A new re-usable shallow foundation for light loads. Load tests and analysis

Une nouvelle fondation superficielle réutilisable pour charges légères. Essais the chargement et analyse

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ABSTRACT: An innovative re-usable shallow foundation system for light loads has been developed consisting of a concrete block and four steel tubes driven into the ground at different orientations. The interaction between the block, the tubes and the enclosed soil ensures a significant enhancement of the bearing capacity compared to that of an equivalent conventional shallow foundation. The paper reports the results of two load tests (compression and tension) carried out to study the performance of the system. The interpretation of the test is assisted by the performance of 3D numerical analyses capable of reproducing satisfactorily the field observations. The results of the analyses have allowed an estimation of a limit load below which the foundation system can be re-used.

RÉSUMÉ: Un système innovateur de fondation superficielle réutilisable pour charges légères a été développé. Il consiste en un bloc de béton et quatre tubes en acier enfoncés dans le sol à différentes orientations. L'interaction entre le bloc, les tubes et le sol environnant assure une capacité portante significativement supérieure à celle d'une fondation superficielle conventionnelle équivalente. L'article décrit les résultats de deux essais the chargement (en compression et traction) effectués pour étudier la performance du système. L'interprétation du test est assistée par des analyses numériques 3D capables de reproduire de façon satisfaisante les observations expérimentales. Les résultats des analyses permettent d'estimer une valeur de charge limite sous laquelle le système de fondation peut être réutilisé.

KEYWORDS: reusable foundation, shallow foundation, light loads, loading tests, numerical analysis

1 INTRODUCTION.

An innovative shallow foundation system has been developed for sustaining light loads of temporary or permanent structures. It consists of a precast concrete block crossed by four inclined steel tubes that are driven into the ground. The interaction of the block, the tubes and the enclosed soil underlies the capability of the system to develop a significant bearing capacity. The system is depicted in Figure 1.

The concrete block is 260 mm x 260 mm square with a height that may vary between 280 mm and 300 mm. In the upper part, the block has different devices to facilitate the connection to the overlying structure. The steel tubes cross the precast block and penetrate into the soil at an angle of 40º and different spatial orientations. Penetration depth usually ranges between 70 cm and 90 cm although a penetration depth up to 120 cm can be utilised if the ground is very soft. The steel tubes have an elastic limit of 500 MPa and an outside diameter of 42.9 mm. The tubes' thickness is typically 2.9 mm but it can be increased if a higher bearing capacity is sought. The different orientations of the steel tubes result in a three-dimensional (3D) assembly that develops a high degree of interlocking with the ground.

The foundation can be installed with very simple tools that can be operated, if necessary, under tight space restrictions. The concrete block is partially or totally buried into the ground, so a limited amount of excavation is required before emplacement. Driving the tubes can also be easily achieved by an electromechanical hammer or a similar device. Naturally, the foundation system can only be used when the tubes can be driven into the soil; it is not applicable to rock, very hard soils or to soils containing abundant cobbles or boulders. The fact that, in case of temporary structures, the foundation can be removed when is no longer needed and used elsewhere adds to the sustainability of the system.

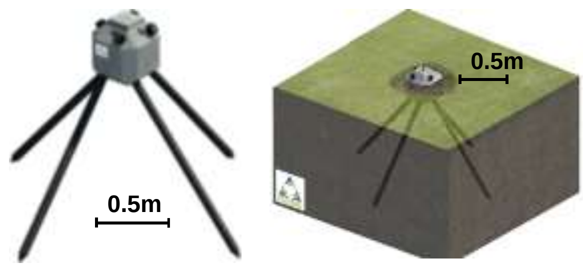

Figure 1. Shallow foundation system for light loads

In spite of the simplicity of installation, the behaviour of the foundation system is quite complex as it involves the interplay of the concrete block, the inclined steel tubes and the ground in a 3D geometrical setting. To understand better the behaviour of the foundation and the development of its bearing capacity, a significant number of load tests the interpretation of which has been assisted by the performance of 3D numerical analyses. In this paper, the results of a compression load test and of a tension load test are presented to illustrate the versatility of the system. The results of the associated numerical analyses are also shown and discussed. A limit load below which the foundation system can be re-used is estimated from the results of the analyses.

2 LOAD TESTS.

Two load tests, a compression one and a tension one, have been selected for presentation herein. The layout of the compression tests is shown in Figure 2. The force was applied by a hydraulic jack and its value was measured by means of a load cell The required reaction was achieved by means of dead weights. The setup for the tension test (Fig. 3) was similar but now the reaction is simply obtained by the ground supporting the loading structure. Settlements and heave of the foundations were measured with respect to a fixed reference system.

These two tests were performed in an alluvial soil, a clayey sand with a fines content of less than 10%, so drained conditions can be reasonably assumed. Water table is 10 m deep. Representative values of SPT are in the range of 10-25 corresponding typically to friction angles of 30° to 36° (e.g. Peck et al. 1974).

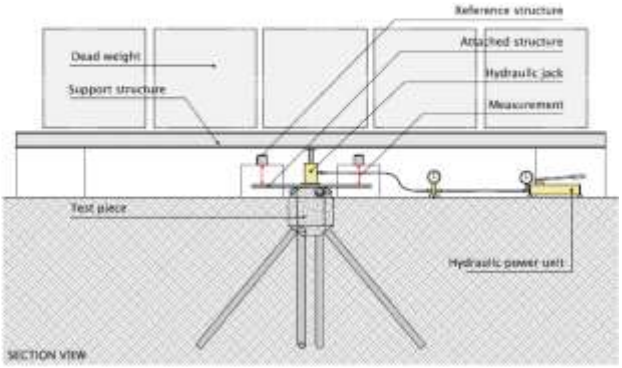

Figure 2. Compression load test layout.

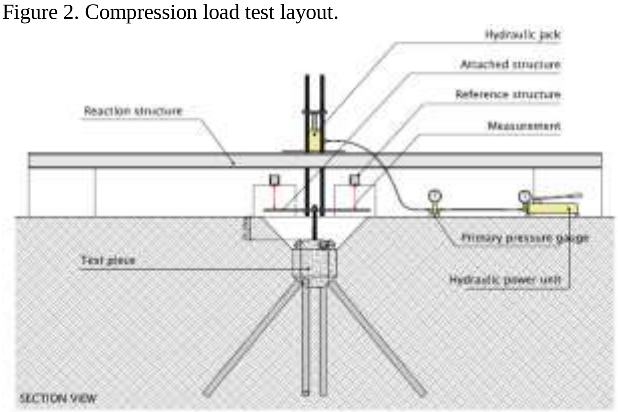

Figure 3. Tension load test layout.

The results of the vertical compression test are shown in Figure 4 in terms of vertical load vs. settlement. In the compression load test, the final failure load was not reached so the bearing capacity is above the maximum applied force of 100 kN. It is also apparent that the response of the system is significantly stiffer upon unloading/reloading. The results of the tension test in terms of heave vs. applied load are presented in Figure 5. In this case, the failure road was reached at a value of just above 30 kN. Again, the behaviour is stiffer during unloading/reloading.

3 3D NUMERICAL ANALYSIS.

The numerical simulation of the foundation system has involved the performance of 3D Finite Element analysis. There is no alternative to adopting a 3D representation of the problem because the interaction between the foundation system and the soil is intrinsically three-dimensional. The mesh used incorporates the concrete block, the steel tubes and the ground and it is depicted in Figure 6. The steel tubes have been modelled as embedded piles and interfaces have been provided between concrete block and soil and between tubes and soil.

As the main focus of the analysis is to compute the bearing capacity, an elasto-plastic Mohr-Coulomb constitutive model has been adopted for the soil. Concrete and steel tubes are assumed elastic. The parameters used in the calculations are listed in Tables 1, 2, and 3.

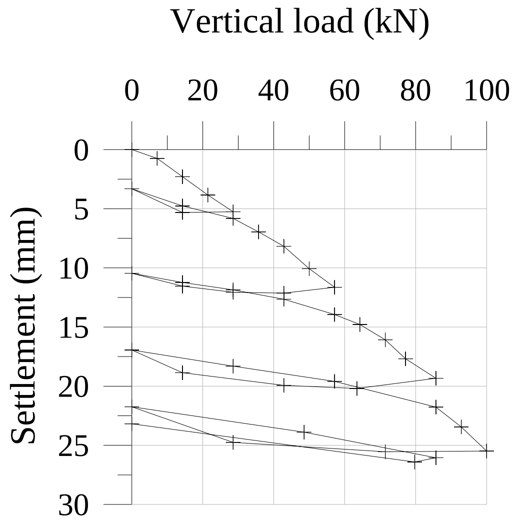

Figure 4. Compression load test results.

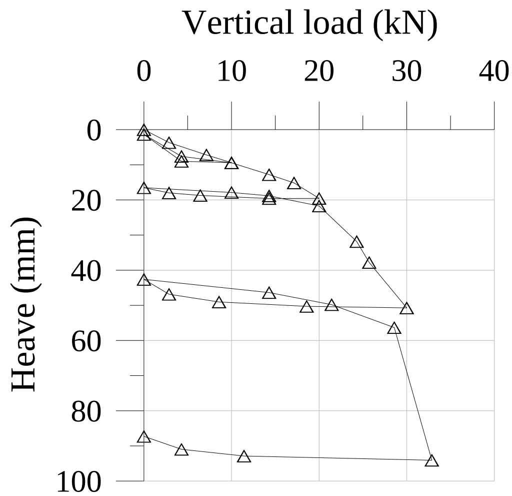

Figure 5. Tension load test results.

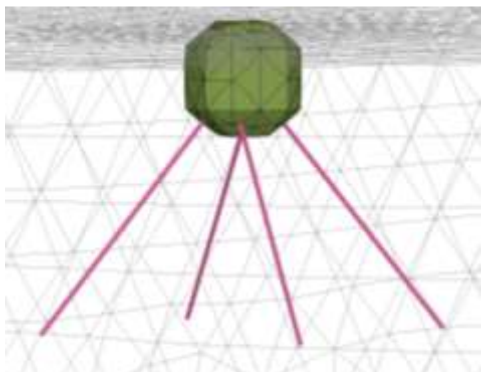
Figure 6. 3D Finite Element mesh.

It has been computed that the steel tubes (for a 2.9 mm thickness) will plastically yield when a bending moment of 1,75kN·m is reached. That event does not correspond to the failure of the system but a plastic hinge will form and the steel tubes will significantly deform locally. In that case, it has been observed in the field that the steel tubes no longer can be extracted and, therefore, the foundation cannot be re-used. So this plastic yield limit provides an estimate of the load above which re-use of the foundation system is unlikely.

Table 1. Parameters for the concrete block

Unit weight γ [kN/m^3]	26
Young's modulus E [kPa]	$2{,}7 \cdot 10^7$
Poisson's ratio, ν	0.15

Table 2. Parameters of embedded piles simulating the steel tubes.

Unit weight, γ [kN/m^3]	78.0
Young's modulus E [kPa]	$2 \cdot 10^8$
Diameter [m]	0.042
Thickness [m]	$2{,}9 \cdot 10^{-3}$
Area [m^2]	$3.56 \cdot 10^{-4}$
Moment of inertia I [m^4]	$6.85 \cdot 10^{-8}$
Skin friction	0.577
End resistance F_{max} [kN]	1.0

Table 3. Parameters of the soil

Unit weight, γ [kN/m^3]	21
Young's modulus, E [kPa]	$6 \cdot 10^4$ / $3 \cdot 10^4$
Poisson's ratio, ν	0.30
Cohesion, c_{ref} [kPa]	5
Friction angle, φ (phi) [°]	30
Interface reduction factor, R_{inter}	0.6

3 .1 *Compression load test*

Figure 7 shows the results of the numerical analysis for the compression load test. It can be observed that the loading history is quite well reproduced, only the stiffness of the soil has been calibrated to achieve this level of agreement. It is also noticeable that the hysteresis in unloading/reloading is significantly higher in the numerical results when compared with the field observations. This is probably a consequence of the failure of the Mohr-Coulomb model to represent adequately the pre-failure behaviour of the material. It is interesting to note that if no inclined steel tubes are included in the calculations, the bearing capacity is just 25kN. The difference must be attributed to the beneficial effects of the interaction of the tubes with the soil. The overall failure mechanism is illustrated in Figure 8; it clearly recalls the bearing capacity mechanism of a foundation significantly deeper than the concrete block.

The final shape of the tubes and the associated distribution of bending moments at the maximum force stage are shown in Figure 9. It can be noted that the critical section lies at the point where the tube enters the concrete block. Figure 10 presents the state of the tubes excavated after testing. It can be clearly observed that a kink (associated with yielding of the steel section) has occurred at the point where the maximum bending moment has been predicted. In Figure 11, the variation of the maximum bending moment with vertical load is plotted. According to this result, re-use of the foundation system will be difficult if the load applied exceeds 50 kN.

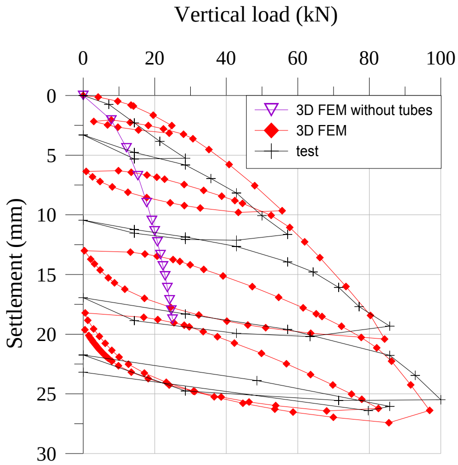

Figure 7. Comparison of the results of the numerical analysis with field observations for the compression load test. The results of the analysis of the foundation without the steel tubes have been added.

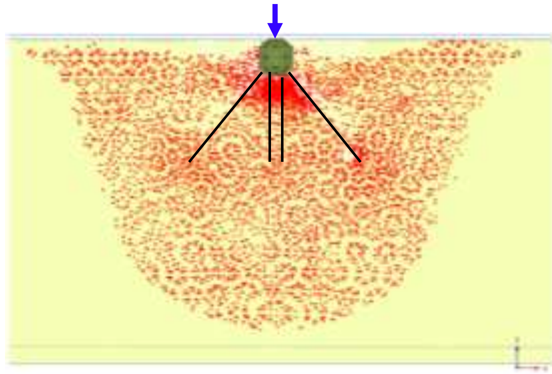

Figure 8. Failure mechanism of the compression load test.

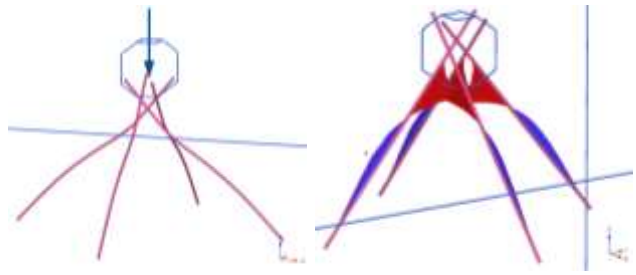

Figure 9. Computed deformed shape (left) and bending moments (right) of the steel tubes in the compression load test (maximum force stage).

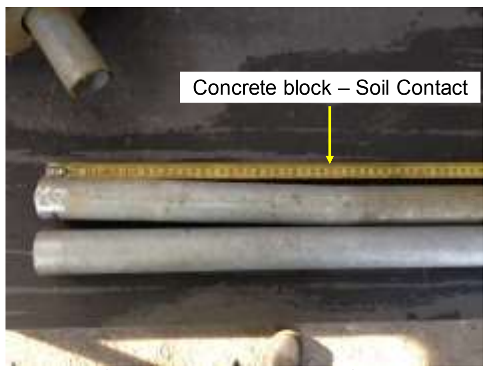

Figure 10. Shape of the steel tubes excavated after testing. The kink at the critical section can be noted.

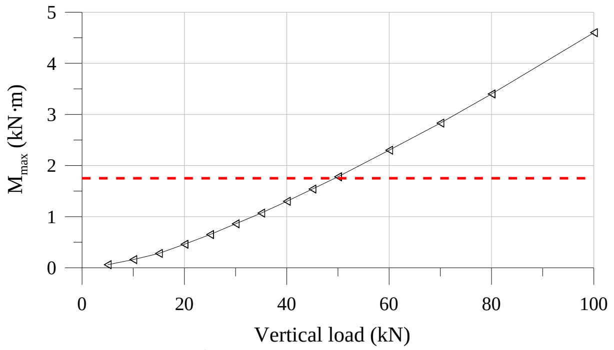

Figure 11. Variation of the computed bending moment with applied load. Compression load test

3 .2 *Tension load test*

The comparison between computed and observed foundation heave is shown in Figure 12. Again a good agreement has been obtained using the same soil parameters as in the previous analysis. In Figure 13 the Mohr-Coulomb failure points and the tension failure points are indicated. It can be observed that two zones are clearly delimited corresponding to shear failure in the soil outside the foundation and tension failure in the soil inside. In this case, the failure mechanism lies wholly above the end tips of the steel tubes

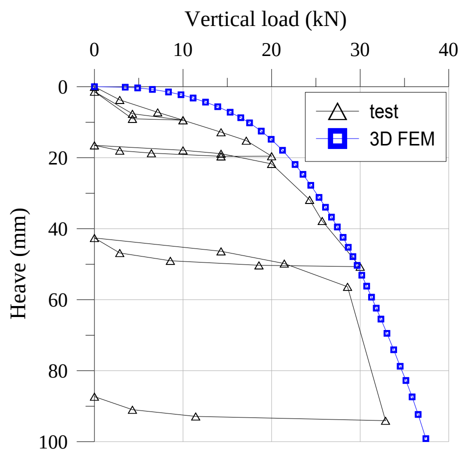

Figure 12. Comparison of the results of the numerical analysis with field observations for the tension load test.

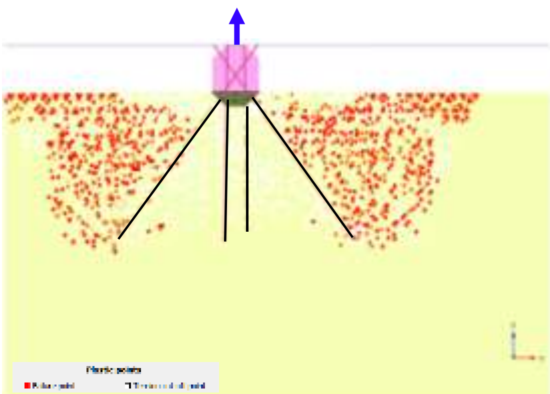

Figure 13. Failure mechanism of the tension load test.

The deformed shape of the steel tubes and the corresponding bending moment distribution at the maximum force stage are depicted in Figure 14 whereas the variation of the maximum bending moment with applied force is shown in Figure 15. It can be noted that the re-usable limit (22 kN) is well below the failure load.

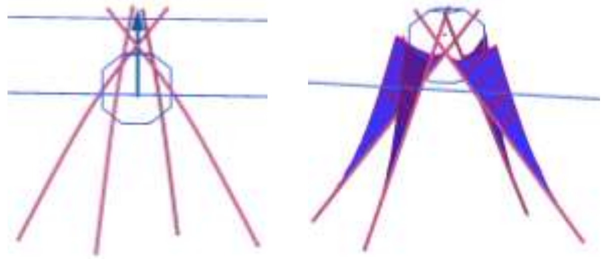

Figure 14. Computed deformed shape (left) and bending moments (right) of the steel tubes in the tension load test (maximum force stage).

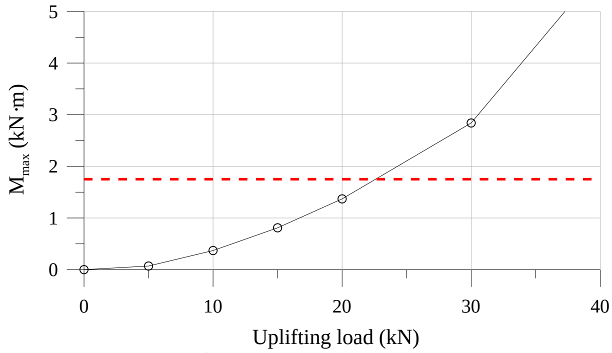

Figure 15. Variation of the computed bending moment with applied load. Tension load test.

4 CONCLUDING REMARKS

An innovative shallow foundation system for light loads has been developed consisting of a concrete block and four steel tubes driven into the ground at different orientations. The interaction between the block, the tubes and the enclosed soil ensures a significant enhancement of the bearing capacity compared to that of an equivalent conventional shallow foundation.

To understand better the behaviour of the foundation system, a number of instrumented load tests have been carried out, the interpretation of which has been assisted by the performance of 3D numerical analyses. Two tests are reported in the paper: a compression load test and a tension load test. Both are satisfactorily reproduced by the finite element computations.

An important feature of the foundation system is the possibility of its re-use. It has been found that reusing the system becomes problematic when the tubes undergo significant local rotations associated with the plastic yielding of the steel section. Estimates of the re-usability limit, in compression and in tension, have been derived from the results of the numerical analyses.

5 ACKNOWLEDGEMENTS

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6 REFERENCE

Peck, R. B., Hanson, W. E., & Thornburn, T. H. (1974). *Foundation engineering*, 2nd Ed. New York, Wiley.