Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-702

Block foundations for railway infrastructure: comparison of physical model test results to analytical design approaches

Gregor Portmann, André Arnold
Institute of Civil Engineering, Lucerne University of Applied Sciences and Arts, Horw, Switzerland,
gregor.portmann@hslu.ch

Ralf Herzog, Ioannis Anastasopoulos
Institute for Geotechnical Engineering, ETH Zurich, Zurich, Switzerland

ABSTRACT: Block foundations have been used to support overhead lines in railway infrastructure for decades. They are reinforced concrete (RC) embedded foundations, designed to resist horizontal and moment loading from a catenary mast. Sulzberger (1945) developed an analytical approach for serviceability-design, which was extended by Steckner (1989) for inclined terrain and supplemented by a new method for the ultimate limit state. The Steckner and Sulzberger methods form the basis for the design of block foundations by the Swiss Federal Railways (SFR). The validity of the theory, especially for soft- or saturated soils is investigated with the aid of lateral pushover tests conducted at the ETH Zurich Geotechnical Centrifuge Centre (GCC). The main objective is to derive better understanding of the load-bearing response of block foundations in soft soils, and to identify the potential for design optimization. The paper offers a brief overview of a centrifuge test conducted in saturated sand. The experimental setup is discussed, along with the developed methodology to directly cast the block foundation into the soil. Preliminary results are presented and compared with the Steckner and Sulzberger analytical approach.

KEYWORDS: Block foundations, Steckner design method, Railway infrastructure, Geotechnical centrifuge testing.

1 INTRODUCTION

Block foundations (*BF*) are prismatic single foundations embedded in the ground, whose dimensions lie between those of shallow and piled foundations. According to Steckner (1989), *BFs* are defined by a width-to-depth ratio (*B*/*D*) in the range of $2/3 \leq D/B \leq 4$, where *D* is the embedment depth and *B* is the width of the foundation (Figure 1). *BFs* are used to support all kinds of masts, such as for railway overhead lines or signal boards. Therefore, such foundations are primarily subjected to horizontal and moment loading due to wind forces on the superstructure and/or cable tensile forces. According to Sulzberger (1945) and Steckner (1989), the stability of such foundations is largely governed by earth pressures acting on the vertical sides of the embedded block. While the approach of Sulzberger (1945) primarily deals with allowable foundation rotations, Steckner (1989) developed an analytical model for the design at ultimate limit state (*ULS*). The Steckner design method determines the maximum allowable moment M_u under a given horizontal H^* and vertical load V (see Figure 1). The Steckner (1989) approach accounts for full mobilisation of active and passive earth pressures, along with equilibrium $\sum V = 0;\ \sum H = 0;\ \sum M = 0,$ calling for an iterative solution. The calculation scheme of Steckner assumes that the soil has an internal friction angle $\varphi'_{cv} > 20°$.

Experience in Switzerland has shown that the Steckner approach works well for *BFs* above the groundwater table, lying in soils with $\varphi'_{cv} \geq 27°$ 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, as no major damage has been reported (e.g., internal documents of the Swiss federal railways SFR). However, in the case of soils that do not fulfil these conditions, piles are often employed, leading to a significant cost increase. This raises the question, whether Steckner's design approach can also be used for soft and/or water-saturated soils. In order to answer this question, centrifuge model tests are conducted to experimentally investigate the load-bearing response of *BFs* in different soils. The produced experimental results can be instrumental for the improvement and potential revision of the analytical models used in practice. In this paper, the ultimate limit state (*ULS*) of a *BF* in saturated sand is calculated according to Steckner, discussing certain peculiarities of the approach. The experimental setup is briefly presented, and preliminary centrifuge test results are compared to Steckner's approach.

2 ANALYTICAL MODEL OF STECKNER

This section describes the main aspects of the Steckner (1989) approach to calculate the allowable M_u at *ULS* for a given set of loads *V*, *H** and *G* (Figure 1). The model is not described in detail, as the calculation mode is rather time consuming, as a minimum of 35 equations must be solved with some 'if-statements', which could further increase the number of equations that need to be solved. However, an overview of the most important calculation steps is provided below:

- It is assumed that active and passive earth pressures (forces E_a, E'_p and E_p) can develop in the front and in the back of the foundation. According to Weissenbach (1962), an equivalent wall width $b_{id} > B$ is calculated to account for three-dimensional (3D) effects, whereby no distinction is made between active and passive earth pressures.
- The vertical components of the earth pressures (forces R_a and R'_p) are calculated with a wall friction angle of $\delta_1 = 2/3$ φ'_{cv}. On the other hand, for R_p it is only required that δ_p lies between 0 and δ_1.
- The earth pressures at rest act on the sides of the foundation that are perpendicular to the direction of loading. They are calculated using the earth pressure coefficient at rest according to Jaky (1944). To calculate the reaction forces R_0 and R'_0, a wall friction of $\delta_1 = 2/3\ \varphi'_{cv}$ is assumed.
- The calculation of the foundation stresses is based on the assumption that the foundation is infinitely narrow. This means that other influencing factors, such as shape factors (to account for 3D effects) or load inclination factors (which are widely used for the extended bearing capacity formula, according to Terzaghi; e.g. Lang et al., 2011), are not considered. Therefore, the magnitude of the base normal force N_u solely depends on the width x for a given foundation depth *D,* and the friction angle of the soil. The base friction R_u is calculated by assuming full friction $R_u = N_u \tan(\varphi'_{cv})$.

- The position of the so-called 'zero line' at y, and the magnitude of the base stresses N_u, which acts on the foundation at $x/2$, are unknown. By requiring that $N_u \geq 0$ and establishing the horizontal and vertical equilibrium as a function of x, y and δ_p (Equations (1) and (2)), a quadratic determination equation for y can finally be derived, see Steckner (1989) for details.

$$\sum V = 0 = V + G + R_a(y) + R'_p(y) - R_p(y, \delta_p) - N_u(x) \tag{1}$$

$$\sum H = 0 = H^* + E_a(y) + E'_p(y) + R'_0(y) + R_u(x) - R_0(y) - E_p(y) \tag{2}$$

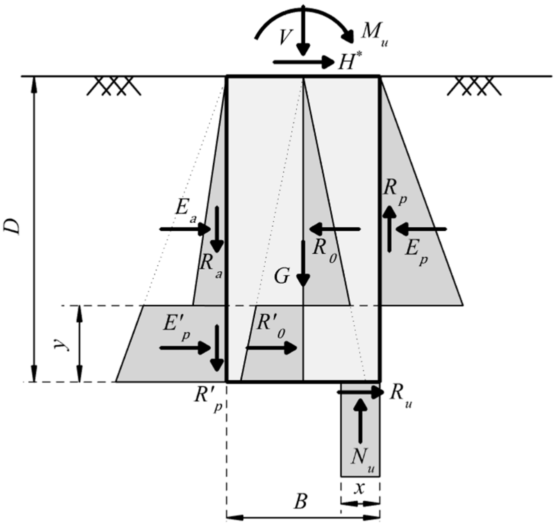

Figure 1. Earth pressures and base resistance N_u acting on *BF* after Steckner (1989).

Finally, after Equations (1) and (2) are solved, M_u is calculated by formulating the equilibrium of moments. From our point of view, the following points in relation to Steckner's model should be emphasized:

- No actual failure mechanism is considered. This becomes clear by the discontinuous earth pressure distributions, as given in Figure 1. Regardless of this, no active earth pressure is taken into account below the zero line at y.
- The equivalent wall width of $b_{id} > B$ is taken into account for the calculation of both the active and passive earth pressure forces. It is questionable whether E_a should at least be calculated with B due to the relative movement of the foundation away from the soil, if not even with a reduced width, in order to account for 3D effects more realistically.

Table 1 summarizes the input parameters for the Steckner calculation for a prototype foundation, as it was tested in the centrifuge model tests. The foundation is constructed in Perth sand, of which the geotechnical properties are well documented (Nater, 2006; Buchheister, 2009; Arnold, 2011). In prototype scale, the mast has a length $L = 8.5$ m and a dead load $V = 34.4$ kN. As the groundwater table is assumed to be at the ground surface, the earth pressures and the dead load of the buried concrete foundation are considered under buoyancy.

Table 1. Input parameters for the calculation after Steckner.

Parameter	Symbol	Value	Unit
Foundation width	B	1.24	m
Foundation depth	D	2.49	m
Length of the Mast	L	8.5	m
Concrete density (buoyancy)	γ_b (γ'_b)	25 (15)	kN/m^3
Dry unit weight sand	γ_d	16.6	kN/m^3
Unit weight sand (buoyancy)	γ (γ')	20.2 (10.2)	kN/m^3
Critical state friction angle	φ'_{cv}	30	[°]
Vertical load	V	34.4	kN
Concrete self-weight	G	57.3	kN
Friction for vertical earth pressure components	δ_1, δ_p	20	[°]

As already described, the Steckner calculation scheme provides the ultimate overturning moment M_u for a given load combination G, V & H^*. Since the results according to Steckner are to be compared with pushover tests in the centrifuge, the maximum force P acting on the mast head will be:

$$P = H^* = {}^{M_u}/_{L} \tag{3}$$

This means that in the Steckner calculation scheme, the force H^* is iterated as an input parameter until $H^* L = M_u$. The most important results of the calculation are summarised in Table 2. For the input parameters of Table 1, a force $P = 23.4$ kN can be applied to the top of the mast at *ULS*.

Table 2. Output parameters of the calculation after Steckner

Parameter	Symbol	Value	Unit
Equivalent wall width	b_{id}	2.10	m
Zero Line	y	0.99	m
Width of base stress	x	0.08	m
Pushover Force at top of the mast	$P = H^*$	23.4	kN
Max. Moment at ULS	M_u	199	kNm

3 PHYSICAL MODELLING

The load-bearing response of *BFs* in saturated soils is investigated through lateral pushover tests in the ETH Zurich geotechnical beam centrifuge. Preliminary results of a model test in saturated Perth Sand, conducted at 30*g*, are presented below.

The test setup is shown in Figure 2a. Unless otherwise stated, all dimensions and results are shown in prototype scale (the corresponding dimensions for model scale are given in millimetres in brackets). The load-bearing response of the *BFs* is investigated by recording the rotation β of the *BFs*, the position of the zero line y, and any settlement or heave z along the centre of gravity in function of the applied load P (Figure 2b). This is achieved by measurements of two horizontal lasers (L1 and L2) and one vertical laser (L4), which measure the distance to laser targets glued onto the *BF*. This ensures that the measurements are unaffected by any deformations of the mast itself and its base plate.

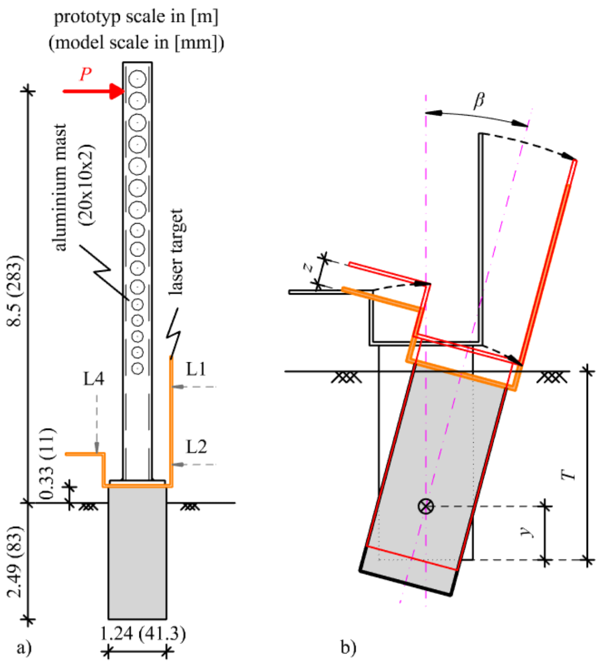

Figure 2. Centrifuge test set up: (a) *BF* with aluminium mast and laser targets; and (b)foundation rotated around the zero line (y) by the angle β (red lines), which has settled by z.

3.1 *Scaling considerations*

According to the scaling laws (e.g., Madabhushi, 2014), the prototype *BF* translates to a model foundation of 41.3 mm x 41.3 mm x 83 mm at a g-Level of 30g. The pushover force in the centrifuge model is scaled according to Equation (4), where F_{mod} is the force in the centrifuge model and N equals 30:

$$F_{mod} = {}^{F}/_{N^2} \tag{4}$$

The scaling of the bending stiffness EI of the mast and the *BF* itself plays a minor role due to the following two reasons:

- The deformations are measured independently of the mast, directly on the block foundation, using laser targets. Therefore, the objective is not to reproduce the stiffness of the mast to scale, but rather to produce a mast that is as stiff as possible without adding too much dead weight, as discussed in Arnold et al. (2024).
- The block foundation is stiff in relation to the soil. Additionally, concrete (FIXIT 586) was used in the model-construction, and therefore it can be assumed that the scaling according to Equation (5) is met, as E is approximately the same for the prototype and the model.

$$EI_{mod} = {}^{EI}/_{N^4} \tag{5}$$

Finally, the influence of the mast's dead weight must also be considered, as this is likely to have a significant effect on the test results. At prototype scale, the mast (HEB 260) and the concrete console, which protrudes above the ground, weigh 1,290 kg. This corresponds to a weight of 48 g at model scale (scaling with a factor of $1/N^3$). However, the mast with the laser targets and the foundation protrusion weighs 130 g in the model. These 130 g correspond to a vertical load of $V = 34.4$ kN at prototype scale. According to internal documents of the Swiss federal railways (SFR), vertical loads of 0 to 150 kN should be taken into account. As long as V is entered correctly for the analytical calculations of Steckner, the model tests and the analytical approach are comparable, even if the smallest pushover load is theoretically achieved with $V = 0$ kN.

3.2 *Soil materials and preparation*

Saturated Perth sand (Nater, 2006; Buchheister, 2009; Arnold, 2011) is used for the centrifuge model test presented herein. The sand is poured in a cylindrical strongbox (ø 750 mm) with the aid of an automated sand pluviator to achieve a uniform density with a target value of $\gamma_d = 16.6$ kN/m^3, which corresponds to a relative density of $I_D = 71.4\%$. The final depth of the sand layer is 400 mm, being equal to five times the embedment depth D of the *BF*. The sand is saturated after pluviation. The top layer of the sand (approx. 100 mm) is then desaturated to provide suction for the construction of the model foundations.

3.3 *Construction of model foundations and test procedure*

BFs are typically constructed in situ: a reinforcement cage is placed in the previously excavated area with the required dimensions, and concrete is then poured directly against the ground. Consequently, *BFs* usually have a rough surface and are slightly larger than the planned foundation size. Since soil-structure interaction (*SSI*) is assumed to have a significant influence on the load-bearing capacity of the model foundation, the latter is constructed in a similar way at 1g:

- After desaturation of the top sand layer, the sand is excavated according to the planned foundation dimensions. This is done with the help of a base plate and a specially made mould to ensure that all foundations have exactly the same dimensions (Figure 3a). The base plate is secured by four screws, which are tightened against the strong box.
- As soon as the excavation for the model foundation is completed, six threaded rods M3, required for the subsequent assembly of the mast, are positioned using a 3D-printed template (Figure 3b).
- Then, the foundation is concreted through the template to 2/3 of its final height with a self-compacting, low shrinkage and quick binding cementitious mortar (FIXIT 586 with a water-cement ratio of 0.24). After half an hour, the template is removed, and the rest of the foundation is concreted with the aid of an additional 1 mm spacer (Figure 3c). The foundations' top edge is therefore 11 mm above the ground surface.
- After 1.5 hours, the additional spacer is removed and a laser target is attached to the foundation using a fast-bonding two-component adhesive (Figure 3d). This ensures that the laser target moves with the *BF,* not being affected by the deformation of the mast base plate.
- Finally, the mast is mounted, with the *BF* secured in position by the base plate (Figure 3e). Once the screws have been tightened, the three-part base plate is removed. The loading and measuring device can now be installed, whereby no direct contact with the mast or foundation is necessary (Figure 3f).

Once the strong box is placed in the centrifuge, the Perth sand is saturated again for the pushover test. Care is taken to ensure that the entire model is submerged by 5 mm of water at 1g. This ensures that the water level at the foundation is at the top edge of the terrain during the test (accounting for the curvature of the water during the centrifuge test).

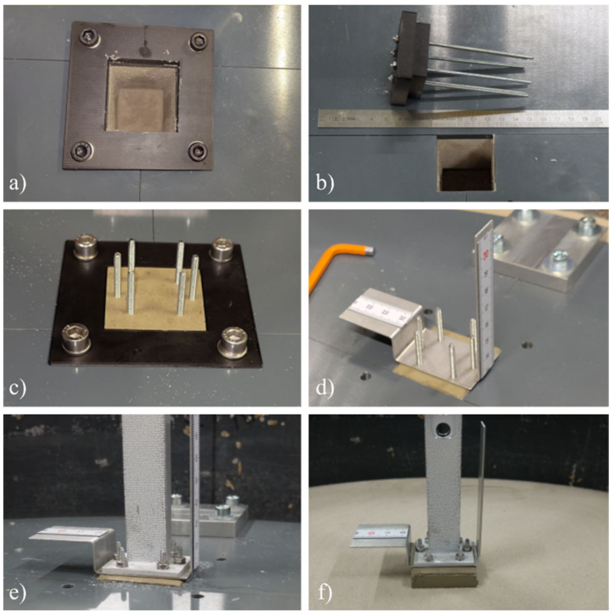

Figure 3. Production of the *BF*: (a) excavation; (b) template for positioning the threaded rods during the first concreting stage; (c) fully concreted foundation with additional 1 mm spacer; (d) laser targets mounted; (e) mast mounted; and (f) base plate removed – mast ready for pushover test.

After spinning up the centrifuge to the required *g*-Level (30g), the water level in the model is checked visually (using the cameras installed in the centrifuge basket) and with the aid of an installed PPT. Finally, the catenary mast is loaded horizontally in a displacement-controlled mode, with a velocity of 0.05 mm/s. Details of the experimental test setup regarding the support frame, the actuator with the load cell and guiding rollers can be found in Arnold et al. (2024). At the end of the test, the mast is unloaded before stopping the centrifuge.

4 PRELIMINARY TEST RESULTS

Indicative preliminary results of one of the tests are shown in Figure 4. The following points should be noted:

- The load *P* measured in the test is converted to prototype scale (Equation (4) and then normalised with respect to the load calculated according to Steckner, $P_{Steckner}$ = 23.4 kN (see Table 2).
- The experimental data is smoothened to remove the noise of the data acquisition system, accounting for the effects of friction of the loading frame and the changing eccentricity of the actuator during the test. The correction factor was determined using a test at 30*g*, in which the force was measured as a function of the displacement of the actuator (without the mast).

5 FIRST CONCLUSIONS

Based on these admittedly preliminary results, it may be concluded that the Steckner approach underestimates the load-bearing capacity of the *BF* by approx. 35 % for rotations greater then 10°, as shown in Figure 4. Of course, more test data are needed to obtain a more concrete result. Currently, the evaluation of such additional tests in saturated sand is underway. The latter includes the investigation of the position of the zero line and the foundation settlements throughout the tests. In the conducted centrifuge model test, the foundation did not experience any significant settlement or heave, but this remains to be confirmed for different configurations.

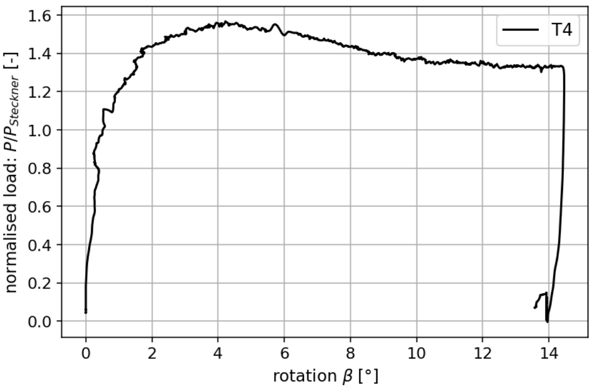

Figure 4. Normalised centrifuge test result.

It is also interesting to note that the foundation starts exhibiting a “softening” response at a rotation of 5 to 10 degrees. Additional tests are needed to derive insights on the factors affecting such softening response. The deformations of the lower mast area were recorded by a digital image correlation *(DIC)* and will be analysed and compared to laser measurements. This may also reveal the shape of plausible failure mechanisms in the soil, which may help us understand the importance of the failure mechanism for realistic ULS calculations.

In addition, the test setup will be adapted in order to allow conducting the tests in smaller diameter containers, which can be crucial for the later planned clay samples.

6 ACKNOWLEDGEMENTS

The authors are most grateful for the financial support provided by “Allianz Fahrweg”, the Swiss Federal Office of Transport (*FOT*) and the Swiss Public Transport Association (*VOEV*). The authors would also like to acknowledge the contribution of Markus Iten, Jürg Giger, and Sandro Barbieri for their support and suggestions for the conducted centrifuge experiments.

7 REFERENCES

Arnold, A. 2011. *Tragverhalten von nicht starren Flachfundationen unter Berücksichtigung der lokalen Steifigkeitsverhältnisse*. Doctoral Thesis, Zürich: ETH Library.

Arnold, A., Herzog, R., Portmann, G. & Anastasopoulos, I. 2024. Block foundations for railway infrastructure – First centrifuge model tests. *Proc. of the 5th European Conference on Physical Modelling in Geotechnics*, Delft.

Buchheister, J. 2009. *Verflüssigungspotenzial von reinem und siltigem Sand unter multiaxialer Belastung.* Doctoral Thesis, Zürich: ETH Library.

Jaky, J. 1944. Coefficient of Earth Pressure at Rest. *Journal of the Society of Hungarian Architects and Engineering.* 78(22), 335-358.

Lang, H.-J., Huder, J., Amann, P., & Puzrin, A. M. 2011. *Bodenmechanik und Grundbau: Das Verhalten von Böden und Fels und die wichtigsten grundbaulichen Konzepte*. 9th Edition. Berlin: Springer.

Madabhushi, G. 2014. *Centrifuge modelling for civil engineers*. Boca Raton: Taylor & Francis.

Nater, P. 2006. *Belastungs- und Verformungsverhalten von geschichteten Bodensystemen unter starren Kreisfundationen*. Doctoral Thesis, Zürich: ETH Library.

Steckner, S. 1989. Gebrauchstauglichkeits- und Standsicherheitsnachweis für eingespannte Blockfundamente. *Bautechnik,* 66 (H.2), 55-62

Sulzberger, G. (1945). Die Fundamente der Freileitungstragwerke und ihre Berechnung. *Schweizerischer Elektrotechnischer Verein – Bulletin,* 10, 289-308.

Weißenbach, A. 1962. Der Erdwiderstand von schmalen Druckflächen. *Bautechnik,* 37 (H.6), 204-211.