Loading behaviour of flexible raft foundations in full scale and centrifuge models

Comportement de radiers flexibles dans des essais grandeur nature et en centrifugeuse

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ABSTRACT: Flexible rafts are commonly used foundation systems for different kinds of constructions. A raft is easy to build and to design even though the dimensioning is not straight forward. Two buildings were equipped to measure the stress distribution between raft foundations and the adjacent soil, and to measure the deformation of the load-carrying column on top of the foundation in order to know the load extent. To compare the full scale measurements with another model, centrifuge tests have been conducted in a drum centrifuge at ETH Zurich. The loading behaviour of different raft foundations has been studied on these two models. This contribution gives a short summary of the comparison between the measurements gained from full scale and the model tests in the centrifuge. The conditions in the centrifuge provide an ideal stress distribution between raft and soil, while different influences on a raft foundation in full scale such as the geometry of the load bringing structure and loading sequences influence the stress distribution in the real world.

RÉSUMÉ : Les fondations flexibles sur radier sont un système de fondations utilisé communément pour différents types de construction. Un radier est facile à construire et à dimensionner, même si le dimensionnement n'est pas immédiat. Deux bâtiments ont été instrumentés pour mesurer la distribution des contraintes entre les fondations sur radier et le sol adjacent ainsi que les déformations de la colonne porteuse située sur la fondation afin de connaitre l'importance de la charge. Des essais en centrifugeuse ont été réalisés dans la centrifugeuse tambour à l'ETH Zürich afin de comparer les mesures grandeur nature à un autre modèle. Le comportement sous charge de différentes fondations sur radier a été étudié pour ces deux modèles. Cette contribution donne un court résumé de la comparaison entre les mesures obtenues grâce aux essais grandeur nature et aux essais dans la centrifugeuse: les conditions dans la centrifugeuse fournissent une distribution des contraintes idéale entre le radier et le sol, alors que les différentes influences sur une fondation sur radier, telles que la géométrie de la structure transmettant la charge et les séquences de chargement ont un effet sur la distribution des contrainte dans une situation grandeur nature.

KEYWORDS: raft foundations, loading behaviour, system-stiffness, centrifuge tests, full scale measurements

1 INTRODUCTION

Raft foundations are frequently used systems to distribute loads of different structures into the ground. They are cheap and fast in construction using simple design assumptions. They provide a robust system which is not sensitive in terms of settlements – especially for overconsolidated clays and coarse grained soils. One may use piled foundations for normally consolidated fine grained soils to avoid unacceptable settlements.

Even though raft foundations are easy to build, the dimensioning of such structures is not straight forward and partially to simplistic. The analytical approaches most commonly used base on equilibrium and linear-elastic behaviour of soils, which usually provides only an ideal shape of the stress distribution acting on a foundation.

The stress distribution between raft and soil has therefore been studied in model tests and in full scale to improve the analytical approach by means of investigating the changing stress distribution due to stiffness variation in soil and structure.

1.1 *Analytical models*

A short summary of the different analytical models is given here. The simplest model to obtain a stress distribution between foundation and soil is to focus purely on the vertical- and on the momentum equilibrium of force. The approach given in figure 1 does not care about the deformation, which must be identical on the foundation plate as well as in the soil. Since the deformation of the foundation system is not regarded, changes in soil- and structure stiffness are neglected with this method. Thus, those models provide only a preliminary distribution of the stresses.

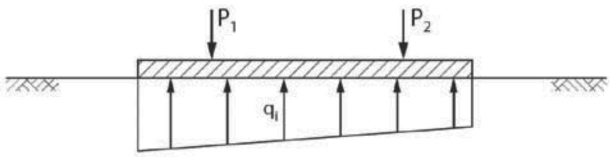

Figure 1: Stress distribution between foundation and soil fulfilling the vertical- and momentum equilibrium (Kany and El Gendy 1996).

Another method deals with a coefficient of subgrade reaction, based on the approach after Winkler (1867) and Zimmermann (1888). As given in figure 2 each spring is independent of the other springs, which results in an unrealistic distribution of settlements especially at the corners of the foundation.

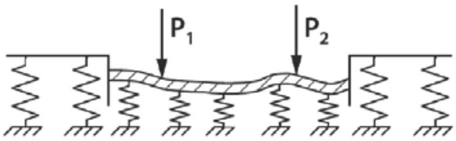

Figure 2: Independent springs on the approach of coefficient of subgrade reaction (Kany and El Gendy 1996).

A third approach is based on the linear-elastic behaviour of soils after Boussinesq (1885) which has been developed to an approach for practical purposes by Kany (1974). This approach provides realistic settlements also at the edges of foundations. But it is not able to describe more complex soil behaviour such as hardening or softening (Muir Wood 1990).

1.2 *System-stiffness after DIN-code*

The DIN-code 4018 (1981) defines a system-stiffness (eq.1), which allows distinguishing between flexible and stiff behaviour of the foundation system.

$$K_s = 1/12 \cdot E_b/E_s \cdot (d/L)^3 \quad (1)$$

K_s: System stiffness [-]
E_b: Stiffness of the foundation structure [N/m^2]
E_s: Stiffness of the soil [N/m^2]
d: Foundation thickness [m]
L: Foundation length [m]

The behaviour of the foundation is distinguished (Meyerhof, 1979) depending on the value of K_s with $K_s = 0$ representing flexible, $0.001 < K_s < 0.01$semi-flexible, $0.01 < K_s < 0.1$semi-stiff and $K_s > 0.1$ stiff behaviour. This allows choosing the stress distribution for design depending on the calculated behaviour (e.g. Leussink et al. 1966).

2 CENTRIFUGE MODELLING

Details about the centrifuge modelling can be found in Schofield (1980) and Laue (2002). The centrifuge tests, which are presented in this contribution, have been conducted in the drum centrifuge at ETH Zurich (Springman et al. 2001). Detailed information about the whole centrifuge test program can be found in Arnold (2012).

2.1 *Centrifuge test on a flexible raft foundation*

80 Centrifuge tests were conducted for studying the loading behaviour of flexible raft foundations (Arnold 2012). The stress distribution between raft and soil was measured with tactile pressure pads (Springman et al. 2002). The test setup is given in figure 3 and 4.

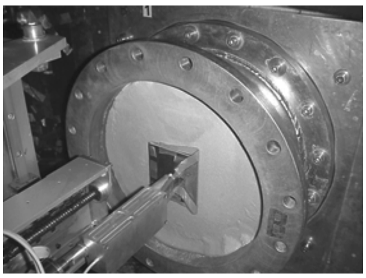

Figure 3: Setup of the centrifuge test (Laue and Arnold 2008).

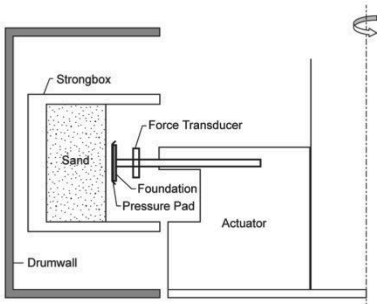

Figure 4: Scheme of the test setup in the drum centrifuge (Laue and Arnold 2008).

The loading of these tests was conducted on a 4 mm thick square aluminium plate as foundation with a side length of 11.2 cm under an enhanced g-level of 50. The model foundation represents a prototype foundation with a side length of 5.6 m and a thickness of 20 cm. Figure 5 shows the measured stress distribution for a load of 4.25 kN (equivalent to a prototype load of 10625 kN) and a settlement of 5 mm (equivalent to a settlement of 250 mm at prototype scale). The white areas show the highest pressure, black areas show no pressure. For these conditions, a flexible behaviour can be observed with maximum stresses distributed near to the column.

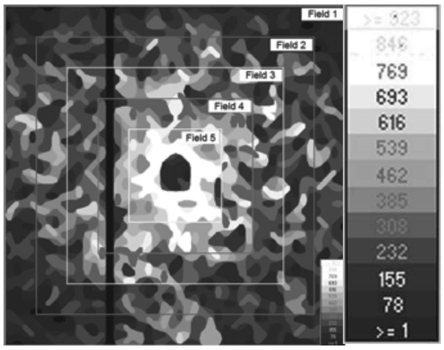

Figure 5: Left hand side: Stress distribution under a 4 mm thick aluminium plate at 50g (Arnold and Laue 2009); right hand side: Resolution of the tekscan measurements given in kPa (Arnold and Laue 2009).

2.2 *Centrifuge test on a stiffened raft foundation (4 unloaded walls)*

Figure 6 shows the stress distribution under a foundation stiffened by four unloaded walls. The stiffened foundation has also a thickness of 4 mm but behaves stiffer as four unloaded walls are placed on top of all sides. Details on this test can be found in Arnold and Laue (2009).

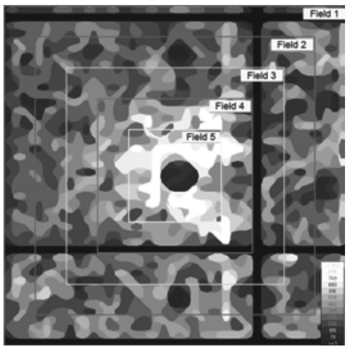

Figure 6: Stress distribution under a 4 mm thick aluminium plate stiffened with 4 unloaded walls situated on the four edges of the foundation. Test conducted at 50g. Protoype load: 10925 kN. Prototype settlement: Approx. 220 mm (Arnold and Laue 2009). The resolution is equivalent to Figure 5.

The stiffer stress distribution can be seen in Figure 6. Less clear peak pressure is situated in the area of the load-bringing column and the distribution is more uniform over the whole area of the foundation slab.

3 FULL SCALE MEASUREMENTS

Detailed information about the full scale measurements is given in Arnold and Laue (2010) and Arnold (2012). Two different buildings were equipped with oil filled pressure plates manufactured by Gloetzl (Schmidt 1991) to gain some information about the load extent on the raft and the stress distribution between raft and adjacent soil. One building is situated in central Switzerland (Alpnach) and the other one in the northern part of Switzerland (Merenschwand). Two foundations of a supporting girder (4 storey-building) were controlled in Alpnach. In Merenschwand two foundations of an earth-fill supporting roof were measured.

3.1 *Measurement equipment*

The measurement equipment consisted of pressure pads which are able to measure the pressure at a reduced area, of strain gage devices and of displacement transducers to measure the deformation of the load bringing columns. Additional geodetic measurement provided information of the settlements. One of the pressure pad used in Alpnach is shown in figure 7.

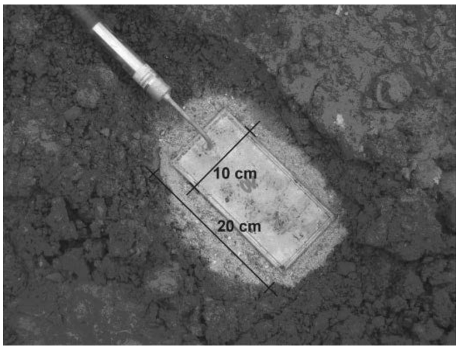

Figure 7: Pressure pad embedded in a layer of fine sand (Arnold and Laue 2010).

4 MEASURING CAMPAIGN IN ALPNACH

The arrangement of the measurement system at the location in Alpnach is given in figure 8. The darker shaded areas in the middle of the foundation indicate the columns (cross-section area: 1.0 m · 0.30 m).

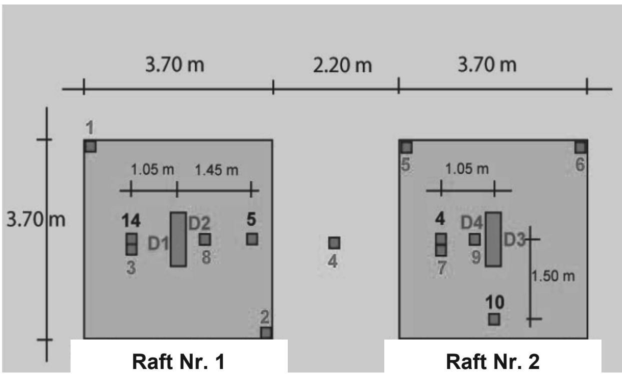

Figure 8: Sketch of the measurement systems in Alpnach: D1 – D4 are strain gages to measure the deformations of the columns. Numbers 4, 5, 10, 14 correlates to the pressure pads under the rafts. Numbers 3, 7, 8, 9 at the center part of the rafts and 1, 2, 5, 6 on the foundation edges indicate geodetic measurement points (Arnold 2012).

4.1 *Results*

The measurements of the pressure pads in Alpnach are given in figure 9.

The measurements in Alpnach show the high dependency of the static system on the development of pressures under a foundation. Higher stresses are measured with the pressure pads 4 and 5, which are positioned at locations towards the inward field between the two foundations while values measured with the other two pads remain smaller. This can be explained using the measured the strains on both sides of the column (Figure 10). Both columns show bending towards the middle field by higher compression on strain gauges 2 and 4 while strain gauges 1 and 3 show even tension at lower rates of loads.

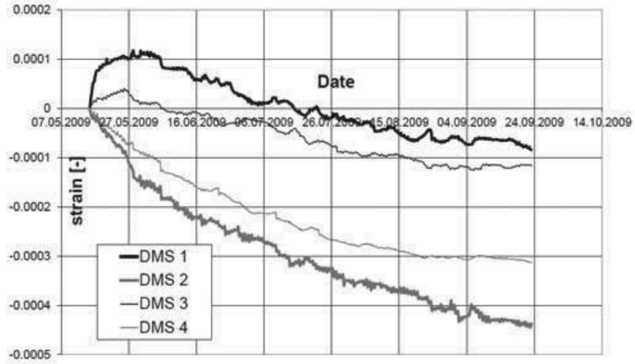

Figure 9: Measurements of the pressure pads 4, 5, 10 and 14 at Alpnach (Arnold, 2012).

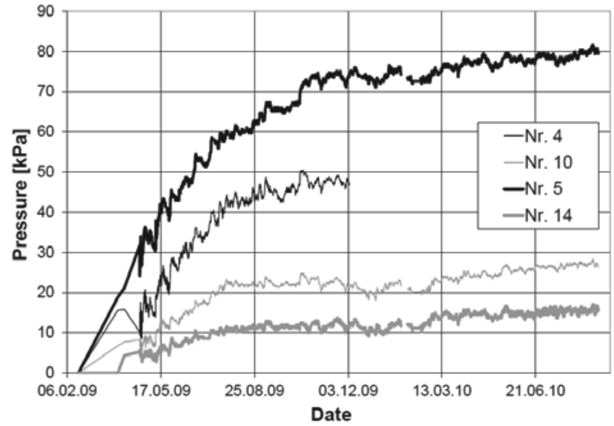

Figure 10: Measurements of the strains in the two investigated columns at Alpnach (Arnold, 2012).

5 MEASURING CAMPAIGN IN MERENSCHWAND

The arrangement and the dimensions of the campaign in Merenschwand are given in Figure 11 while results of the measurements with the pressure pads are shown in Figure 12.

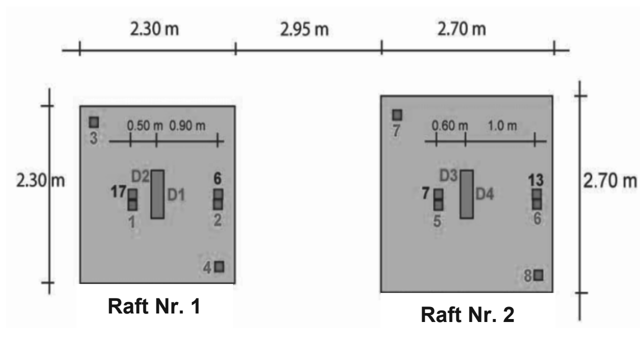

Figure 11: Sketch of the measurement systems in Merenschwand: D1 – D4: Displacement transducers to measure the deformations of the columns; 6 & 17 at Raft Nr. 1 and 7 & 13 at Raft Nr. 2: Pressure pads to measure the pressure between foundation and soil; 1 – 4 at Raft Nr. 1 and 5 – 8 (7 at foundation edge) at Raft Nr. 2: geodetic measurement points (Arnold 2012).

Higher loads are introduced into the ground under raft 2 than under raft 1. Even though the strain measurements in the column showed small bending of the columns, the stress distributions anticipates a more expected behaviour here. Higher loads are distributed near the columns (Pads 7 and 17) while lower stresses are distributed in the outer areas. The measurements under these foundations with a thickness of 0.40 m (raft 1) respectively 0.50 m (raft 2) indicate a flexible behaviour of this particular footing.

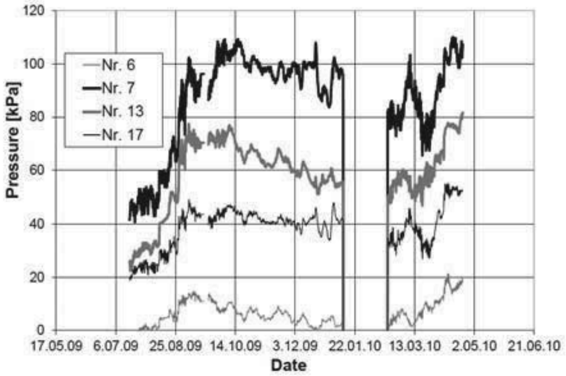

Figure 12: Measurements of the pressure pads 6, 7, 13 and 17 at Merenschwand (Arnold, 2012).

6 COMPARISON OF THE RESULTS

There is a clear difference between the two measured foundation systems (Alpnach & Merenschwand) concerning the stress distribution between foundation and adjacent soil. The bending moment in the girder originating from the loads of the 4 storey building is dominating the stress distribution at the building in Alpnach. It is passed from the supporting girder to the column and further down to the foundation. This bending moment can be verified by the measurements of the strain gages and allow the construction process to be followed. The moment clearly dominates the stress distribution while a stiff behaviour can be noticed.

Little bending moment is passed from the earth-fill supporting roof to the foundation at the building in Merenschwand. Therefore the stress distribution here can be more easily compared to the ideal situation assumed with some of the simplified models and the results of the centrifuge model tests. A flexible behaviour (as expected by the definition of DIN 4018) can be identified.

7 CONCLUSION

The full scale measurements show a clear influence of the loading situation to the stress distribution between raft and adjacent soil. Bending moments are passed from roofs via columns and walls to the foundations where they influence the soil-structure interaction by changing the stress distribution between structure and adjacent soil. The so found influence of the loading situation to the stress distribution could not be shown in the centrifuge tests where the ideal test conditions without bending moments have been studied. The system-stiffness equation is only valid for this type of “ideal” loading situations, where bending moments in the structure do not play a significant role. Bending moments among other parameters like e.g. inhomogeneous design of a foundation do influence this stress distribution. Thus a single value of system stiffness for the whole foundation can be misleading as the stress dependency of the modulus of the ground is not taken into account but will have for rafts an influence on the design. This opens a new field for future research, where the interaction of the whole building-structure with the soil should be investigated.

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