General Report
Shallow foundations

Rapport général
Fondations superficielles

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ABSTRACT: Ten papers, from different countries, were accepted to this Discussion Session on Shallow Foundations. This General Report reviews and summarizes the main contents and objectives of each of the submitted papers. This review shows that different themes are treated and studied. Most of them are related to the improvement of models for predicting settlements of shallow foundations in granular soils and in clayey soils. Accuracy and uncertainties in estimating settlements are assessed through probabilistic analyses in four of the accepted papers. The definition and the determination of moduli and elastic soil properties are also studied, like for instance the use of measured non-linear dynamic properties of soil. One paper addresses the settlement reduction by aggregate piers (stone columns) and defines, through a full scale loading program, the corresponding "improvement factor". Another theme related to the eccentrically and inclined loading of shallow foundations is treated in three papers. The interaction of nearby footings submitted to inclined loading is studied through Finite elements analyses. Foundations submitted to dynamic loadings are also emphasized through a paper presenting the study of an improved type of foundation combining massive block and plates.

RÉSUMÉ : Dix articles provenant d'auteurs de différentes nationalités ont été acceptés pour cette session de discussion sur les Fondations superficielles. Le présent rapport fournit une synthèse du contenu et des objectifs de chaque article. La revue montre que différents sujets ont pu être abordés. La plupart porte sur l'amélioration des modèles de prédiction des tassements de fondations aussi bien dans les sols granulaires que dans les sols argileux. La précision et les incertitudes associées à l'estimation des tassements sont évaluées au travers d'analyses probabilistes dans quatre des articles présentés. La définition et la détermination des modules et des propriétés élastiques des sols, comme par exemple, l'utilisation des propriétés dynamiques non linéaires, mesurées sont également abordées. Un article traite de l'amélioration des tassements par des colonnes ballastées et définit, sur la base d'un important programme de chargement de semelles en vraie grandeur, les facteurs de réduction des tassements. Trois des articles de la session concernent les semelles soumises à des charges inclinées et excentrées. L'interaction entre semelles rapprochées soumises à des charges inclinées est également étudiée par l'intermédiaire de modélisations aux éléments finis. Les fondations soumises à des chargements dynamiques sont également abordés par la présentation d'un système combinant un bloc massif associé à une ou plusieurs dalles.

KEYWORDS: shallow foundation, settlement, probabilistic approach, dynamic properties.

1 INTRODUCTION.

This general report reviews and summarizes the main contents and objectives of each of the papers submitted to the Shallow foundation session. Different themes are covered and studied by these papers.

Most of them are related to the study of settlements under shallow foundation either in granular soils or in clayey soils.

The definition and the determination of moduli and elastic soil properties are also studied. The use of non-linear dynamic properties, measured in-situ, to predict settlement is covered in one of the submitted papers.

Accuracy and uncertainties in estimating settlements are also assessed through probabilistic analyses.

The settlement reduction by using aggregate piers (stone columns) and a proposal for the definition, through the results of a full scale foundation loading program, of the corresponding "improvement factor" is given.

Another theme subject is related to the eccentrically and inclined loading of shallow foundations. The interaction of nearby footings submitted to inclined loading is studied through Finite elements analyses.

Foundations submitted to dynamic loadings are also emphasized through a paper presenting a study of an enhanced type of foundation combining massive block and plate.

2 SETTLEMENT OF SHALLOW FOUNDATIONS

2.1 *Settlement measurements*

In the paper of **Dapena & *al*.** from Spain, the settlements of major-scale shallow foundations of large biodigesters tanks of a Waste Water Treatment Plant have been recorded over the first ten years after they have been put in operation and loaded.

These biodigesters are located on top of a layer of dark gray silty clay alluvial sediments between 15 and 20 m thick

Dapena *& al*. discuss the amount of settlement recorded over the first 10 years and how it has developed over time. It also identifies how the pools have behaved differently, delimiting the areas with similar settlement rates.

The measured settlement values vary between 50mm and 200mm (figure 1).

They show (figure 2) that the settlement s, which occurs with time, fits the model $s = a\sqrt{ta} + b$, where ta is the time in years since the tank has been full.

Coefficient "a" is related to the rate of settlement and its distribution is similar to the settlement values.

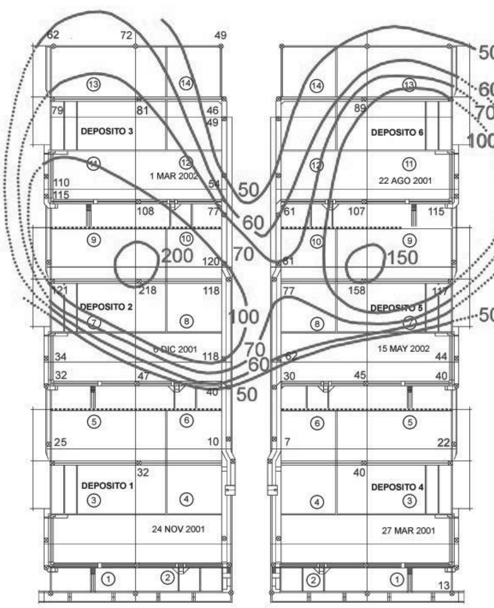


Figure 1. Contour lines for settlement at the biodigesters (in mm).

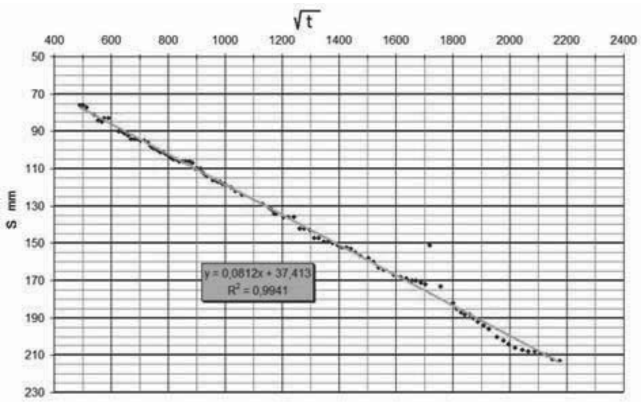


Figure 2. Settlement at point 53 of pool 2 based on the root of t (t= time in minutes) between 0.5 and 9 years and adjustment of the model.

2.2 *Settlement prediction*

In their paper, **Yang Guang-hua *& al*.** from China, analyze the nonlinear settlement results of five plate loading tests carried out on the sand foundation in Riverside Campus (Texas A & M University) by using tangent modulus method.

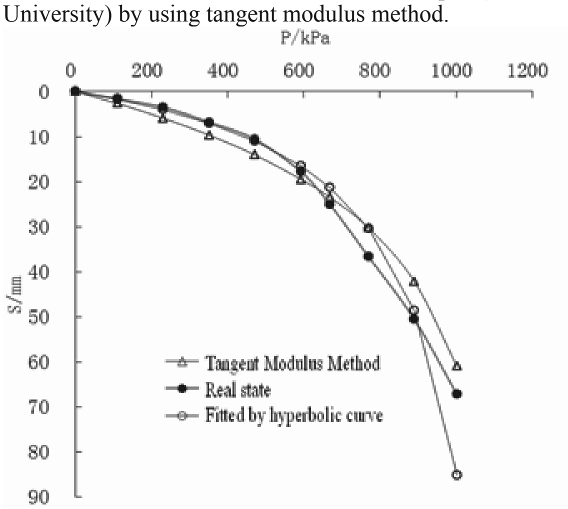


Figure 3. Example of experimental and calculated Loading curves for a 1.5m x 1.5m footing.

They show that the tangent modulus method can calculate the nonlinear settlement of foundation in a better way (see figure 3).

They also seek for simpler in-situ tests such as the Cone penetration test and the pressuremeter test to determine the soil parameters required in nonlinear settlement calculation.

Their paper attempts providing a more convenient way of using the tangent modulus method for calculation of the nonlinear settlement of foundations.

In the paper of **Stokoe *& al.***, an approach based on field seismic evaluation of small-strain ("elastic") shear modulus (Gmax) combined with nonlinear normalized shear modulus-shear strain (G/Gmax-log γ) relationships is presented. The effects of increasing confining pressure and strain amplitude on soil stiffness during loading of the footing are incorporated in this formulation.

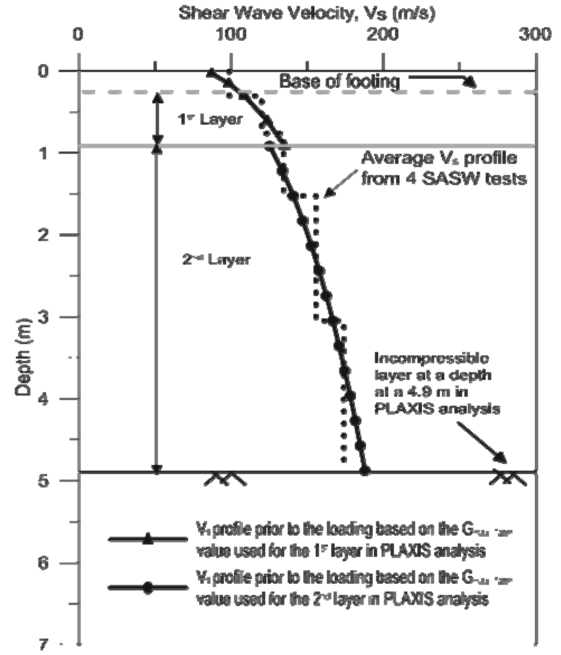


Figure 4. Average Vs profile from SASW tests and the two-layers model used in the finite element analysis..

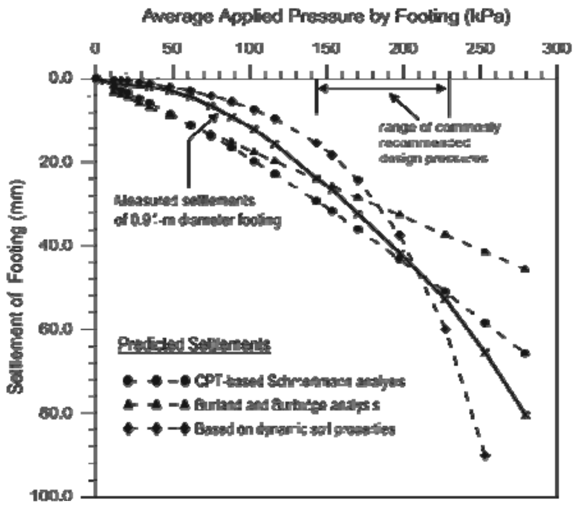


Figure 5. Measured and predicted load-settlement curves for the 0.91-m diameter footing.

The presented approach has several important benefits including: (1) in-situ seismic testing (figure 5), such as surface wave tests (SASW), which can readily be performed in all types of granular soils, including gravels and cobbles, (2) continuous load-settlement curves that are evaluated to stress states considerably above those expected under working loads, and (3) a methodology that is appropriate for all types of geotechnical materials, even those where the effective stresses change with time.

The method was investigated by comparing with a load-settlement test using a 0.91-m diameter footing. In the working stress range, predicted nonlinear footing settlements matched quite well with the measured ones (figure 6). The predicted nonlinear settlements in this range were also in reasonable agreement with predictions from traditional CPT and SPT procedures.

3 PROBABILISTIC APPROACHES

3.1 *Bearing capacity of shallow foundations*

In their paper, **Tian & Cassidy**, from Australia and **Uzielli**, from Italy, investigate the effect of the spatial variability in undrained shear strength S_u on the bearing capacity of a shallow strip footing on two-layered stiff-over-soft clay (see figure 6).

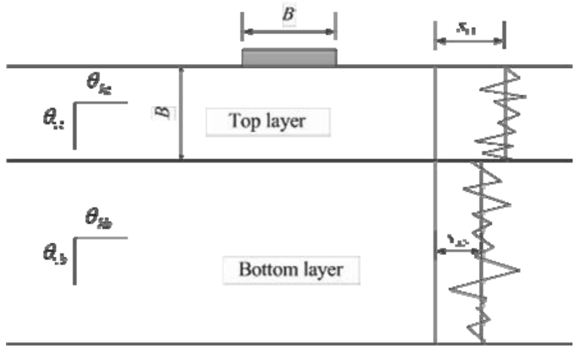


Figure 6. Definition of problem being investigated: stiff clay top layer over soft clay bottom layer.

They analyze the probabilistic assessment of the resistance factor N_c for bearing capacity for a strip footing on a stiff-over-soft clay profile. The analysis is performed by applying the Random Finite Element Method, which combines finite elements simulation, spatial variability analysis and Monte Carlo simulation.

Finite-element analyses are performed on meshes in which undrained strength values are assigned on the basis of quantitative estimates of the vertical and horizontal spatial variability and the probabilistically modeled scatter of undrained strength itself (see figure 7).

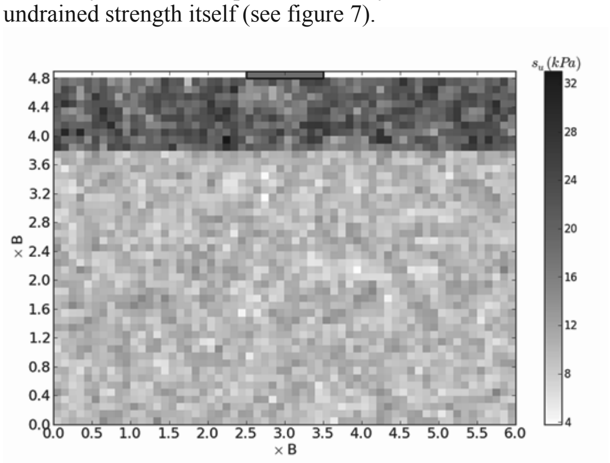


Figure 7. Example of random field mesh.

The study first results indicate that with high spatial variability in the undrained shear strength there is a significant reduction in the bearing capacity.

Mean bearing capacity factors and statistical distributions were provided for 12 cases of s_{ut}/s_{ub} = 2.

However, the 12 cases presented here represent a small subset of 1600 cases analyzed in a more ambitious numerical experiment.

3.2 *Settlement of shallow foundations*

Generally accepted methods for estimating immediate settlement of spread footings require the use of linear elastic models to simulate soil behavior; this approach does not capture the true non-linear behavior of soil. **Strahler & Stuedlein** present a statistical evaluation of a commonly used elasticity-based method and soil stiffness correlation using a load test database. Then, a simple non-linear model capturing observed load-displacement curvature in footing load tests is presented and its accuracy is characterized. The undrained initial elastic modulus is back-calculated using the load test database, and is found to vary as a function of overconsolidation ratio.

The use of a single undrained Young's modulus to predict the highly non-linear response of footings supported on cohesive soil has been shown to be slightly conservative at low displacements but increases in error with increasing displacement. A method to estimate displacements based on the non-linear Duncan-Chang model was shown to be slightly conservative and more accurately captures the overall load-displacement curve. The proposed method also allowed the estimation of an initial undrained Young's modulus, which appears to be correlated with OCR (see figure 8). This trend can be used to estimate the initial Young's modulus for use in the non-linear model or additionally modified to be used in elasticity based methods.

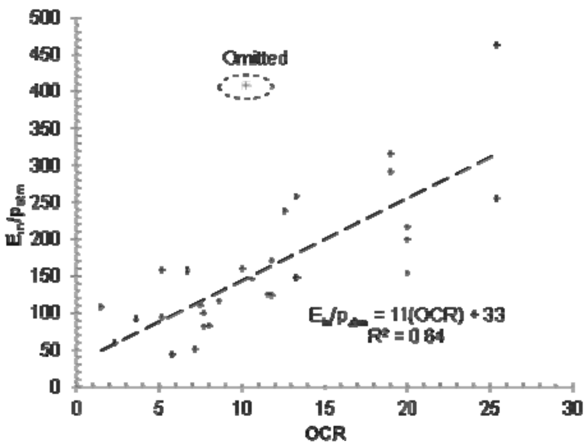


Figure 8. Back-calculated initial Young's modulus using Duncan-Chang model.

Despite the improvement in modeling footing response reported herein, significant uncertainty in the response remains without the adequate characterization of inherent soil variability, transformation error associated with correlations, and model error. Improved site characterization presents the best approach to reducing the uncertainty of footing load-displacement response.

Bungenstab *& al.* from Brazil, discuss about probabilistic settlement analysis of footings in sands, focusing on the load curve (estimated settlements). For this purpose, three methodologies that take the First and Second Order Second Moment (FOSM and SOSM), and Monte Carlo Simulation (MCS) methods for calculating mean and variance of the estimated settlements through Schmertmann's 1970 equation are discussed.

The deformability modulus (E_{Si}) is considered varying according to the division of the soil into sublayers and it is analyzed as the only independent random variable.

As an example of application, a hypothetical case in state of Espirito Santo, Brazil, is evaluated. Simulations indicate that there is significant similarity between SOSM and MCS methods, while the FOSM method underestimates the results due to the non-consideration of the high orders terms in Taylor's series. The contribution to the knowing of the uncertainties in settlement predictions can provides a more safety design.

Figure 9 shows the results for the probability of the predicted settlement to exceed different values of limiting settlements in a range between 10 to 50 mm. For example, the probability of the predicted settlement to exceed 25 mm is about 1,1%.

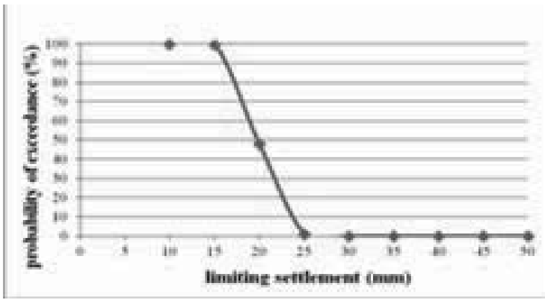


Figure 9. Probability for the predicted settlement, to exceed different values of limiting settlement.

The analysis of the sources of uncertainties indicates that about 80% of the settlement variance is influenced by the uncertainties due to inherent soil variability and measurement test errors.

4 SHALLOW FOUNDATIONS UNDER INCLINED LOADING

In their paper, **Atalar & *al.*** present laboratory model tests that were conducted in a dense sand to determine the bearing capacity of shallow strip foundation subjected to eccentrically inclined load. The embedment ratio (ratio of the depth of embedment *Df* to the width of the foundation *B*) was varied from zero to one.

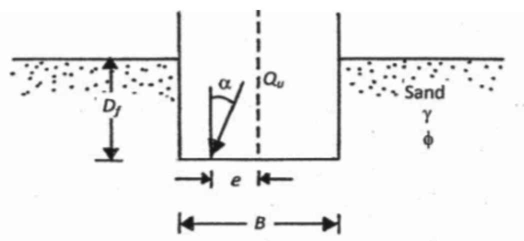


Figure 10. Shallow foundation on granular soil subjected to eccentrically inclined load.

Load eccentricity e was varied from zero to 0.15B and the load inclination with the vertical (α) varied from zero to 20 degrees. Based on the results of the present study, an empirical non-dimensional reduction factor *RF* has been developed. This reduction factor (see Eq. (1)) is the ratio of the bearing capacity of the foundation subjected to an eccentrically inclined load (average eccentrically inclined load per unit area) to the bearing capacity of the foundation subjected to a centric vertical load.

It was assumed that, for a given D_f/B:

$$RF = \text{reduction factor} = \frac{q_{u(D_f/B,e,\alpha)}}{q_{u(D_f/B,e=0,\alpha=0)}} = \left[1-a\left(\frac{e}{B}\right)^m\right]\left(1-\frac{\alpha}{\phi}\right)^n \quad (1)$$

The determined values of *a* ≈ *2*, *m* ≈ 1 and *n* ≈ *2-(Df/B)*, based on the test results and within the range of parameters tested, have been proposed.

A comparison between the reduction factors obtained from the empirical relationships and those obtained experimentally shows, in general, a variation of ±15% or less. In a few cases, the deviation was about 25 to 30%.

The interaction of nearby footings resting on homogeneous soil bed and subjected to vertical and inclined loads has been studied by **Nainegali & *al.***, from India.

Two rigid strip footings of symmetrical width, *B* rest on the surface of the homogeneous soil layer of depth H, as shown in Figure 11.

The two footings are placed at a clear spacing, *S* and an inclined load, *P* is applied at an angle of inclination θ_L and θ_R with horizontal on the left and right footings, respectively. The effect of angles of inclination of load (θ_L and θ_R) and the clear spacing between the footings on the ultimate bearing capacity and settlement are analyzed.

A two dimensional finite element analysis is then carried out using the commercially available finite element software, ABAQUS.

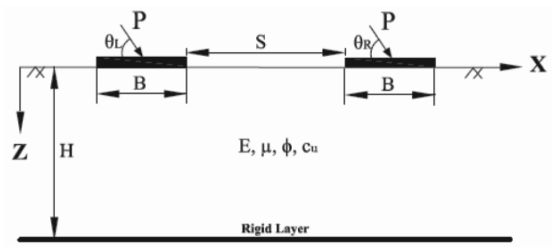


Figure 11. Problem definition for footings interaction.

Their study shows that the interference phenomenon has a considerable effect on the ultimate bearing capacity, increasing this capacity when footings are vertically loaded. For the cases where footings are subjected to inclined load the effect of interference on the bearing capacity has no significant effect. However for all cases of inclined loading condition, the interference effect on the settlement is quite significant. The settlement of interfering footings in the range of working load decreases with increase in the clear spacing between the footings and attains a value similar to isolated footing at greater clear spacing (S ≥ 5B).

5 IMPROVEMENT OF SHALLOW FOUNDATIONS

In their paper, **Kuruoglu & *al.***, from Turkey, study the settlement improvement factor for footings resting on rammed aggregate pier groups. They use a 3D finite element program, calibrated with the results of a series of full scale instrumented load tests.

Four large plate load tests were conducted with rigid steel plates of 3.0m by 3.5m. One of the load tests was on non-treated soil. Second load test was Group A loading on improved ground with aggregate piers of 3.0m length, third load test was Group B loading on improved ground with aggregate piers of 5.0m length and finally fourth load test was Group C loading on improved ground with aggregate pier lengths of 8.0m.

The aggregate pier groups under each footing, consisted of 7 piers installed with a spacing of 1.25 m in a triangular pattern. The pier diameter was 65cm. (See Figure 12)

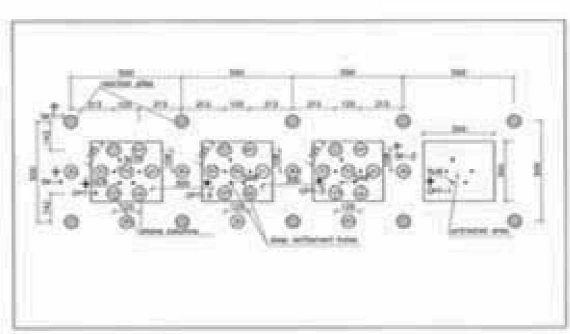


Figure 12. Location of aggregate piers at the test site.

A simplified 3D finite element composite soil model was then developed, which takes into account the increase of stiffness around the piers due to the ramming process. Design charts for settlement improvement factors of square footings of different sizes (B = 2.4m to 4.8m) resting on aggregate pier groups of different area ratios (AR = 0.087 to 0.349), pier moduli (Ecolumn = 36MPa to 72MPa), and with various compressible clay layer strengths (c_u = 20kPa to 60kPa) and thicknesses (L = 5m to 15m) were prepared using this calibrated 3D finite element model (see example in figure 13).

It was found that, the settlement improvement factor increases as the area ratio, the pier modulus and the footing pressure increase.

On the other hand, they observe that the settlement improvement factor decreases as the undrained shear strength and thickness of compressible clay and footing size increase.

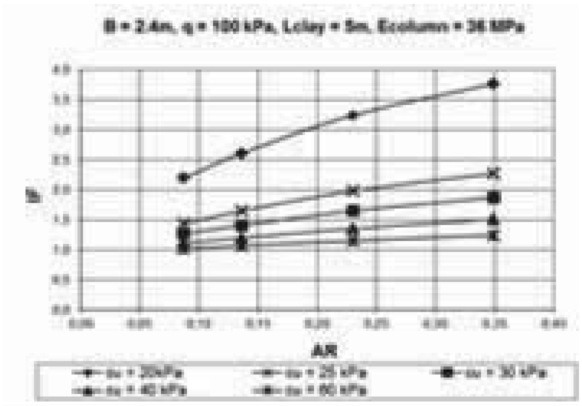
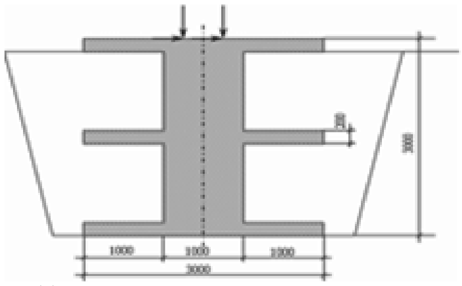


Figure 13. Settlement improvement factor (IF) vs. area ratio (AR) charts for a rigid square footing (B=2.4m) with a foundation pressure of q=100 kPa resting on end bearing rammed aggregate piers (L=5m, E=36 MPa).

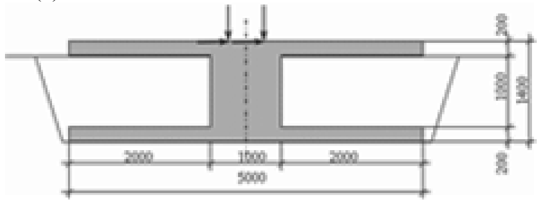
Heavy machinery with rotating, reciprocating or impacting masses requires a foundation that can resist dynamic loadings and the resulting vibrations. **Y.Kirichek & V.Bolshakov** present in their paper new forms of foundations under machines with low dynamic loadings. They are named «Combined massive and plate foundations" (see Figure 14).

This type of foundations consists of deepened rigid solid mass, and attached to it in soil, thin horizontal plates.

Its natural frequencies can be sat in a wide frequency range by changing dimension and location of the attached thin horizontal plates in soil.



(a)



(b)

Figure 14. Combined massive and plate foundations: (a) – a solid block and three plates, (b) – a solid block and two plates.

As a result natural frequency of such foundation can be significantly higher in amount than of block-type foundation, and vibration level of the combined massive and plate foundations under low-frequency loading and impacting machinery generally is considerably lower.

For studying the behavior of the combined massive and plate foundations under low-frequency, large-scale field loading tests were conducted by **Kirichek & Bolshakov**. The comparison of the footing vibration tests with theory was done. For these tests, the vertical and horizontal dynamic forces on footing were generated by rotating mass vibrators. The large-scale models were 1.5 m in wide and 3.71 m in length.

The comparison of the amplitude-frequency responses of the combined massive plate foundations enable to evaluate influence of the dimension of plates on responses of foundation. It shows that the vibration amplitude decreases half as much with increasing of the plate area *F* twice as many.

The plate thickness *h* has less effect on the responses of foundation (see figure 15).

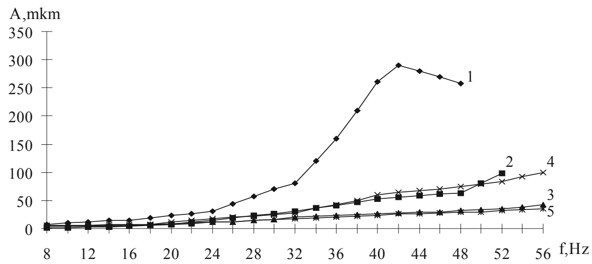


Figure 15. Amplitude-frequency responses of the combined massive and plate foundations with the plate on the top of the foundations to horizontal periodic load: 1 – amplitude-frequency response of the block, 2 – F=2.13, h=0.05, 3 – F=4.5, h=0.05, 4 – F=2.13m, h=0.1, 5 – F=4.5m, h=0.1m

It was experimentally determined that the effect of top plates was more effective under horizontal dynamic loading and the effect of bottom plates was more effective under vertical dynamic loading.

A thin plate on the soil can significantly reduce the vibration level of the block foundation.

6 ACKNOWLEDGEMENTS

We would like to thank the members of the Technical Commission of the CFMS "Comité Français de Mécanique des

Sols" for their contribution in reviewing the submitted papers to this session.

7 REFERENCES

Papers in this parallel session:

Atalar C., Patra C. R., Das B. M., Sivakugan N. 2013. Bearing capacity of shallow foundation under eccentrically inclined load.

Bungenstab F. C., Bicalho K. V., Ribeiro R. C. H. Aoki N. 2013. Estimating settlements of footings in sands – a probabilistic approach.

Dapena E., Roman F., Pardo de Santayana F. and Cuéllar V. 2013. Settlement velocity measured over ten years in major-scale shallow foundations on a preloaded 20-m thick silty alluvial layer.

Kenneth H., Stokoe K.H., Onur Kacar I., Kacar O., and Van Pelt J. 2013. Predicting Settlements of Shallow Footings on Granular Soil Using Nonlinear Dynamic Soil Properties.

Kirichek Y. and Bolshakov V. 2013. Combined massive and plate foundations under machines with dynamic loadings.

Kuruoglu O., Horoz A. and Erol O. 2013. Settlements Under Footings on Rammed Aggregate Piers.

Nainegali L. S. , Gosh P., Basudhar P. K. 2013. Interaction of Nearby Strip Footings Under Inclined Loading.

Strahler A. W. and Stuedlein A. W. 2013. Characterization of Model Uncertainty in Immediate Settlement Calculations for Spread Footings on Clays.

Tian Y., Cassidy M. J., Uzielli M. 2013. Probabilistic Assessment of the Bearing Capacity of Shallow Strip Footings on Stiff-Over-Soft Clay.

Yang G., Luo Y., Zhang Y. and Wang E. 2013. Application of The Tangent Modulus Method in Nonlinear Settlement Analysis of Sand Foundation.