Block foundations for railway infrastructure – First centrifuge model tests

Conference Paper · October 2024

DOI: 10.53243/ECPMG2024-7

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ABSTRACT: Block foundations have been used to support overhead lines in railway infrastructure for many years. Steckner (1989) and Sulzberger (1945) have developed an analytical design approach for block foundations subjected to horizontal and moment loading coming from the catenary mast. Recently, block foundations for railway infrastructure are built in more complex soil conditions, such as soft, fine-grained, layered sediments. The existing analytical design approach of Steckner and Sulzberger was not developed for such soil conditions, and therefore needs to be revised and extended for this type of soils. The load-bearing behaviour of block foundations in such soft soils is investigated through lateral pushover tests in the ETH Zurich geotechnical beam centrifuge. The paper focuses on the development of the experimental setup, such as the actuators used to apply horizontal loading on the catenary mast, the on-site created block foundation including details for attaching the mast, and the instrumentation to measure the deformation of the block foundation via mast-displacements in the horizontal and vertical direction. The first results of centrifuge model tests in sandy soils are described and critically discussed.

1 INTRODUCTION

A block foundation is a prismatic single foundation embedded in the ground, with its dimensions lying between a shallow foundation and a pile. According to Steckner (1989), a block foundation is characterised by a ratio of width B to embedment depth D in the range $2/3 \leq D/B \leq 4$. Block foundations are used to support overhead lines in railway infrastructure. Their load-bearing behaviour in terms of horizontal and moment loading is described with an analytical model given by Steckner (1989) and Sulzberger (1945). The use of such analytical model for the dimensioning of block foundations has been proven in practice for soils with an internal friction angle $\varphi' \geq 27°$ and soil stiffness $M_E > 12$ MPa for fine grained (clayey and silty) soils, or $M_E > 25$ MPa for coarse grained (sandy to gravelly) soils (e.g. internal documents of the Swiss federal railways SFR).

However, in soft soils with $M_E \leq 12$ MPa, block foundations are often supplemented by piles due to the low soil stiffness and strength. There are certain types of fine-grained soils, such as lake deposits with some glacial preloading, where block foundations could be used without additional piles, as the soil stiffness could be high enough. In these cases, it is a matter of ongoing discussion whether the analytical model of Steckner (1989) and Sulzberger (1945) can be considered appropriate for dimensioning tasks.

Centrifuge modelling can shed more light into the problem, offering experimental evidence on the load-bearing behaviour of block foundations in soft soils, in soils with a high water table and block foundations on a slope. Such experimental data can be instrumental for the improvement and potential revision of the analytical models used in practice.

2 ANALYTICAL MODEL GIVEN BY STECKNER (1989)

This section briefly discusses the main aspects of the model of Steckner (1989). The model is not described in detail, as the calculation mode is not clearly organised and rather time consuming. However, Steckner (1989) does account for the earth pressures that act on the block foundation, as well as a base resistance N_u which is related to the bearing capacity of a shallow foundation. The model also accounts for the friction (R_0; R'_0) that acts on the two side walls of the block foundation. Both, earth pressures and friction are dependent on an initial unknown pole of rotation of the block foundation, given with the so-called zero line with the distance y to the bottom of the foundation (Figure 1).

Steckner (1989) calculates a critical value of a resisting moment M_u, which the foundation is able to sustain at ultimate limit state, taking into account active- and passive earth pressures, base resistance N_u and friction on the side walls (R_0; R'_0).

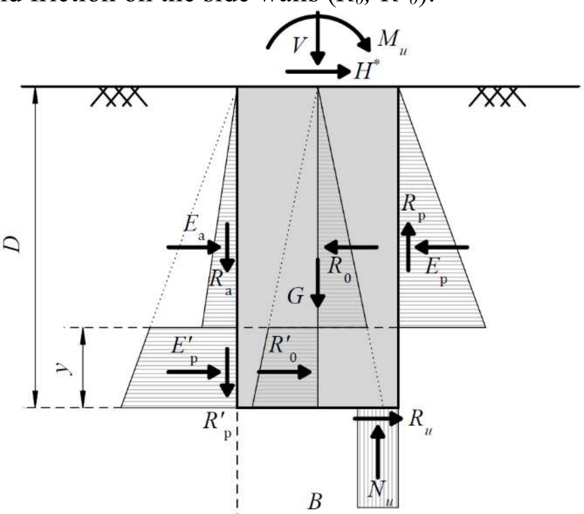

Figure 1: Earth pressures and base resistance N_u acting on the block foundation after Steckner (1989).

It is noticeable that Steckner (1989) does not consider any plausible failure mechanism in the surrounding soil due to horizontal- and moment loading of the block foundation. Instead, the method accounts for the fully mobilised active and passive earth pressures, independently of the deformation of the block foundation in the soil.

Additionally, Steckner (1989) proposed an analytical model to calculate the serviceability of block foundations. The latter is based on the Winkler (1867) method and the subgrade reaction modulus k_s. The independent springs of stiffness k_s in the analytical model are placed on the side wall, where the foundation is leaning due to horizontal- and moment loading. As k_s is unknown and depends on the mobilisation of passive earth pressure, Steckner assumes an increasing k_s with depth, depending on the friction angle φ' of the soil. However, the dimensioning in terms of serviceability of hundreds of block foundations in recent years shows that the approach of Steckner (1989) tends to give good results for coarse-grained soils with $\varphi' \geq 30°$. For fine-grained and rather soft soils, the determination of k_s is highly uncertain. Therefore, the serviceability analysis model should be improved.

3 PHYSICAL MODELLING

The load-bearing behaviour of block foundations in soft, saturated soils will be investigated through lateral pushover tests in the ETH Zurich geotechnical beam centrifuge. Indicative results of the first model test in saturated sand, conducted at 30*g*, are presented herein.

3.1 Soil materials

Saturated Perth Sand (Buchheister, 2007) is used for the centrifuge model test presented herein. It is, however, planned to conduct centrifuge model tests in soft soils using Birmensdorf-Clay (Weber, 2007).

3.2 General test setup

In the prototype problem (reality), block foundations are built in-situ, pouring concrete into an excavation of the required size. This results in the block foundation having a rough surface, and typically being slightly larger than the planned foundation size. As soil-structure interaction (SSI) is expected to have a significant influence on the load-bearing capacity, the model foundations are produced in a similar way as the prototype foundations. The procedure is explained step by step below:

- Perth Sand (Buchheister, 2007) is poured in a strongbox (ø 750 mm) using an automated sand pluviator to achieve a uniform density (target value γ_d = 16.6 kN/m^3 which corresponds to a relative density of I_D = 71.4%). The final depth of the sand layer is 400 mm.
- The sand layer is saturated under vacuum and desaturated afterwards to maintain suction for the model foundation construction.
- With the help of a base plate and a specially made mould, the sand is excavated according to the planned foundation dimensions (Figure 2a).
- As soon as the excavation for the model foundation is completed, four threaded rods, required for the subsequent assembly of the mast, are positioned using a 3D printed template (Figure 2b).

- Finally, the foundation is concreted through the template to 2/3 of the height with a self-compacting, low shrinkage and quick binding cementitious mortar (FIXIT 586 with a water-cement ratio of 0.24). After one hour, the installation aid is removed and the rest of the foundation is concreted (Figure 2c & d).

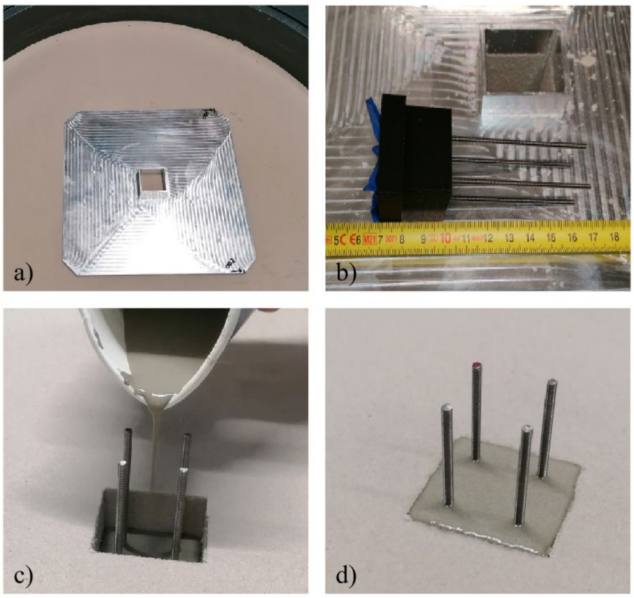

Figure 2: Production of the model block foundation: (a) tool used to maintain the excavation geometry; (b) finished excavation and preparation of the template with the threaded rods; (c) filling the last third of the block foundation with FIXIT 586; and (d) finished block foundation.

The prototype block foundation is 1.2 m x 1.2 m x 2.4 m (width x length x depth). According to scaling laws (Garnier et al., 2007), at a scale of 1:30 (testing at 30*g*), this translates to a model foundation of 40 mm x 40 mm x 80 mm.

The model of the catenary mast is produced using a 3D printer (Mark Two from Markedforged). This FDM (Fused Deposition Modelling) printer uses a nylon material, mixed with microfibres. To further increase the strength, the printer's capability to lay carbon fibre is used. Together with a rectangular cross-sectional mast, instead of an I-beam, this results in a stiff catenary model mast weighing 78 grams (Figure 3).

After the installation of the mast, the Perth Sand is again saturated for the pushover test. Care is taken to ensure that the entire model is submerged with 5 mm of water at 1*g*. This ensures that the water level at the foundation is at the top edge of the terrain during the test (curvature of the water during centrifuge test).

3.3 Loading & measuring devices

The loading device consists of a displacement-controlled electric actuator, acting on the top of the catenary mast with a defined lever arm of 283 mm. The actuator is equipped with a 200 N load cell to measure the displacement-dependent load. The horizontal displacement of the actuator is measured with a laser sensor, located opposite to the actuator (Figure 4).

Figure 3: Catenary mast placed on top of the foundation.

The loading device is guided by rollers (not installed in Figure 4a but shown in Figure 4b & c), resting on the support frame in order to minimise the bending on the actuator- and load cell-system due to high *g*-level. Finally, two cameras are used to perform a DIC (Digital Image Correlation), which allows the pole of rotation of the mast to be recorded during the test.

The catenary mast is loaded horizontally in a displacement-controlled mode, with a velocity of 0.01 mm/s.

3.4 Scaling considerations

The stiffness scaling of the catenary mast at model scale was not a priority because the main interest lies in the load-bearing behaviour of the block foundation itself. Therefore, the mast serves only as a load application to the block foundation. As long as the connection between mast and foundation is rigid, the deformations of the foundation through DIC analysis can be determined separately from the mast deformations.

The scaling of the mass of the foundation and the catenary mast are crucial, as they strongly influence the load-bearing behaviour of the block foundation. A greater weight of foundation and mast means that the foundation is able to transfer more horizontal load to the subsoil. The scaling of the foundation mass is straightforward as the material of the model foundation has approx. the same density as the prototype foundation. The scaling of the force given by the self-weight of the catenary mast and acting as a vertical load V (Figure 1) on the block foundation is done via the comparison of the vertical stresses on the bottom of the block foundation given by the mast load V. The approx. weight of a prototype-scale catenary mast is 800 kg which is equal to $V = 8$ kN. This results in a vertical stress σ'_v equal to approx. 5.5 kN/m^2 at prototype scale. To induce the same stress σ'_v at model scale at 30g V is equal to 8.8 N. This means that the self-weight of the catenary mast at model scale should not exceed 30 grams (8.8 N at 30g).

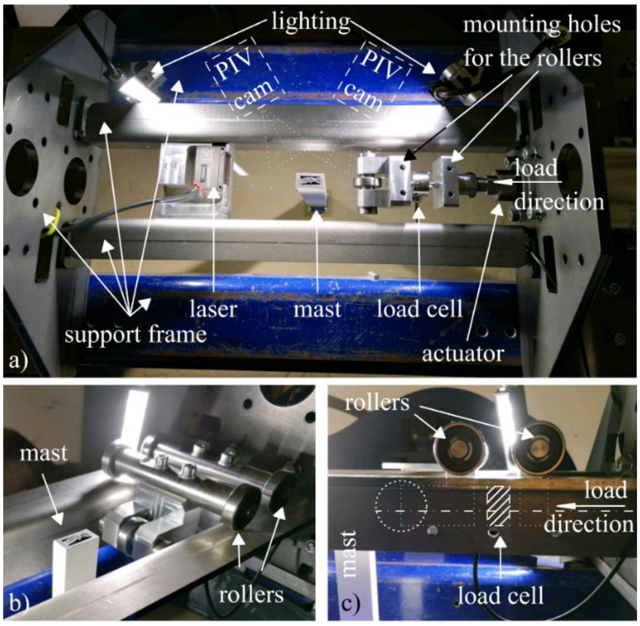

Figure 4: Experimental setup: (a) showing the actuator used to apply horizontal loading to the top of the catenary mast, and the two DIC-cameras installed near the sand layer (below the support frame) and the top of the block foundation respectively; (b) and (c) showing details of the guiding rollers.

4 FIRST TEST RESULTS

A first centrifuge test at 30g has been carried out at displacement-controlled mode with a block foundation in Perth Sand. Indicative results are presented in Figure 5 in terms of force-displacement response. Unless otherwise stated all results are presented in prototype scale. The force is applied at the catenary mast top (8.43 m above the foundation). The head deformation could be measured up to about 1.1 m, due to the limited range of the laser sensor. Beyond the range of the laser sensor, the displacement is determined using the known actuator speed (all data was recorded over time).

Figure 5 shows an increase in horizontal load up to approximately 27 kN, which can be considered as the ultimate limit state of the block foundation. Figure 6 shows the deformed state of the block foundation in the sandy soil after the test. The foundation has tilted by approximately 6° at the end of the test.

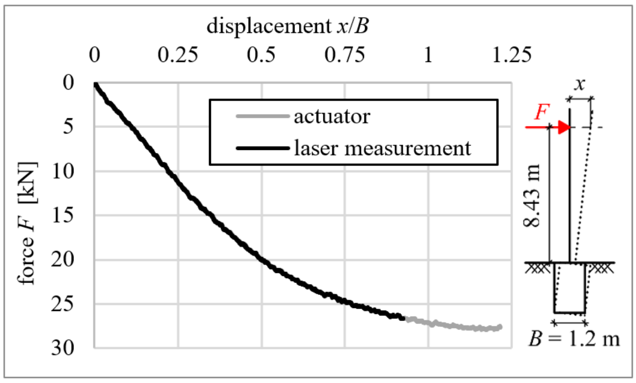

Figure 5: Horizontal force-displacement response of the block foundation (no unloading inflight).

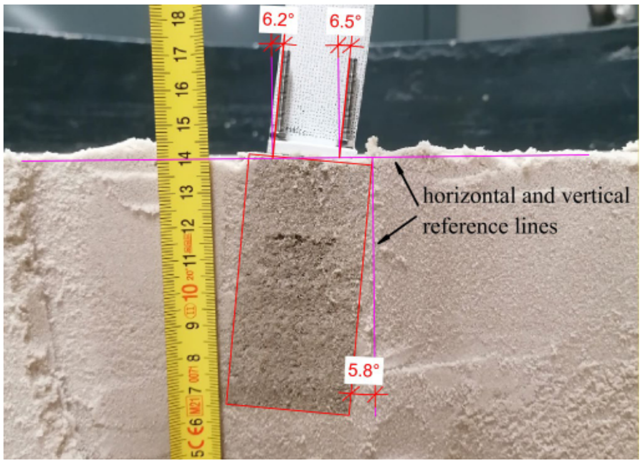

Figure 6: Block foundation after the pushover test.

Provided that the centre of rotation is at the bottom of the foundation, a rotation angle of approx. 7.6° at the end of the test can be calculated from the data shown in Figure 5 (the foundation has a height of 2.4 m). The theoretical angle of rotation is therefore greater than the angle measured during dismantling (Figure 6). There are two possible reasons for this finding:

- The mast is not adequately stiff and undergoes therefore greater deformation than the foundation.
- The pole of rotation of the foundation itself is lower than the base of the foundation.

The base stiffness of the mast was analysed during the test using image data. As it can be seen in Figure 7, the base of the mast deforms significantly during the pushover test. The laser measurement at the top of the mast also includes the flexural deformation of the mast which explains the difference in the measurements. As the reference surface for the DIC analysis is located on the base of the mast, the pole of rotation for the foundation cannot be reliably determined in the present test, as the angle α (Figure 7) which stands for the rotation of the mast in relation to the block foundation is unknown and constantly changing during the pushover test.

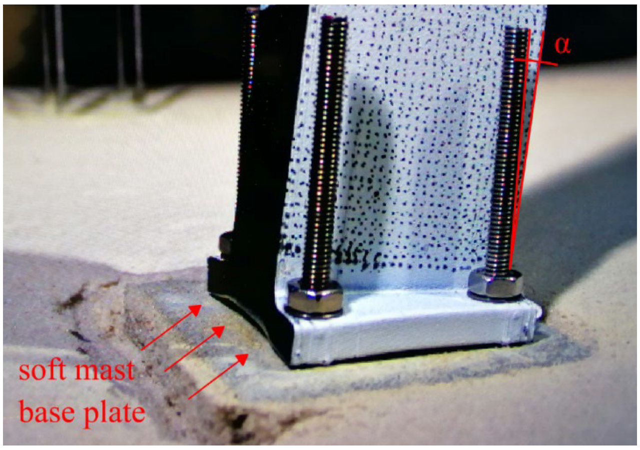

Figure 7: Deformed mast base plate during the centrifuge pushover test.

5 CONCLUSIONS

The results of a first centrifuge test in sand showed that the stiffness of the 3D-printed catenary mast is not adequate, especially its connection to the block foundation is the one that deforms. Therefore, to correctly measure the rotation of the block foundation at ultimate limit state, additional laser measurements from different positions need to be combined with the DIC measurements. A stiffer catenary mast would be necessary to achieve more rigid response, but its construction is not straight forward, as its dead weight also needs to match that of the prototype which is not given so far.

The available DIC-data will be analysed in a next step to see whether enough information on the deformation behaviour of the mast itself is available. The base detail of the catenary mast will be improved for the subsequent tests, and more focus will be given on the measurement of the deformation of the foundation itself with lasers at different positions. As of now, it seems reasonable to directly connect the reference surface required for the DIC analysis to the foundation and thus make it independent of any mast deformation.

The unloading of the block foundation will also be conducted inflight for the subsequent tests to ensure proper control measurements on the deformed block foundation upon dismantling.

ACKNOWLEDGEMENTS

The authors are most grateful for the financial support provided by “Allianz Fahrweg”.

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