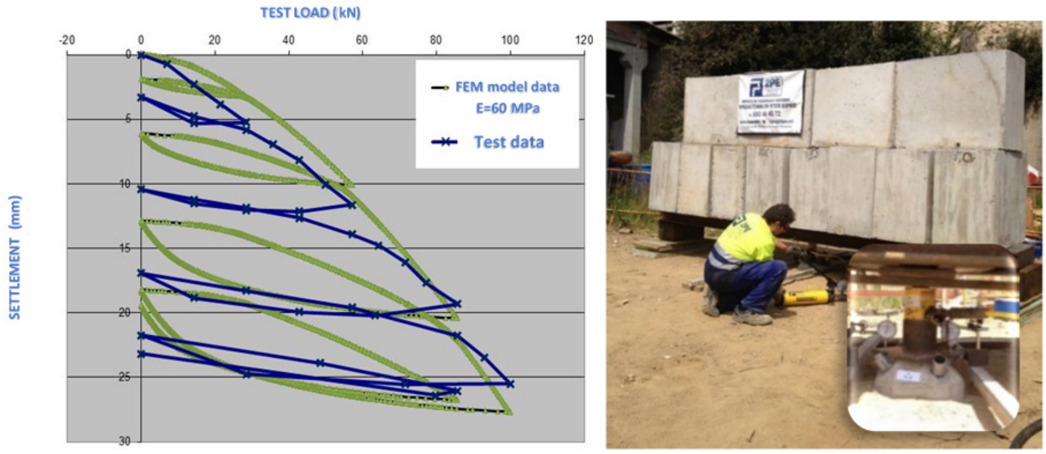

Figure 7.
Results of the load test where loads were applied in phases (left). Photograph of the test assembly (right)

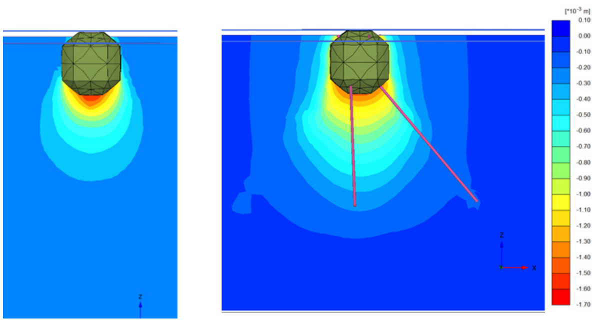

Figure 8.
Movement field considering only the concrete piece (left). Movement field with the full foundation (right)

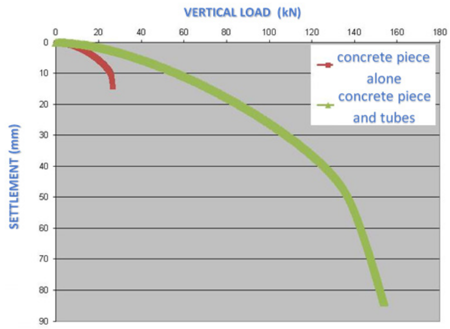

Figure 9.
Comparison of the load/deformation relation considering the concrete piece without tubes(red) and the complete foundation (green)

Internal friction angle (º)	Cohesion (kPa)	Ultimate resistance (Analytical method) (kN)	Ultimate resistance (numerical model) (kN)	Observations
20	5	22	>39	From 39 kN the model presents stability problems. It is assumed that this value is close to the breaking point.
25	5	35	>100	From 100 kN the model presents stability problems. It is assumed that this value is close to the breaking point.
30	5	63	>100 (150)	At 100 kN the model stops without stability problems. Studying the load deformation curve, the breaking point is estimated at 150 kN.
35	5	110	>100 (180)	At 100 kN the framework stops without stability problems. Studying the load deformation curve, the breaking point is estimated at 180 kN.
0	15	15	>90	From 90 kN the framework presents stability problems. It is assumed that this value is close to the breaking point.
0	50	48	>100 (180)	Since 100 kN the framework stops without stability problems. Studying the load deformation curve, the breaking point is estimated at 180 kN.

Table 2.
Estimated ultimate resistance in the numerical model (column 4) compared to the estimated ultimate resistance using the proposed analytical method (column 3)

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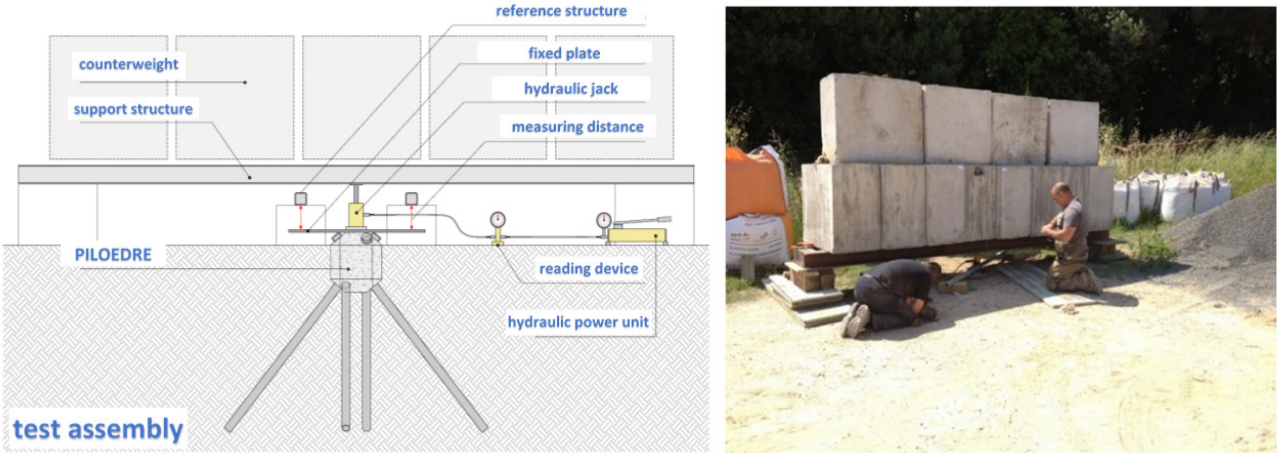

Figure 10.

Load test assembly sketch (left). Load test photograph (right)

Internal friction angle (°)	Cohesion (kPa)	Ultimate resistance (analytical method) (kN)	Ultimate resistance (load test) (kN)	Observations
20-24	0-5	Between 11 and 25	>26	4 load test were done with a minimum value of 26 kN and maximum value of 62 kN (average 43 kN)
25-30	0-20	Between 18 and 80	>80	11 load test were done with a minimum value of 80 kN and a maximum value of 120 kN (average 90 kN). Two of the load tests could have reached higher values but the capacity of reaction of the system didn't allow it.
30-35	0-20	30-120	>120	2 load test were done, both exceeding the maximum capacity of reaction of the test system,120kN.

Table 3.

Estimated ultimate resistance on the load test (column 4) compared to the estimated ultimate resistance using the proposed analytical methodology (column 3)

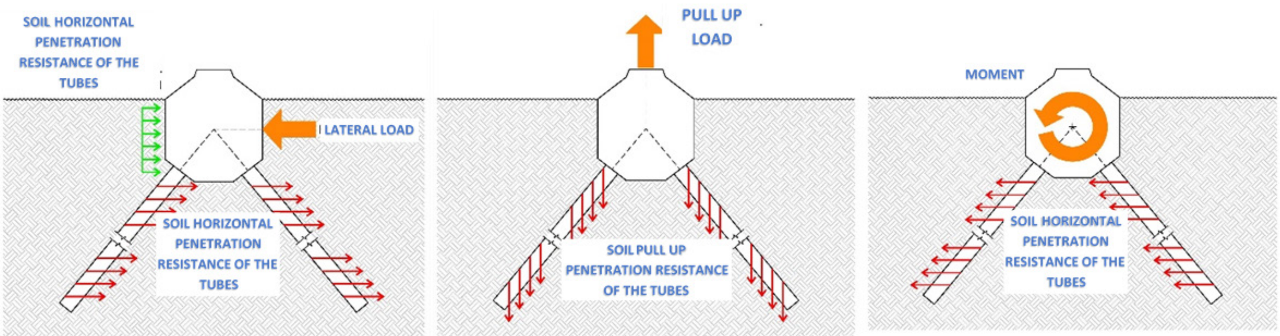

Figure 11.

Components of the loads: lateral, pull up and torsion

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5. Experimental testing

In order to better understand the performance and behaviour of the new foundation, a series of load tests was done (Figure 10). For the realisation of these tests, nine test fields were identified and characterised with geotechnical surveys and field tests.
The load tests required a previous study for their design, with the objective of providing the researched data and agreeing with the generally accepted regulations. The regulation used for the elaboration of the protocols was the Standard Test Method for Pilar Under Static Axial Compressive Load from ASTM [1]. This regulation is usually applied to static load tests on deep foundations.

The data obtained from the load tests was used to adjust the numerical model explained in the previous chapter, and allowed us to verify that the proposed analytical method used to estimate the ultimate capacity of the new foundation resulted in estimations inferior to the ones obtained in load tests (see Table 3).

6. Conclusions

This article shows a few of the results from part of the investigation on the function of a non-traditional foundation typology formed by a concrete piece with four steel bars inserted diagonally at a 40° angle with the vertical axis. All in all it weighs about 50 kg. This foundation is characterised by being prefabricated, mountable with manual tools, removable and reusable.
Specifically, this article presents an analytical verification tool for calculating the ultimate resistance of the new foundation against vertical descendent forces. This analytical method is based on the assumption that the resistance mechanism of the new foundation can be reinterpreted as the combination of two traditional resistance mechanisms: the associated mechanism of the resistance of the concrete piece to subsidence and the mechanism associated with the vertical sink resistance of the four tubes.
The validity of the developed analytical method has been proven using numerical modelling to simulate in 3D the interaction of the foundation with different kinds of soils. These numerical models have allowed us to get close to the actual behaviour of the new foundation and to verify that the designed analytical method estimates lower resistance values, so it is on the safe side, if you compare it to the ultimate resistance obtained by a complex numerical 3D model.
With the exposed analytical and numerical study, an intense series of load tests on the new foundation has been done. The data obtained has allowed us to develop numerical models and to verify that the result of the analytical method for determining the ultimate capacity of the new foundation is also on the safe side.
This article is focused on analysing the behaviour of the foundation against vertical descendent loads. This is the first step towards understanding the behaviour of the foundation against generic loads with ascendant, lateral and torsion components (Figure 11).

Acknowledgements

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Notes

(1) ASTM., " Standard test Methods for Deep Foundations Under static axial Compressive Load", Designation D1143/D1143M-07, American Society for Testing and Materials.

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