Influence of unloaded walls on the stress distribution under a raft foundation

Influence de parois non chargées sur la répartition des pressions sous un radier de fondation

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ABSTRACT

For the calculation of flexible rafts, the rising structure is often not taken into account on the design with the exception of the load transfer location. Mostly, a uniform stress distribution is assumed below a footing, even though this is only valid if the footing is totally flexible and is able to follow the movement of the soil at every point. The assumption of flexibility is dependent on load and stiffness of the footing while already both, the flexible raft made of concrete as well as the structure itself are influencing the stiffness of a raft. Local stiffening of the foundation, e.g. by locally increased thickness of the raft or flexural rigid connected walls, is not taken into account in the design approach. In this contribution centrifuge model tests are carried out for different raft systems to explore the development of the stress distribution under a flexible raft foundation. Focus is given to identify the influence of the stiffening effects of outside walls for structures mostly loaded via middle columns.

RÉSUMÉ

Souvent on ne tient pas compte de la structure sus-jacente dans les calculs des radiers flexibles à l'exception de l'emplacement du transfert des forces. La plupart du temps, on admet une répartition uniforme de la pression sous la fondation même si ceci n'est valable que dans le cas d'une fondation parfaitement flexible capable de suivre le mouvement du sol en chaque point. En fait les deux, le radier béton et aussi la structure elle-même, donnent des rigidités différentes à la fondation de telle façon que l'hypothèse de la flexibilité est dépendante de la charge et de la rigidité de la fondation. De plus, le renforcement local de la fondation n'est pas pris en compte durant la conception. Dans cette contribution, on présente des essais à l'échelle en centrifuge de différents systèmes de radier pour étudier le développement de la répartition des pressions sous un radier souple. L'accent est mis sur l'influence des effets de renforcement dus aux parois extérieures des structures chargées principalement par l'intermédiaire de colonnes centrales.

Keywords : Centrifuge modelling, raft foundations, soil structure interaction, flexible rafts

1 INTRODUCTION

In past times it was common to construct buildings founded on strip foundations under the walls. The resulting cellars did either not include any floor or a floated sealing was used and provided mainly storage rooms especially for groceries. In opposite, most houses are built nowadays on continuous raft foundations, which are integrated by reinforcement into the structure of the building to use cellars for living space, office or workshops or as car parks. Concerning the calculation method most raft foundations are calculated similar to the former strip footings using the concept of allowable bearing pressures without taking the load depending stiffness of the soil and differential stiffness of the raft into account. For example, Laue & Arnold (2008) showed clearly the differences of stress distribution in the raft between two load carrying walls using classical calculation methods based on Winkler's (1867) approach and further developed by e.g. Kany (1974) and a physical model. These preliminary investigations showed clearly the non uniformity of the stress distribution and even differences in the prefix for the resulting stresses in critical cases.

In the frame of this contribution, focus is given on the effect of unloaded side walls, which increase the side stiffness of a raft while the main portion of the load is introduced via a central column. Physical model tests have been carried out in the drum centrifuge of the Institute for Geotechnical Engineering at ETH Zurich (Springman et al. 2001). The stress distribution is measured using flexible pressure pads (e.g. Laue 2002), which allow direct comparison with results gained from numerical modelling (com. Laue & Arnold 2008, Arnold & Laue 2009). These measurements are supported by strain gauge measurements to identify the deformation of the raft.

2 ANALYTICAL MODEL

Common approaches for the calculation of the stress distribution between a foundation and the soil below are for example summarized by Smoltczyk (2001). The methods shown are based on some variation of Winkler's (1867) spring approach. The most sophisticated methods incorporating not only locally attached vertical springs but connecting the effects of local deformation via influence lines are developed from Kany (1974). In the framework of this type of models, the stiffness of the foundation is taken into account by an equivalent system stiffness (after DIN 4018 1981, Equation 1).

$$K_s = 1/12 \cdot E_b/E_S \cdot (d/l)^3 \qquad (1)$$

With:

- K_s = System Stiffness
- E_b = Young's modulus of the raft foundation
- E_S = Stiffness modulus of the soil
- d = height of the raft foundation
- l = length of the raft foundation

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Even though Netzel (2002) studied some of the aspects to incorporate the structural stiffness into the calculation by developing equations for upgrading the homogeneous stiffness of the raft, the incorporation of different stiffness' occurring from walls, columns or even only deeper founded areas in one raft is rarely possible with this solution. Nevertheless, these methods are based on the concept of elasticity as non linear springs can be incorporated in the calculation.

3 CENTRIFUGE MODELLING

The physical modelling took place in the drum centrifuge at the Institute for Geotechnical Engineering at ETH Zurich (e.g. Springman et al. 2001, Laue et al. 2002). Model foundations are connected to an actuator and loaded on soil model in a circular container. The used soil is a fine grain sand used already in previous studies (e.g. Nater 2006). The specific boundary conditions for the tests reported here are given in table 1 and figure 1 (compare also Laue & Arnold 2008).

Table 1. Test specific soil parameters of the used fine grained sand

Indication	Symbol	Unit	Value
water content	w	[%]	18.9
dry density	γ_d	[kN/m^3]	17
spec. weight	γ_s	[kN/m^3]	26
porosity	n	[-]	0.3
pore value	e	[-]	0.5
saturation level	S_r	[-]	0.9
rel. density	D_d	[-]	0.69

Three different types of idealised structures on a flexible raft are considered. The raft is made of Aluminium with a thickness of 4 mm and a width of 11.2 x 11.2 cm in model scale. Conducting the experimental work at 50 times gravity, this equivalents to applying the scaling relationships e.g. by Schofield (1980) to a 26.5 cm thick concrete plate with a size of 5.6 x 5.6 m. Loading is provided in all tests via a single column located in the centre of the foundation and has been applied with a constant velocity of 0.01 mm/s in model scale. The idealised structures include a plain raft (Fig. 2), a raft with two flexural rigid walls opposite to each other and a raft with four unloaded side walls. The walls will change the stiffness of the raft (Fig. 3).
All tests were run on sand models with well repeatable boundary conditions (Table 1, Fig. 1).

The stress distribution has been recorded via tactile pressure pads (Springman et al. 2002, Tekscan 2007). A result for the three types of rafts is given in Figs. 4-7. The load applied by the single column is equal to about 11000 kN in prototype scale. In comparing the measured "footprints" of the stresses the influence of the increasing stiffness caused by the walls gets visible. The stress distribution changes slightly from concentrated stresses in the centre of the foundation for the single column towards a more uniform stress distribution for the tests with the unloaded walls.

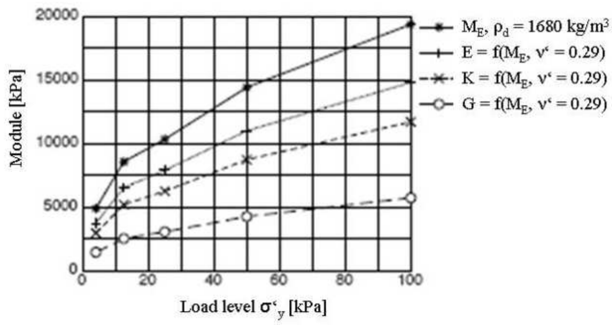

Figure 1. Soil stiffness M_E on different load levels (Nater, 2006)

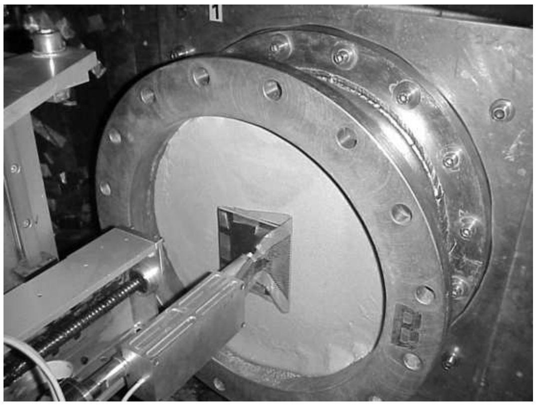

Figure 2. Model-raft with single column (Laue & Arnold, 2008).

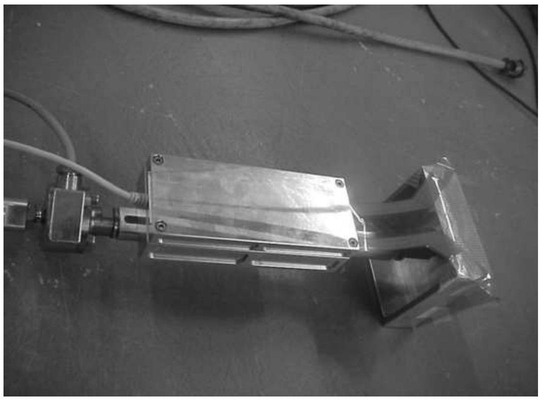

Figure 3. Model-raft with four unloaded walls, loadcell, Tekscan-device.

Due to the increase in stiffness, the load is transferred away from the centre more towards the edges, which results in a more uniform stress distribution. A further evaluation of the footprint measurement is given in the figures 8-9. The raft has been subdivided into different fields as indicated in the Figures 4-6. The integrated stiffness of these fields is plotted against the time equivalent to the induced settlement under the column. Again it can be noticed that the load transfer for the pure raft is concentrated in the centre with a minimum stress at the edges. For the raft with four unloaded walls, the outer fields (with the exception of field 1 and 2) show an almost constant distribution in the phase of increasing the load. In the unloading phase (with stiffer subsoil due to the loading phase and without the effects of localised stress distribution at beginning of contact) the change from flexible to stiff behaviour is clearly visible at a stress of approximately 300 kPa. In the unloading phase of the single loaded column even an increase at the sides can be observed as the deformation of the foundation played a major role in the stress distribution.

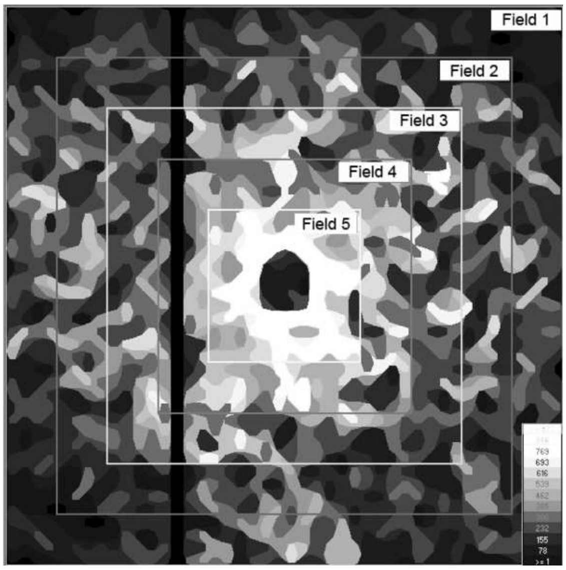

Figure 4. Single column at 4.25 kN (model scale).

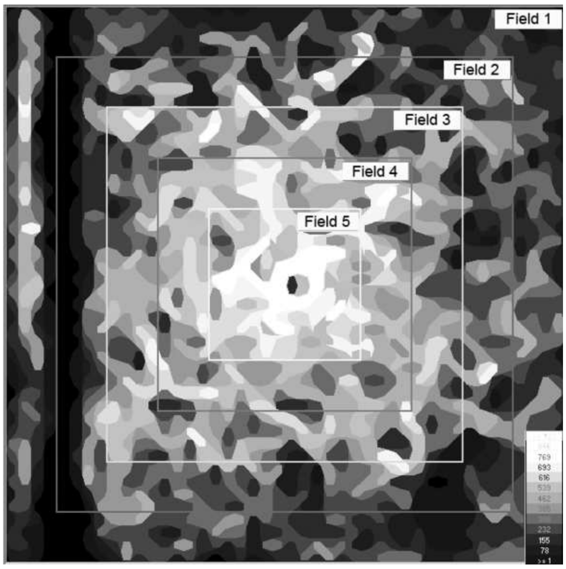

Figure 5. Two unloaded walls at 4.27 kN (model scale).

Additionally it can be noticed, that the deformation required to carry the maximum load (Fig. 8, 4.25 kN in model scale, maximum load reached after appr. 600s) was about 50% higher for the pure raft than for the raft with four walls (Fig. 9, foundation loaded up to 4.37 kN were the maximum planned load was reached after about 400s). This indicates that a raft with a single column will show higher settlements than a raft under a real structure.

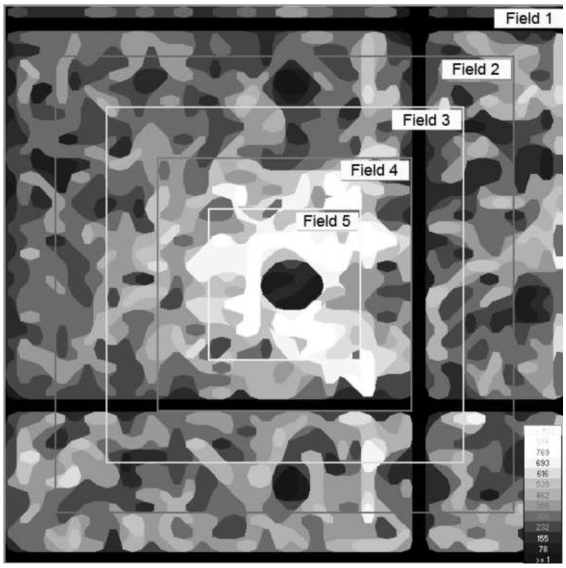

Figure 6. Four unloaded walls at 4.37 kN (model scale).

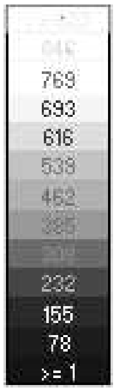

Figure 7. Resolution of the Tekscan pads. The units given are kPa.

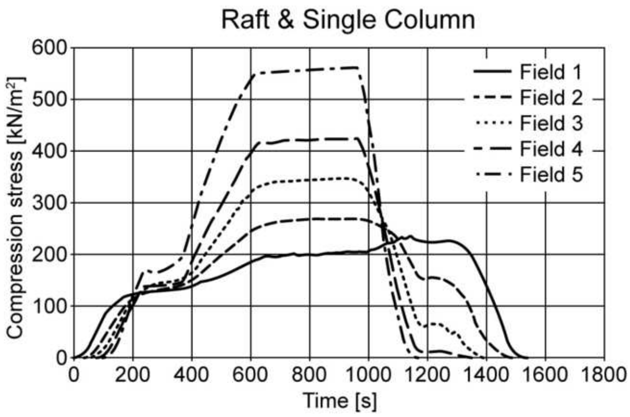

Figure 8. Stress distribution for the single column-test.

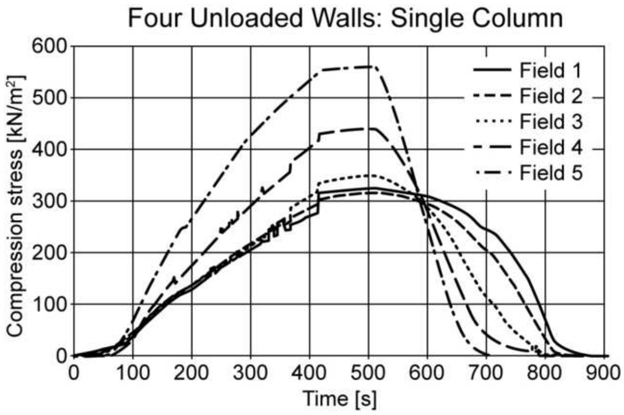

Figure 9. Stress distribution for the test with four unloaded walls.

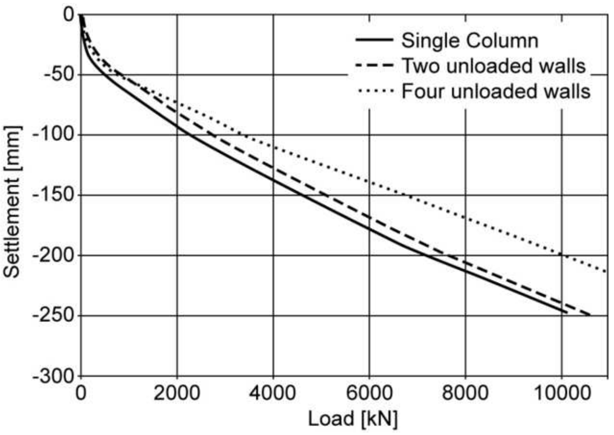

Figure 10. Load-Settlement-Behaviour for the three tests (prototype scale).

Larger settlements under a single column foundation without any stiffening members compared to the foundations with stiffening walls can directly be seen comparing the load-settlement-behaviour of the whole foundation, which is given in Fig. 10. The load is measured by an external force transducer and is equivalent to the integrated pressures measured via the tactile sensors (e.g. Fig. 5). The raft without stiffening members shows a settlement of approximately 250 mm for a load of 10MN. The raft with the two unloaded walls settles slightly less (240 mm). The foundation with the four unloaded walls shows the most stiff reaction. The settlements under the same load conditions were approximately 20% smaller. These results confirm the influence of structural members on the stiffness of the foundation. They also show that the influence is not insignificant. Thus they should be considered in the design approaches for raft foundations.

4 SUMMARY AND OUTLOOK

Foundations with and without flexural rigid side walls have been studied in physical model tests in the drum centrifuge of ETH Zurich. It could be shown that flexural rigid side walls can change the stress distribution under a raft foundation significantly. The stress distribution at the interface gets more uniform for rafts with unloaded walls for load ranges causing flexible behaviour. For lower stresses a more Boussinesq (1885) type of stress distribution can be observed. Structural members also influence the flexibility of the raft and reduce settlements under a given load. First numerical models showed some of the measured trends but great care has to be given on the way how structural elements can be modelled by the various numerical codes, and on the choice of an appropriate soil model.

Further studies with physical modelling supplemented by numerical analysis will focus on the influence of the stiffness of the raft itself as well as on various other structural members used as load transfer element or purely stiffening the system.

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