Stability of foundation of transmission tower model subjected to horizontal alternating load

La stabilité d'un modèle de la fondation du pylon d'électricité sous une charge horizontale altérée

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ABSTRACT: An interaction of a group of foundations subjected to an external load is a very complex problem. In the paper some theoretical considerations and model investigations regarding this subject are presented. The analysis shown is a step towards a determination of the calculation procedures of a bearing capacity for a group of mushroom foundations subjected to complex loading.

RESUME: Le document presénte des méthodes proposéspour les calculs pourle dimensionement des fondations de supports aeriens et, en particiulier les problemes d'interactions des foundation en group.

1. INTRODUCTION

High voltage lines are an important element of a transportation and transmission system of electric energy connecting power plants and transformer stations with energy consumers. One of the sub-elements of that system are supporting structures and foundations of transmission towers. These structures should be designed in such a way in order to fully secure a continuity of electric energy supply. They have to assure a safety work of above-ground parts of a structure together with a rational transmission of loading on a subsoil. A proper design of such foundations, which are subjected to a complex loading state requires an appropriate evaluation of work of a whole system. Standard design of supporting structures foundations is normally based on an assumption, that bearing capacity of such a system is regarded as a value of ultimate overturning moment. An appropriate approach to the problem requires consideration of a character of loading applied which vary with respect to force value and its direction. In the rational design every possible combinations of these loads have to be taken into account.

2. LOADING - DISPLACEMENT CURVE

Foundations of supporting structures with four footings are loaded by an inclined pushed or pull-out force. In the literature regarding such constructions, most of the authors suggest to neglect an influence of a horizontal force on a bearing capacity and work of such a system. The elimination of the horizontal force influence significantly simplifies the investigations and potential theoretical analysis of a problem.

The detailed investigations regarding an influence of the horizontal force component on a bearing capacity of foundation together with relation between vertical component of a force and vertical displacement were carried out by Zmudzinski (1986). In the *in situ* tests different mushroom foundations models at various depths were investigated. A comparison of the results for foundations pulled out by a vertical force with foundations pulled out by a force inclined at the angle of 10° to the vertical direction has shown almost identical values of a bearing capacities and displacement-loading relations.

Taking the above into account it has been assumed that the bearing capacity of single mushroom foundations which are being pulled out by a force with a small inclination to the vertical direction is similar to the case of vertically pulled foundations. So, in the planned investigations the foundations were loaded by a vertical force, exclusively.

Neglecting an influence of the horizontal component makes an analysis of a problem substantially easier. In order to include the elasto-plastic behaviour of a soil medium additional simplifications were made. It has been accepted, that the construction works in such a way that top of all four foundations creates a common plane. Practically, it is equivalent to a situation where three of peaks (two of them must be extreme ones) belong to a common plane, and a location of the last one (internal one) is very close to the plane. This simplification enables a construction of a set of forces equilibrium equations. The equations take into account distribution of forces on particular foundations and theirs vertical displacements as a function of external loads. According to the simplifications accepted for further analysis a foundation framework loaded by a vertical force and overturning moment has been assumed. It has been also accepted that the foundation framework is rested on elastic supports with non-linear elastic characteristics.

The analysis of test results as well as numerous contributions of other authors show that load-displacement curve can be satisfactorily approximated in terms of either hyperbolic or exponential functions. As a most suitable form of a description of the displacement-load behaviour a modified hyperbolic relationship proposed by Alejnikow (1990) was assumed:

$$\varphi(x) = \frac{P}{\left(1-\left(\frac{P}{Q_{gr}}\right)^{m}\right)^{n}} \qquad (1)$$

where:

$\varphi(x)$ - modified loading function,

P - applied vertical load acting on the foundation,

Q_{gr} - ultimate bearing capacity of the foundations subjected either to pushing or pulling out,

m, n - function indexes.

The solution (1) was applied for description of load-displacement curves for footing foundations subjected to pushing. The analyses of the curves have shown their general character with respect to wide range of shapes considered.

In the authors' analysis it has been assumed, that the first phase of loading is purely elastic. It means, that the directional coefficient of a tangential at the origin (point (0,0)) of a plot for pushed foundations has to be equal to an equivalent elastic constant. It, in turn leads to some modifications of equation (1) by reduction of a bearing capacity it terms of coefficient θ.

The coefficient reflects a dependence of a bearing capacity on a depth of foundations, spacing, mutual influence, theirs location with respect to the direction of main load and its repeatability.

Thus, a modified equation takes a following form:

$$s(P)=\frac{P}{k\left(1-\left(\frac{P}{\theta\cdot Q_{gr}}\right)^{m}\right)^{n}} \quad (2),$$

where:

s(P) - displacement as a function of loading [m],
k - an equivalent elastic constant of pushed foundation [N/m],
P - applied vertical loading acting on the foundation [N],
Q_{qr} - ultimate bearing capacity of pulled out or pushed foundation [N],
θ - coefficient reducing a value of Q_{qr}, depending on a mutual depth and location of foundation in a group and on alternating loading,
m, n - function indexes assumed on the basis of curves obtained from single foundations' tests.

The authors' intention was to receive preliminary solution of a problem of the group of foundations, so Eq. (2) can be used for a description of every foundation. It subsequently allows a substitution of the elastic coefficients by non-linear forms for equivalent set of foundation framework.

The equivalent elastic constant of pushed foundation is a magnitude which describes a ratio of load to unit settlement caused by this load. That problem has been solved in terms of Mindlin (1936), Fox (1948) and Poulos (1967) formulae. Settlement of deep foundation can be calculated according to the following relationship:

$$s=\frac{\alpha q B\omega\left(1-\upsilon_o^2\right)}{E_o} \quad , (3)$$

where:

α - settlement coefficient,
q - load at the surface of a half space [Pa]
B - a diameter of area loaded [m],
ν_0 - lateral expansion coefficient,
E_0 - strain module [Pa],
ω - influence coefficient depending on a shape of area (foundation) loaded, rigidity and a location of a given point in relation to the area loaded.

After some algebraic rearrangements and application of elastic constant definition, equation for the equivalent elastic constant of foundation takes a following form:

$$k=\frac{\pi R^2 E_o}{\alpha B\omega\left(1-\upsilon_o^2\right)} \quad , \quad (4)$$

where R is a radius of foundation's base and other parameters as in Eq. (3).

The equivalent elastic constant expresses a flexibility of foundation on settlement due to loading. It also indicates an initial phase of pushed foundation behaviour. As a result of the assumption that the initial phase of loading of foundations' group is purely elastic it has been accepted that the value of equivalent elastic constant is the same for both pulled out and pushed foundations for this phase.

The reciprocal of equivalent elastic constant k is equal to directional coefficient of the tangential to strain-load curves. It can be easily expressed by a differentiation of Eq. (2) and calculation of a limit for such a derivative in the vicinity of the point (0,0), according to the following:

$$\lim_{P\to 0}\frac{ds(P)}{dP}=\frac{1}{k}, \quad (5)$$

It has been found that 3D strains method for subsoil half space together with geometry description and proper evaluation of physical parameters enables a preliminary determination of the equivalent elastic constant of foundation, and subsequently layout of the initial tangential of the load-displacement plot.

The factor Q_{gr} in the Eq. (2) denotes an ultimate bearing capacity of the foundation caused by either pulling or driving. The authors intention was to find a value of Q_{gr} in I series of tests in order to experimentally justify the assumptions of the theory for four footings foundations.

The coefficient θ in Eq. (2) can be compared to the coefficient of homothety with respect to (0,0) point, used for a displacement of a given horizontal asymptote Q_{gr}. The introduction of coefficient θ is caused by a need to include factors influencing the bearing capacity of particular foundations working in the group. On the basis of so far existing investigations and theoretical solutions these factors can be summarised as follows:

- an influence of the mutual spacing of foundations and their depth,
- an influence of load direction on the work of construction,
- location of the foundation in a whole system,
- an influence of repeatability of load applied.

The function s(P) in Eq. (2) , contains one variable P and constant parameters such as k, Q_{gr}, θ and shape coefficients m and n. Values of these coefficients for particular types of foundations should be determined experimentally.

3. EQUILIBRIUM EQUATIONS OF A SYSTEM.

Bearing capacity of a system is treated as a value of ultimate overturning moment transmitted through a group of mushroom foundations. An analysis of a problem takes into account the elasto-plastic character of foundations' behaviour and the assumption that the peaks of foundations belong to a common plane.

An initial set of equations has to include standard conditions of a system equilibrium. Load applied on foundation contains two elements e.g. the values of overturning moment and vertical load (the weight of construction). Due to an alteration of the external load direction the vector of moment was distributed onto two components. In the analysis the following notation has been assumed:

Q - vertical load due to weight of construction [N],
M_{OX} - moment in the OX direction [Nm],
M_{OY} - moment in the OY direction [Nm].

The basic characteristics of a system are: geometry of a bearing capacity system, depth, geotechnical parameters e.t.c. Taking into account non-linear dependence of the displacement on the loads for individual foundations a set of the basic characteristics will be verified and changed.

The following space characteristics were assumed:
x_1, x_2, x_3, x_4, - OX co-ordinates for individual foundations [m],
y_1, y_2, y_3, y_4, - OY co-ordinates for individual foundations[m],
a - spacing of foundations (square base) [m],
and foundation characteristics:
Q_{gr1} - maximum bearing capacity of pulled foundation from the tests for single foundations[N],
Q_{gr2} - maximum bearing capacity of pushed foundation from the tests for single foundations [N],
k - elastic constant determined from Eq. (4)[N/m],
m - coefficient of a function approximating displacement - load curve.

n - coefficient of a function approximating displacement - load curve,

Overturning moment, forces and displacements for individual foundations are unknown values which have to be found for the given boundary values.

The following notation for unknown values has been assumed:

M - ultimate overturning moment [Nm],

P_1, P_2, P_3, P_4 - the values of vertical forces acting on the individual foundations [N],

s_1, s_2, s_3, s_4 - values of vertical displacements acting on individual foundations [m].

An idea of finding a solution requires an introduction of equivalent variables in the form of coefficients describing a common plane of foundations' displacement. So, the following associate A, B, C variables have been assumed which play a role of coefficients in the general equation of a plane being created by the peaks of foundations.

Set of equations describing a problem consists of seven following relationships:

$$P_1 + P_2 + P_3 + P_4 = Q$$

$$P_1 * a + P_2 * a - P_3 * a - P_4 * a = 2 * M_{OX}$$

$$P_1 * a - P_2 * a - P_3 * a + P_4 * a = 2 * M_{OY}$$

$$k * (A * x_1 + B * y_1 + C) = \frac{P_1}{\left[1 - \left(\frac{P_1}{s * Q_{gr1}}\right)^n\right]^m}$$

$$k * (A * x_2 + B * y_2 + C) = \frac{P_2}{\left[1 - \left(\frac{P_2}{s * Q_{gr2}}\right)^n\right]^m}$$

$$k * (A * x_3 + B * y_3 + C) = \frac{P_3}{\left[1 - \left(\frac{P_3}{s * Q_{gr3}}\right)^n\right]^m}, \quad (6)$$

$$k * (A * x_4 + B * y4_4 + C) = \frac{P_4}{\left[1 - \left(\frac{P_3}{s * Q_{gr4}}\right)^n\right]^m}$$

A solution of the above set of equations will enable the determination of the maximum value of the overturning moment for which either ultimate bearing capacity of at least one foundation or ultimate settlement of the construction will be exceeded.

The theoretical considerations were subsequently verified by model tests, described in next chapter.

4. MODEL TESTS

The main goal of the investigations was the determination of the interaction way of mutlifooting supporting constructions of the energetic system (high-tension systems) which undergo cyclic pulling and driving due to alternating horizontal loads caused by wind, for example. Additionally, the tests served for the verification of basic theoretical assumptions. The tests were being performed in the natural subsoil in 3D strain state conditions. In all tests the mushroom foundations were used. The test programme consisted of two main parts:

- investigations of single mushroom foundations subjected to alternating vertical load,
- investigations of the same foundations working as foundations of four-footing supporting construction of the energetic system subjected to horizontal load.

In all tests an uniform medium dense sea sand was used with the following characteristic parameters: U=1.4; γ=16.9 kN/m^3, w_n=0.11%, I_D=0.58, ϕ=27°.

Three types of foundations (Fig.1) have been applied in the experiments, namely:

- model „20" - R=0.1 m, r=0.04 m, H=0.20 m, weight 0.098 kN
- model „40" - R=0.1 m, r=0.04 m, H=0.40 m, weight 0.074 kN
- model „60"- R=0.1 m, r 0.04 m, H=0.60 m, weight 0.05 kN.

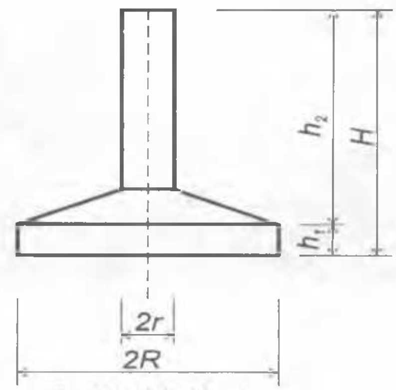

Fig. 1 Model of foundation.

The experiments have been carried out in the sand of the Geotechnical Laboratory of the Gdansk Technical University. The experiments were performed for two different set-ups. The first set of experiments dealt with testing of single foundations whereas the second one regarded the same foundations used as a group.

The aim of the investigation of foundations being rested at the three different depths was a simulation of the action of alternating vertical load and determination of parameters required for the analysis of the behaviour of foundations' group. The vertical load was applied continuously it terms of mechanical jack. During every test a continuous measurement of load applied and displacement of the foundation were taken.

Each of three foundations was subjected to five series of pulling and driving. In every series the experiments were repeated twice.

The results obtained show a decrease of the bearing capacity of pulled foundation caused by repeated loading and clear process of foundation's lifting. Decrease of the bearing capacity has been included in calculations regarding the group of foundations in terms of coefficient θ (see Eq. 2).


Fig.2 Model setup.

Fig.3 Model setup.

In order to verify calculation model the second set (Fig.2,3) of experiments has been carried out. In this set the examination regarded mushroom foundation of transmission tower model which was subjected to the alternating horizontal force. During experiments values of vertical forces, vertical displacements and horizontal load were monitored continuously. In every experiment new values of parameters were applied. The following parameters were being changed in each test:

- a height of application of the horizontal force,
- an angle between the tower and direction of horizontal force (0°, 15°, 30°, 45°) (Fig.4),
- type of foundation - H=0.20 m, 0.40 m, 0.60 m.

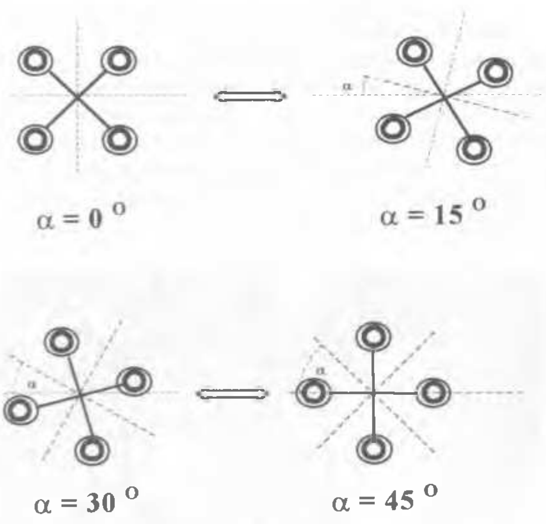

Fig. 4 Scheme of different direction of loading.

5. FINAL CONCLUSION

The analysis of the influence of repeated loading on the response of soil shows that there exists a critical level of the loading, under which soil deformations stabilise and failure mechanism does not occur and over which the accumulation of leading to failure displacements takes place. In general, the problem is related to different strength characteristics of soil and its deformations. It requires including a character of volume changes as well as drain conditions during loading. It can be done it terms of introduction a new influence coefficient reflecting these problems. General determination of such a coefficient extends a scope of this paper. In the work presented the influence of above problems has been limited to the conditions of experiments performed by authors and expressed in terms of empirical reduction coefficient. For other cases such coefficient should be determined independently.

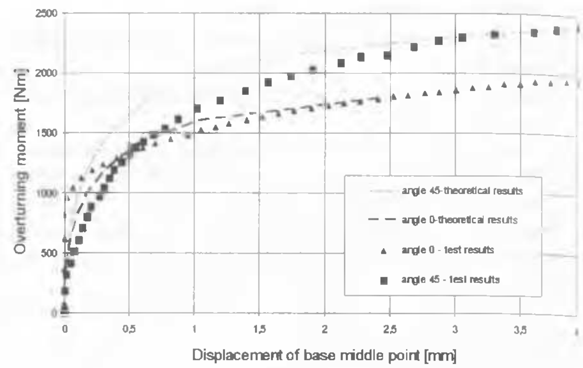

Fig.5 Overturning moment - test and accounting results.

The main aim of investigations was the determination of the procedure serving for bearing capacity calculations of group of mushroom foundations taking into account elasto-plastic character of interaction of a subsoil and the influence of alternating loading. Calculated bearing capacity of such a system consisting of four foundations together with distribution of forces and displacements obtained are similar to the results of model tests (Fig.5). An idea to perform the experiments for a single foundations first and next application of the results for the determination of the displacement-load function appeared to be the proper choice. This relationship and set of equations (6) enable quite accurate determination of the ultimate overturning moment of the group of mushroom foundations with respect to boundary conditions, and distribution of forces and displacement in each foundation.

The problem of foundation interaction in group can be developed towards more general problem for larger number of foundations e.g. piles and similar loading scheme.

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