Modular Bridge Foundations - Accelerated Execution Solutions

Numerical study

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1 Abstract

This dissertation aims to study a deep foundation solution for modular bridges able to meet the requirements of current codes of pratice, namely the Eurocodes. Mainly, it will be necessary to address the field of modular bridges and propose a foundation solution compatible with the requirements of military bridges.

In the present dissertation, a reference was made to the development of modular bridges in the history and influence of the military in this field, and also to specific modular bridges and their characteristics.

Subsequently, the specificities of the deep solutions were exposed, namely the need for a geotechnical survey to access the geological scenario allowing to optimize both the structural and geotechnical solutions. Referring to the previous topics, it was finally defined a solution of TRM type micropiles, with ductile cast iron.

It was then specified the components of TRM micropiles and described in detail the construction process of this type of solution.

For the application and analysis of the proposed solution, a case study was analysed, where a finite element program (2D Plaxis) was used for its evaluation. The case study involved data from a geotechnical survey previously carried out by the company ENGGEO. With the support of the *BERD* company, it was possible to apply the adopted bridge loads (MB60) and vehicles according to the AASHTO standard.

Finally, the main conclusions are presented and some proposals for future developments are mentioned.

Key-words: modular bridges, TRM micropiles, construction process, numerical study

2 Modular Bridge Framework

From the beginning of their employment in an operational environment, the modular bridges were mostly used for war environments. These bridges served to support the military forces and would have to be equipped to withstand military loads, i.e. dimensioned with more demanding criteria. (ThinkDefence, 2011a)

Depending on the obstacles that the military force encountered in the field and with the advance in this technology, it was possible to use bridges with larger spans and for greater loads.

Regarding the typology of modular bridges, it is important to distinguish between assault bridges, support/logistics bridges and communication bridges.

The modular bridge that will be most outstanding during the thesis is the MB60. MB36 and MB60 are bridges designed by the *BERD* company and that have advantages in their versatility, assembly and safety. These bridges consist of two main longitudinal beams and prefabricated panels that are joined by uprights that support the deck.

The MB36 bridge is rated for spans close to 36 meters, while the MB60 bridge is prepared for spans close to 60 meters.

For the abutments, bridge MB36 uses single foundation abutments, while bridge MB60 uses double foundation abutments, as we can see in **figure 1**.

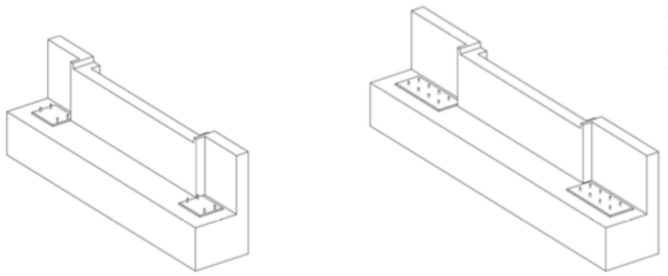

Figure 1 : Single configuration meeting on the left and double configuration meeting on the right (taken from (BERD, 2019))

3. Deep Foundations for Modular Bridges

TRM micropiles are made of ductile cast iron and later sealed with microconcrete. Ductile iron is used due to its high chemical and mechanical resistance and microconcrete to offer greater resistance to compression.

The microconcrete is used during the setting (wet method) or after the setting (dry method). It is essential that it has sufficient properties to guarantee fluidity to cover the reduced diameter and reach the pile depth.

For wet method, the microconcrete should also seal the outside space between the steel tube and the ground during the driven process.

The construction process of the TRM micropiles is particularly fast, its realization rates are very high, with the possibility of realizing 200 to 400 meters of micropiles per day. They are, without a doubt, a fast execution solution of great interest for modular bridge.

The TRM dry pile driving method, as its name indicates, does not use microconcrete during the driving process. This method limits the load capacity since it only enhances the tip resistance.

The fact that these micropiles work as tipped piles, that is, they do not resist the tension efforts that may arise due to reasons such as accidents or floods, so there should be another mechanism in the support capable of supporting the anti-gravity loads.

As for the wet method, and unlike the dry method, it uses microconcrete during the driving process. The final objective of this method is to form a sandwich type model with the TRM tube and the microconcrete inside and outside the tube. The microconcrete on the inside has the same function as in the dry method, the modification is in the presence of the microconcrete between the TRM tube and the surrounding ground, this change ensures the micropiles lateral resistance caused by tangencial stresses between the microconcrete and the tube.

Thus, the micropiles driven in the wet method are destined especially for cases where the ground present good mechanical properties and consequently it is possible to explore the shaft resistance. Generally they are granular soils with medium density, or soils with a high percentage of gravel and sand. In these situations, the micropiles behave as a floating solution. To confirm and improve the shaft resistance, the annular space between the tube and the ground is filled with microconcrete to create a rough surface, thus increasing the friction between the TRM pipe and the outer layer. (Caetano, 2014)

4 Design Criteria

The design of the deep foundations foresees the study of the resistant capacity of both the pile and the soil.

In the case of the dissertation, it will not be efficient to obtain results from soil parameters by means of a laboratory, since it is a technique that would consume possibly essential time.

According to EC7 (2010), for the case of the micro piles driven, it is important to consider two situations.

STR - "internal rupture or excessive deformation of the structure or structural elements (including, for example, shoes, piles or basement retaining walls), where the strength properties of the structural materials have a significant influence on the resistant capacity".

GEO - "excessive ground breaking or deformation, where the resistance properties of the soil or rock have a significant influence on the resistant capacity".

The following equation demonstrates the application of the formula for the driven piles, where the values of γ_M for the material properties and γ_R for the resistant capacity of the ground are adopted.

$$R_d = \frac{R}{\gamma_R}\left\{\gamma_F F_{rep}; \frac{X_k}{\gamma_M}; a_d\right\} \quad (1)$$

For the assessment of the compression resistance it is necessary to consider the adopted materials present in the foundation and their different properties. Thus, the resistance of ductile cast iron and the resistance of microconcrete must be included in the calculation. For this calculation, the standard EN 14199 (2010) refers to the methodology of the document EC4 - design of mixed steel-microconcrete structures.

$$N_d = A_b \times f_{cd} + A_s \times f_{yd} \quad (2)$$

Table 1 shows the compression strength values for each type of TRM micropiles, considering a C25/30 microconcrete.

Table 1 : Cross-sectional areas of microconcrete and cast iron and the respective maximum compression loads for each TRM micropiles (Caetano, 2014))

Micropile (Ø x e) $(mm \times mm)$	$A_b\ (mm^2)$	$A_s\ (mm^2)$	$N_d\ (kN)$
118 x 7,5	2604	8332	897
118 x 9,0	3082	7854	1028
170 x 9,0	4552	18146	1628
170 x 10,6	5308	19557	1835

5 Numerical Model (Plaxis 2D)

In order to test the solution described in the dissertation, it was used the data from the ENGGEO's prospecting campaign in Sarilhos Grandes, Montijo. The geological-geotechnical study of the campaign focused on the identification of geological formations. **Table 2** shows the geotechnical parameters of the terrain, obtained from SPT tests in bores at the study site.

The geological-geotechnical site investigation focused on defining a geological-geotechnical model, and estimating the resistance and deformability characteristics.

To model the solution, a micropile with circular section and axial loading was analyzed an axissimetric model executed by means of triangular elements of 15 knots (finite element mesh), where only half of the section was defined, as shown in **figure 2**. This type of axissimetric model is indicated for pile solutions with section circular, since the state of deformation and stress are identical in the radial direction.

Table 2 : Geotechnical soil parameters (ENGGEO, 2020)

Color	Geotechnical Zone	$\gamma\ (kN/m^3)$	$C_u(kPa)$	$E_u(MPa)$	$c'(kPa)$	$\phi'(°)$	$E(MPa)$
GZ7	Landfill: silt heterometric sand (11 to 30 strokes)	18 a 20	-	-	2 a 5	28 a 32	3 a 15
GZ6	Landfill: fine to medium sand, sometimes with silt heterometric sand passages (1 to 10 strokes)	18 a 19	-	-	0	<28	<8
GZ5	Clay sludge with muddy sand intercalations (1 to 2 strokes)	<16	<10	<3	<5	17 a 22	<2
GZ4	Sand, sometimes with silt (11 to 30 strokes)	19 a 20	-	-	0	30 a 32	10 a 20
GZ3	Sand, sometimes with silt (31 to 50 strokes)	20 a 21	-	-	0	32 a 35	20 a 45
GZ2	Clays with sand (12 to 36 strokes)	18 a 21	75 a 200	10 a 35	10 a 40	22 a 27	7 a 30
GZ1	Sand sometimes with silt (31 to 50 strokes)	20 a 21	-	-	0	32 a 35	20 a 45

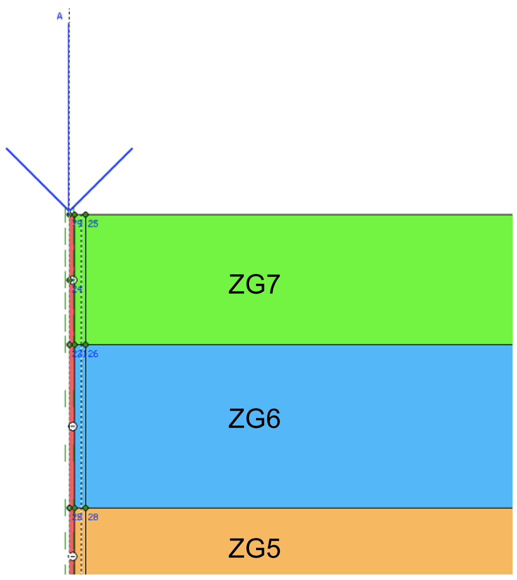

Figure 2 : Finite element model, half of micropiles 170x9.0 modeled

Based on the loads defined by the BERD company, the load value for the ELU was initially calculated in order to define the TRM micropiles. In order to reach the most unfavorable situation, the 61.6-meter span bridge (bridge with larger span, MB60) was chosen in order to reach the most demanding loads. Thus, analyzing the values according to EC7, explained in the previous chapter, the following results were obtained (**table 3**).

Table 3 : Values used for ELU load definition

Calculation Approach	Partial Coefficient γ_G	Partial Coefficient γ_Q	Permanent Load (kN)	Variable Load (kN)	ELU Load (kN)
AC1-C1	1,35	1,5	290	491	1128

Thus, from the result for the ELU, and according to the values in table 3, it was decided to select for this case the TRM 170x9.0 mm micropiles solution.

Due to the distance between abutments (more than 5 meters) it is sensible to model the case with only one micropiles, this is because the micropiles will not influence each other.

For the case study, and based on the data from the site investigation campaign, a 12-meter micropiles executed by the dry method was defined, using the Linear Elastic constitutive model to evaluate its behaviour.

The results obtained for the proposed solution are explained in the following illustrations, where the load vs. settlements curve and the plasticized points at the time of application of the load defined by the ELU can be analyzed.

Regarding the ELS analysis, the load value is in **table 4**, taking into account the procedures also according to EC7.

Table 4 : Values used for ELS load definition

Calculation Approach	Partial Coefficient γ_G	Partial Coefficient γ_Q	Permanent Load (kN)	Variable Load (kN)	ELS Load (kN)
AC1-C1	1,0	1,0	290	491	781

From these data, it was possible to obtain the structure settlements. In **figure 3** the linear deformation diagram is illustrated and in **figure 4** the load vs. settlement curve is presented for the analysed case study. For the ELS load a maximum settlement value of approximately 8,8 mm was estimated.

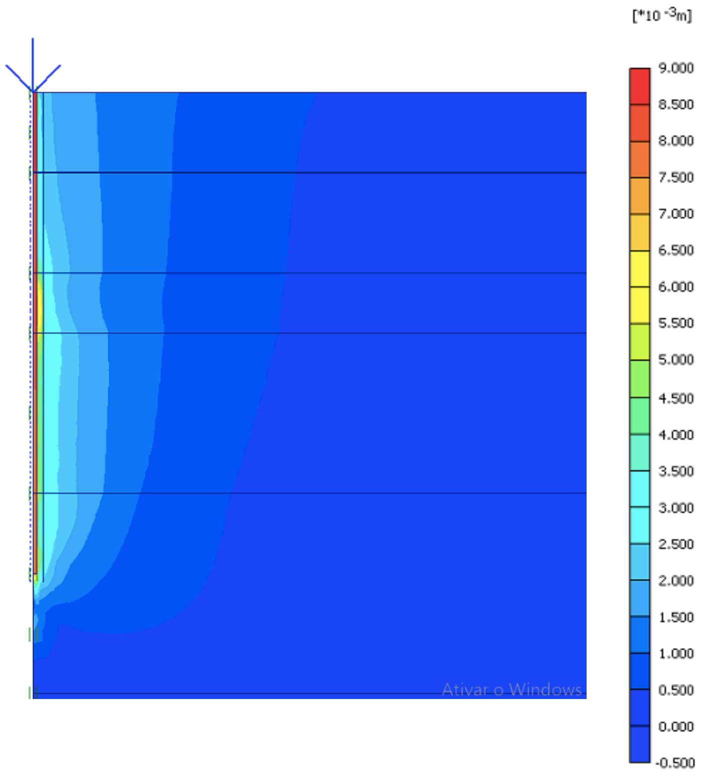

Figure 3 : Vertical deformations diagram for ELS

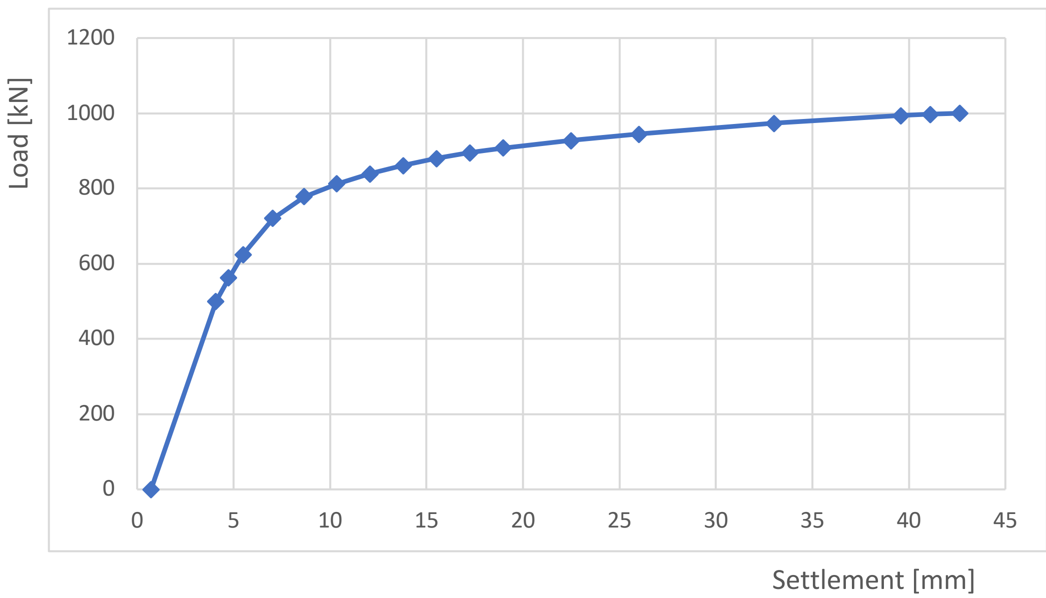

Figure 4 : Load vs. settlement for ELS

Thus, it is verified that the estimated settlement obtained corresponds to an expected value. As regards the maximum values defined by the EC7 and by the *BERD* company, the maximum value for the ELS load is admissible.

- Maximum vertical displacement (EC7)

$$d_{v,max} = H \times \frac{1}{1000} = 12 \times \frac{1}{1000} = 0{,}012 = 12\ mm > 8{,}8\ mm$$

- Maximum vertical displacement (*BERD*)

$$d_{v,max} = 10\ mm > 8{,}8\ mm$$

In order to evaluate the plastification of the soil in the most critical areas of the model, it was necessary to analyze the tangential stresses of the soil and compare them with the same values of TRM micropiles estimated by *Tiroler Rohren- und Metallwerke*.

Thus, from the results of the SPT tests (N_{30}) made in the field inspection, it was possible to obtain the tangencial stresses τ. In **table 4** are the estimated tangencial stress values for each geotechnical zone. The layers accounted for are only those that are influenced by the pile (12 meters) since they are the ones that are most affected by tangential stresses.

Table 3 : Estimated values of lateral resistance (tangencial stresses) for the different geotechnical zones *(Tiroler Rohre, 2014)*)

Layer	N_{30}	$\tau\ (kN/m^2)$
ZG7	11 a 30	100
ZG6	1 a 10	50
ZG5	1 a 2	40
ZG4	5 a 10	80
ZG3	11 a 30	100

Figure 4 shows the linear diagram of the tangencial stresses estimated through the numerical analysis. In figure 6 are the lighter blue (ground stresses). Thus it is possible to conclude that the values of the tangential stresses are around 30 a 40 kN/m^2, depending on the respective layer.

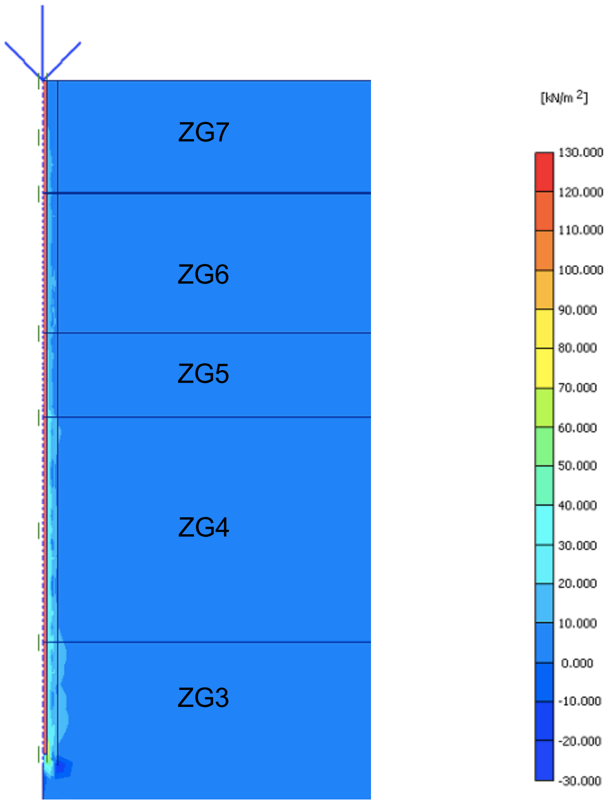

Figure 4 : Tangencial stresses diagram

Observing the diagram, its possible to verify that the tangencial stress values are around 30 to 40 kN/m^2, depending on the ground layer (ZG7 to ZG3). Thus, its possible to conclude that the values of tangencial stresses are lower than those proposal by *Tiroler Rohren- und Metallwerke* lateral resistance of TRM micropiles (table 4).

6 Final Remarks

In this dissertation it was studied a TRM type micro piles foundation as a solution for modular bridges. In this framework, the dissertation focused on three key points: studying the field of modular bridges to understand their basic characteristics, analyzing the adaptability of TRM micropiles in modular bridges foundations and thus the behavior of this type of foundation, and finally, study the solution using a finite element model and estimating its behavior at the geotechnical and structural level.

This being said, the importance of these structures, namely in the urgency to which they are employed, is shown in the state of the art. This factor was the most important for the rest of the work. That is, besides defining a foundation solution compatible with the structure geometry and loads, it was considered the need of a fast and flexible constructive process, in order to be employed in a rescue or used in the military environment.

Once a solution was defined to met those requirements, it was necessary to explore the basic characteristics of a deep foundation, such as the one chosen, and also to better understand its construction process. Regarding the construction process of TRM micropiles, it was important to evaluate the functionality of the whole process in an urgent environment, such as ease of transportation, materials, equipment, applicability in various soils and speed of execution.

Therefore, it was proposed in the case study, the application of the TRM 170x9.0 mm micropiles as a foundation solution of a MB60 modular bridge, on a soft soil. From the geotechnical site investigation it was defined that the construction method of the TRM micropiles would be dry method.

From the MB60 bridge loads, defined by the company *BERD*, and from the model vehicle loads defined by the AASHTO standard, it was possible to model the case study in the 2D Plaxis software. Using Eurocode 7, for ELS and ELU analysis, it was evaluated the behavior of the micropiles, at the level of the settlements and plastic points.

In conclusion, the objectives of the dissertation were achieved, because we can admit that the TRM micropiles deep foundation solution is an efficient solution for a structure like a modular bridge.

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