Settlements of shallow foundations subjected to combined static and repeated loadings

Tassement de fondations superficielles sous des événements de charges combinés, statiques et répétés

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ABSTRACT: The development of settlement of shallow foundations in cause of combined static and repeated loading is described for several different types of structures as there are tanks and silos, columns for crane runways, offshore structures and even every structure subjected to wind. These settlements can greatly exceed the initial settlement caused by the addition of static dead load and first loading. The estimation of settlements suffers in the planing phase of structures under unavailable measurements at the still existing buildings and on the necessarity of the idealised knowledge of settlement during the first cycles, which generally excludes any settlement during construction and previous state of use. To find a realistic method for the estimation of settlements, centrifuge model tests have been carried out on circular shallow foundations on sand under combined static and repeated loadings varying the depth of embedment and load histories. After an exemplary overview on existing methods and a short discussion on the reliability of the results and the presentation of the centrifuge model tests on circular shallow foundations, the method of estimation is presented in three steps, parted in the determination of settlements in cause of static and monotonic increasing loadings, in cause of repeated loadings and the description of the influence of preloads. Thus it is possible to offer a calculation method easy to handle to precalculate the settlements of shallow foundations for complete load histories.

RESUMÉ: Un tassement croissant de fondations superficielles, exposées à des événements de charges statiques et répétés, peut être déterminé sur différents ouvrages, par exemple sur des réservoirs et des silos, des support de grue et des ouvrages de forage ou également sur des ouvrages avec la charge du vent. Ces tassement peuvent dépasser les tassements résultant de la première charge un grand nombre de fois. Vu qu'aucune mesure existe à l'ouvrage établi, l'évaluation du tassement se révèle déjà difficile dans la phase de planification. Pour le tassement, les valeurs d'appui manquent aussi à cause des premières séries de charges. L'histoire de chargement ne peut pas non plus être considérée selon la méthode courante. Quand au développement d'une méthode de calcul réalisable pour la détermination du tassement, sous des événements de charges statiques et répétés, des essais ont été réalisés sur fondations circulaire sur sable avec des modéles centrifugeuse. Ces essais de centrifugeuse seront présentés aprés un court résumé des méthodes de calcul existantes et une brève discussion sur la transmissibilité des différents modèles de lois. La méthode de calcul sera présentée en trois parties. La première partie comprendra la détermination de tassement sous des charges statiques. La deuxieme partie traitera de la description du développement de tassement sous des charges répetés. La dernière partie comprendra la présentation d'une méthode avec laquelle il sera possible de contrôler l'influence de la précrompression. Avec cette méthode il sera possible de déternniner les tassements de fondations superficielles qui sont exposés aux événements de charges répétés, pour toute l'histoire de chargement.

1 INTRODUCTION

An increasing development of settlements caused by repeated loadings is described in several publications. Sweeney and Lambson (1991) show an increasing settlement of tanks and silos, mostly based on granular soils, in dependency on the number of cycles of filling and emptying. Due to preloads no large increasing or even in some cases a decreasing of the settlement is observed for small numbers of cycles (Fig.1). For higher number of cycles an increasing of settlements can be found in any case. Heller (1995) reported the development of settlements for columns of crane runways also layered in sand. Even the foundation is very stiff and of large dimensions an increase of settlement can be observed during several years. These settlements reach higher values than allowed for the state of serviceability, so that the structure has to be restorated.

For the estimation of these settlements several equations have been found by means of interpreting in situ measurements, 1g model tests and laboratory investigations. Methods gained from in situ measurements are still dependent on the knowledge of the settlement at a fixed time or even on the settlement on the first load phase (Burland & Burbridge 1985; Bjerrum 1964). These methods allow the determination of settlements of existing buildings. Solutions gained with 1g model tests on small scaled foundations. (e.g. Holzlöhner 1978; Hettler 1981) suffer under the scale effects which causes different bearing mechanism for small foundations. They are additionally related to the value of the settlement of the first load cycle, which can in realistic values only be evaluated by means of a test itself.

Cyclic triaxial or compression tests (eg. Güttler 1984; Brown

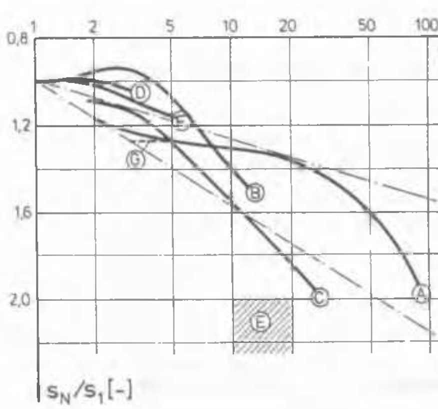

Figure 1. Development of settlements of tanks and silos (Sweeney & Lambson, 1991)

1996) lead to several methods of estimation of settlements. Using these results, as for example the determination of the stiffness which corresponds to the development of strains given by Thiel (1988) to determine the settlement of shallow foundations or even of a layer of soil, the settlement of the whole system will be underestimated. Methods based on laboratory tests generally reduce the settlement to a problem of densification. As to be seen further in this paper, the settlement under cyclic loadings is a combined problem of several kinds of resistance factors. The densification is overlayed by softening effects as for example described by Kysela & Firt (1974) in local shear areas and a geometrical changing of the bearing zone.

Based on centrifuge model tests and a related discussion on the scaling effects and bearing mechanisms, a calculation method can be presented with the possibility of an analytical estimation of the settlements caused by dead loads, a logarithmic approach for the increasing of settlements and a method to follow the whole load history for cyclic loaded structures including the evaluation of influences of pre- and overloads.

2 CENTRIFUGE MODEL TESTS

The centrifuge model test presented in this paper have been conducted in the geotechnical centrifuge Z1 at the Institute of Soil Mechanics and Foundation Engineering at the Ruhr-University Bochum. For the research on cyclic loaded structures special hydraulic actuators and a fast data acquisition is needed with the aim to research also the influence of the load frequency. The details of this systems are described in Laue et al. (1996). The basic scaling rules of centrifuge modeling for the test on the settlement behaviour of circular shallow foundations under cyclic loadings on dry sands are given in table 1.

All tests have been conducted with a fine grained sand (Bochum Standard Sand 942D) filled in the containers by pluviation to high density. The parameters of this sand can be found in table 2.

Table 1. Scaling law relationships

	prototype	centrifuge - model test (ng)
Length	1	1/n
Aerea	1	$1/n^2$
Stresses	1	1
Stiffness	1	1
Frequency	1	n
Acceleration	1	n

Table 2. Parameter of the Bochum Standard Sand 942

Density of grains ρ_s	2,66	t/m³
Minimal density ρ_{min}	1,41	t/m³
Maximal density ρ_{max}	1,70	t/m³
Minimal pore ratio e_{min}	0,89	-
Maximal pore ratio e_{max}	0,56	-
Angle of friction φ	38	°
Mean diameter of grains d_{50}	0,23	mm
Grading parameter U	2,08	-

Figure 2 shows a principle scheme of the test set-up. A model foundation of constant diameter of d_M = 5,6 cm representing with the chosen level of acceleration of n = 30 a prototype diameter of d_P = 1,68 m, has been placed on top of the sand layer. The depth of embedment is varied between t_P =0, 0.6 and 1.68 m. The index M represents model, the index P prototype scale. The foundation is loaded by a hydraulic jack placed on a beam on top of the container. The settlement of the foundation is observed using the internal LVDT of the hydraulic jack. A force transducer, placed between the rot of the hydraulic jack and the foundation, controls the load history and the load function which is given by a function generator. Further measurements have been taken in the half space in the surrounding of the foundation. LVDT's in vertical and radial direction or even in faster tests acceleration transducers are placed at defined locations in the half space (Figure 3). With this it is possible to indicate the influenced zones in the halfspace and the bearing mechanism which is caused by static and repeated loadings.

The loading consist of a static dead load varied in dependency of the relation dead load V vers theoretical rupture load V_R overlayed by a cyclic sinusoidal loading varied in the relation of amplitude V' vers dead load V. The sinusoidal loading is applied in periods of thousand cycles. The measurements during the cyclic load periods is taken at specified times with increasing gaps for increasing numbers of cycles. Some of the foundations have been loaded after the first period with an increased amplitude. In some tests preloadings of a larger amplitude than the normal loading are applied. At least six foundations can be researched in one container

3. SCALING LAW RELATIONSHIPS

The settlement of shallow foundation is one of the most studied

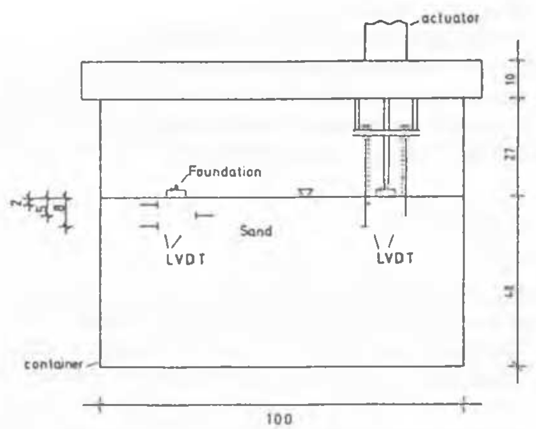

Figure 2. Test set-up

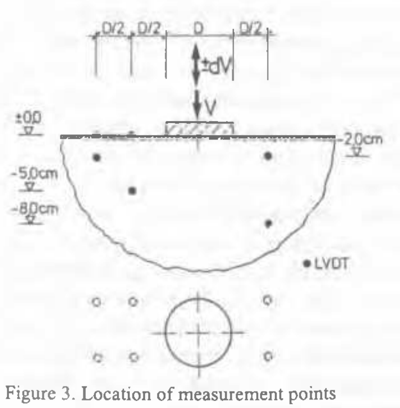

Figure 3. Location of measurement points

basic problems in soil mechanics and dynamics. It has been treated with different kind of test methods previously. Ovesen (1979) discusses the comparability of simulations with full scale, 1g and ng (centrifuge) model tests.

For a better understanding of the necessary interpretations and of the comparison between still existing results with the new findings this discussion has to be continued. Also some further points of view have to be regarded.

3.1 Angle of friction

One of the dimensionless theorems presented by Ovesen, the transferability of the angle of friction has to be regarded carefully. The value of the friction angle is strongly dependent on the actual stress level. The decreasing of the value of friction with an increasing stress level is known since a long time (de Beer, 1965). In the interpretation of 1 g model tests, a "one to one" comparison of the angle of friction leads to an overestimation of friction and by this to an overestimation of bearing capacity.

3.2 Scale effects of grain size

Ovesens theorem d_{50}/d, the comparison between parameters describing the graduation curve and the diameter of the foundation, needs further discussion. Ovesen stated that there is a non-equal simulation of the sand in centrifuge and 1g model tests. The use of fine grained sand in centrifuge modeling results, using the scaling rules given in table 1, in a simulation of a wider grained sand multiplying the radius of the grain with the chosen value of acceleration. Thus a wider grained sand is the prototype to be modeled.

3.3 Scale effect of the structures

Correlating 1g model tests with the prototype scale also the bearing mechanism have to be regarded while proofing the reliability of the results. As already shown by findings of Kögler & Scheidig (1948), the settlement for very small foundations decreases for constant loads with increasing diameter up to a critical diameter (Figure 4). A further increasing of diameter increases additionally the settlements. Due to different bearing mechanism, a direct transferring of 1g model tests to the prototype scale is not allowable. Again an overestimating of the influence of friction as one part of the total resistance against settlements will be resulting.

4 SETTLEMENTS IN CAUSE OF STATIC AND MONOTONIC INCREASING LOADINGS

To evaluate the settlements caused by static and monotonic increasing loadings and to compare the boundary conditions in each container at least one bearing capacity test has been conducted in every container for each depth of embedment. Comparing this results with classical assumptions of evaluating the settlement for the state of serviceability and for the rupture load in limit conditions it has been sightable that the measured load settlement curve in most cases does not fit for a wide range of loads. Only for very small loads comparable values of the settlements can be evaluated by classical methods. An ideal rupture load has not been found in any tests due to progressive failure effects.

As already shown in chapter 1 it is necessary to find a method to estimate a realistic value for the settlement due to dead load and initial loading. Drawing the measured curve (Fig. 5a in principle) in a hyperbolic diagram s vers s/q (following Pietsch 1982) a linear relationship can be found. This relationship can be

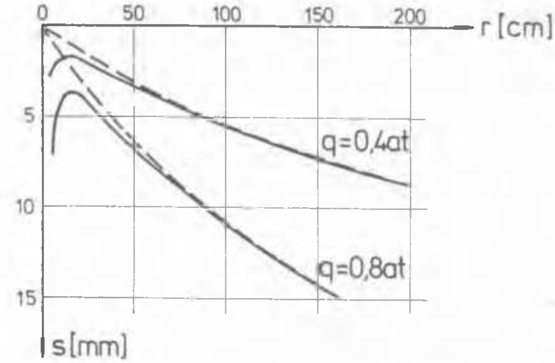

Figure 4. Settlement of circular foundations at constant loads in dependency of the diameter (after Kögler & Scheidig, 1948)

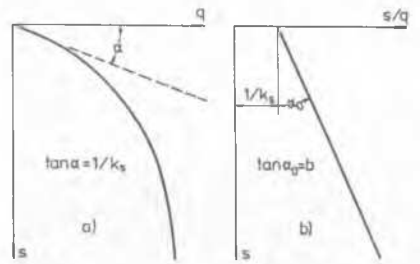

Figure 5. Load settlement curve in s-q and s-s/q plane

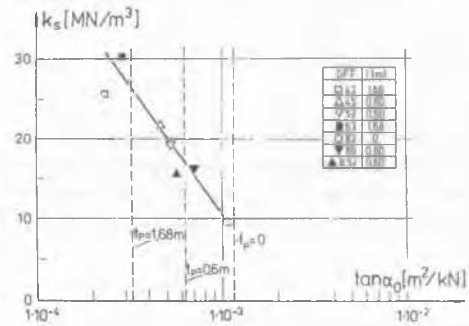

Figure 6. Stiffness coefficient k_s and factor for rupture load $1/\tan\alpha_0$ evaluated from the test results.

described using two initial values:

Using this assumptions, the settlement due to the static dead load can be described with equation 1. The value k_s represents the initial stiffness of the system, $\tan\alpha_0$ represents the reziproce of the theoretical rupture load.

$$s = \frac{\frac{1}{k_s}}{\frac{1}{q} - \tan\alpha_0} \qquad (1)$$

Interpreting the test results on circular shallow foundations for the variation of depth of embedment a linear dependency between stiffness and rupture load $1/\tan\alpha_0$ is found. This relationship is shown in figure 6. The variations in the results of the tests belong mainly to small variations in density.

Comparing the theoretical values of the rupture load (e.g. following DIN 4014) with the measured $\tan\alpha_0$, the rupture load is underestimated with values between 25% for surface foundations and 45% for foundations with a depth of embedment of 1.68m. Also the influence of the depth of embedment on the initial stiffness is underestimated. Following Gazetas (1983), the stiffness coefficient for circular shallow foundations can be

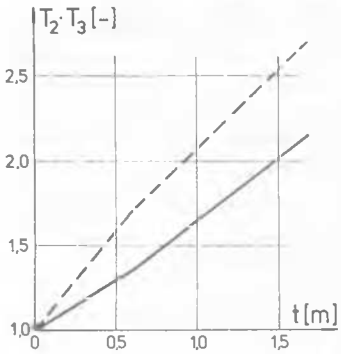

Figure 7. Comparison of theoretical (full line) and measured (dotted line) increasing factors on the stiffness coefficient for the influence of depth of embedment

estimated using equation 2.

$$k_s = \frac{4 \cdot G \cdot r}{1 - \nu} \cdot T_1 \cdot T_2 \cdot T_3 \qquad (2)$$

The additional terms T1, T2 and T3 regard the relation between height of the elastic layer, diameter of the foundation and depth of embedment. For constant diameter and height of the elastic layer the relation of the increase of stiffness can be compared between theory (eq.3) and measured values. The results of this comparison is given in Fig. 7.

$$T_2 \cdot T_3 = (1 + 0.5\frac{2 \cdot t}{d}) \cdot (1 + (0.85 - 0.28\frac{2 \cdot t}{r}) \cdot \frac{t/h}{1 - t/h} \qquad (3)$$

Using equation 1 the settlement caused by static dead loads can be described realistically especially for circular shallow foundations on dense sand. For other geometry's the theoretical values of stiffness coefficient and rupture load can be used for first assumptions.

5 SETTLEMENTS CAUSED BY REPEATED LOADINGS

As the load frequency has less influence on the value of settlement up to a load frequency of $f_P = 2$ Hz. in prototype scale, the initial settlement can be evaluated with the same method used for the evaluation of settlements under static loads. Thus the increasing of settlements can be described independent of the first load cycle. The description of the settlements caused by repeated loadings reduces to a determination of the increasing settlements.

Regarding the development of settlement in a natural logarithmic time scale, the settlements for further load cycles s_N can be described with equation 4 for N > 1.

$$s_N = b \cdot \ln N \qquad (4)$$

The increasing parameter b has been found between b = 0.003 for a depth of embedment of t_P = 1.68m for load ratios V/V_R = 0.33 and V'/V = 0.2 and b = 0.06 for a surface foundation with V/V_R = 0.5 and V'/V = 0.8. Further values for the increasing parameter b are given in Laue (1996).

6. INFLUENCE OF PRELOADS ON THE DEVELOPMENT OF SETTLEMENT

The influence of preloadings on the development of settlements is obvious. For a small number of cycles, preloadings can reduce or

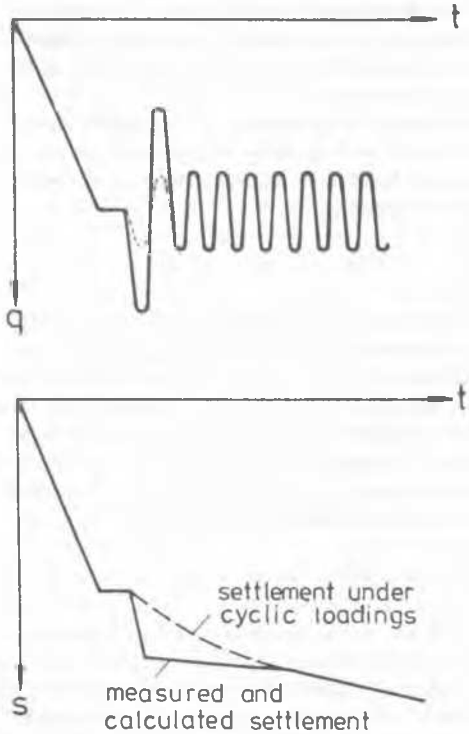

Figure 8. Principle scheme of repeated loadings (dotted line) including preloads (full line) and the correlated settlement

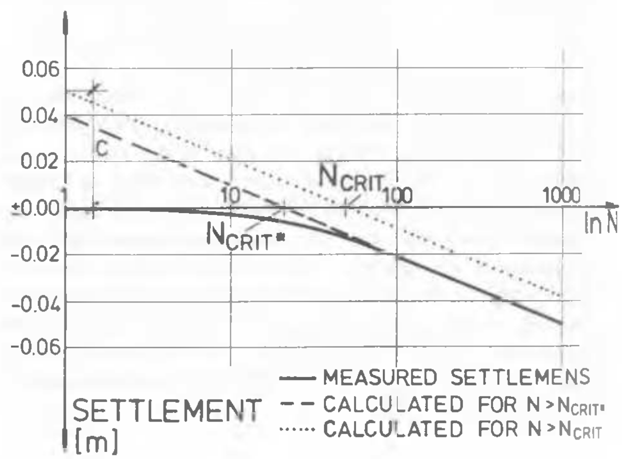

Figure 9. Comparison of measured and calculated settlements for a preloaded foundation.

even prevent additional settlements. After a certain number of cycles, which is called in the following N_{CRIT}, an increasing of settlements is to be regarded. The value of N_{CRIT} depends on the preloading and on the increasing parameter b. Figure 8 shows the situation of preloading in principle. For higher values of N the total settlement curve fits with the settlement curve of a purely repeated loaded foundation.

A measured curve of the irreversible settlements depending on the number of load cycles for a test with a higher preloading is given in Figure 9. The zero value of settlements is given to the settlement after the first load cycle. Settlements caused by preloads larger than the maximum value of the actual repeated load value and of the settlements due to previous cyclic loadings can be added up to a constant C. For one load phase, this constant value C has to be regarded as the starting value for the determination of settlements. Overlaying the constant value C with the increasing line for an unloaded foundation, N_{CRIT} can be evaluated. The increasing of settlements for load cycles of N beyond N_{CRIT} are neglected. They should be regarded reducing the factor of N_{CRIT} with at least a safety factor of 2 comparable to conditions in structural engineering. Beginning with the resulting N_{CRIT*}, the settlement can be estimated with a similar function

$$s_N = -C + b \cdot (\ln \frac{N_{CRIT}}{N_{CRIT*}} + \ln N) \quad (5)$$

given by equation 5, leading to good comparison between measured calculated values.

7. DISCUSSION

The problem of a theoretical determination of the influencing parameters is the unknown bearing mechanism of foundation under repeated loadings. The bearing of a foundation is the sum of several resistance factors. The densification due to settlements and also a small slip zones of plasticity under the edges of foundations are well known and activated due to repeated loadings. Nevertheless, these parts of the resistance against settlement are overlayed by further mechanism. The evaluation of the deformation in the halfspace, which has been measured in the presented tests, show a changed zone of bearing during an increasing of cycles. At the beginning, a wide zone around the foundation is influenced whereas this influencing zone is rather flat. With increasing number of cycles the depth of this zone increases, the area decreases (Laue 1996). A further mechanism can be seen regarding the evaluation of cyclic shear box tests. For constant load values a hardening behaviour is measured. After a certain number of load cycles the slip surface softens and failure can occur. These mechanism lead to additional resistance factors, which should be regarded and evaluated with further research work. Further resistance factors depending for example on the geometric boundary conditions are possible.

With the findings presented in the previous chapters, it is possible to estimate the settlements for the whole load history of a foundation loaded with static and repeated loadings. For circular shallow foundations on dense sand, the influencing parameters are evaluated by means of centrifuge model tests. These parameters have to be transferred to other foundation systems and other soils. Further parameter, valid for changed systems, can be evaluated by interpreting the results of measurements in situ or using the centrifuge model technique as a low cost experimental tool.

8. ACKNOWLEDGEMENT

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