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PRINCIPLES FOR TEST-LOADINGS OF LARGE BORED PILES BY HORIZONTAL LOADS

PRINCIPES D'ESSAIS DE CHARGE AVEC DES FORCES HORIZONTALES AUX GRANDS PIEUX FORÉS

ПРИНЦИПЫ ИСПЫТАНИЯ БОЛЬШИХ БУРОВЫХ СВАЙ ГОРИЗОНТАЛЬНЫМИ НАГРУЗКАМИ

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SUMMARY. Large bored piles are mostly vertical, because the production of inclined piles is difficult and expensive. Vertical piles, therefore, have to transfer horizontal forces into the subsoil by means of bending and lateral bedding. As at present no other method gives sufficient reliable results, test loadings are necessary whenever exact information about the relation between the horizontal force and the deflection of the pile head is needed. From the test loadings it is then possible to calculate the soil parameters by the Theory of Elasticity or the Winkler Medium Theory (Bedding Value Theory). The latter is the most suitable. Because of the non-elastic behaviour of the subsoil (i.e. creeping and the violation of Hookes Law), the test load has to simulate not only the magnitude and duration of design loads, but also the repetitive and alternating stresses in the soil in relation to the design loads. Since the simultaneous application of vertical, horizontal and bending moment loads is difficult and expensive, possibilities are shown which omit the vertical load and substitute the bending moment load at the pile head by an additional horizontal load ΔH . Finally a practical example is given for the determination of bedding values.

1. INTRODUCTION

Large bored piles, which are piles of more than 1 m diameter, are mostly produced vertically, since the production of inclined piles is more difficult and also more expensive. Horizontal forces, therefore, have to be transferred into the subsoil by means of lateral bedding, the piles being subjected to bending moments and being displaced horizontally.

Should the amount of the horizontal displacement be of no importance to the building based on the piles, then the dimensions of the piles must only be chosen to be capable of taking the bending moments arising from the horizontal forces. This may be done with sufficient accuracy by use of the Winkler

Medium Theory and by estimating the bedding values, e.g. Terzaghi (1955). Since in the calculation of the bending moments merely the fourth or fifth root of the bedding value is needed, errors in this estimation do not play an essential part, and the internal forces of the pile are obtained with sufficient accuracy.

The horizontal displacements, on the other hand, are directly proportional to the bedding value. Thus loading tests are necessary, if the horizontal displacements for a given building have to be known exactly. No other method is available at present to give sufficiently reliable predictions of the horizontal displacements. Experience shows that all attempts to find the bedding value by

laboratory experiments with small soil samples or the horizontal displacement itself by model-test are unsatisfactory.

2. METHODS FOR ANALYSING A LOADING TEST

In simple cases, the relation between horizontal force and lateral movement of the pile head may be read off directly from a horizontal loading test on the foundation piles themselves. In other cases, however, if the geometry or other boundary conditions of the foundation piles differ greatly from those of the test piles, loading tests must serve as a basis for calculation of soil parameters. These parameters enable the calculation of horizontal force-movement relations for the foundation piles, particularly when the boundary between an upper soft layer and an underlying harder layer do not lie in the same depth as in the case of the test piles, or the bearing conditions at the head of the foundation piles may differ from those of the test piles.

To extrapolate the results of loading tests to such other piles, it is advisable to apply one of the methods for dimensioning horizontally loaded piles, but with the modification that now the soil parameters are to be calculated from given values of load, deformation and pile dimensions. The parameters found in this way can then be used for further calculation of piles with different layer boundaries or bearing conditions. Usually one of the following methods is employed: the Theory of Elasticity or the Winkler Medium Theory.

In connection with recent developments in the calculation of beams on the soil surface according to the Theory of Elasticity, it has been repeatedly proposed in the last few years to also use this theory for the calculation of horizontally loaded piles (e.g. see H. Grasshoff 1970, J. Kerisél and M. Adam 1967). There are mainly two objections to this procedure:

a) Contrary to the assumption, the soil is not elastic; its reaction to deformation de-

pends on magnitude and duration of the loading (e.g. see the test results of B. McClelland and J.A. Focht 1958).

b) In many pile foundations there is a horizontal layer boundary separating an upper soft layer from the harder subsoil, i.e. there is a discontinuity of the strength properties. Since the stress distribution can as yet only be determined for homogeneous elastically isotropic semi-space, the influence of such a discontinuous change of the strength properties is not taken into account. This leads to errors in the stress distribution, which are difficult to estimate. (In shallow foundations the layer boundaries are usually more or less parallel to the base of the building; in this case the error in the stress distribution is much smaller.)

Setting aside the expensive calculations with finite elements, only the Winkler Medium Theory remains as a practicable method.

There again, there are two objections to this theory:

a) In contrast to the assumptions of the Winkler Medium Theory, the soil does not behave elastically but more or less plastically, and moreover it creeps under the load. This means that the bedding value decreases with the increasing magnitude and duration of the loading. This objection corresponds to the first one regarding the Theory of Elasticity. (The consequences are shown in section 3.)

b) In assuming an Winkler continuum that is an elastic medium without shear resistance it is supposed that the soil beside the pile is not compressed by the movement of the pile relative to the soil (Fig. 1). That is, because the bedding value does not account for the propagation of the bedding stresses towards the sides. To compensate this fault in the bedding value theory, a new equation has been introduced $k_1/k_2 = D_2/D_1$, where k_1 and k_2 are the bedding values and D_1 and D_2 the pile diameters (Terzaghi 1955). This formula corresponds with the Theory of Elasticity

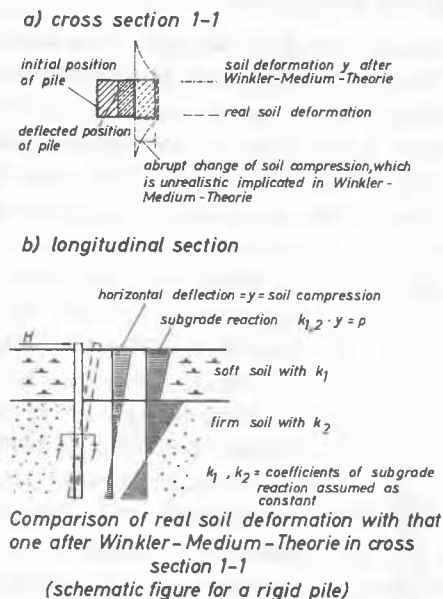


FIG.1. Comparison of real and theoretical soil deformation in cross-section 1-1

and means that the horizontal "settlements" increase linearly to the pile diameter at constant bedding stresses. The results of loading tests show indeed that this is qualitatively correct, but the quantitative accuracy of such calculations is rather poor. Consequently the formula $k = 1.4 E_s/D$ given by F. Andres (1966) and H.U.Smoltczyk (1963) following K. Terzaghi (1954) cannot be regarded as satisfactory because of the only qualitatively valid proportionality to $1/D$ (E_s = elastic soil modulus from oedometer test in kg/cm^2). In this connection it is of some interest that the semiempirical relation $k_1/k_2 = 4/(1 + D_2/D_1)^2$ given by Terzaghi (1955) for sand is also too inaccurate (see L. Bjerrum 1963) and that the suggestions of A. Kezdi (1964) and of K. Kubo (1965) are unsatisfactory too (see H.G. Schmidt 1971). For this reason it is recommended that the bedding values be determined with test piles which have nearly the same diameter as the foundation piles. Fortunately in the longitudinal direction of

the pile are no such large and abrupt deformation changes (Fig.1) as across the pile axis. In the longitudinal direction of the pile, therefore, only negligible horizontal shear stresses occur. For the longitudinal direction, therefore, the assumption made in the Winkler Medium Theory of a continuum without shear resistance is a good approximation even at the layer boundaries. This means, the bedding value theory allows in contrast to the Theory of Elasticity to treat abrupt changes in strength of the soil at the layer boundaries, and is therefore the more useful of the both methods discussed. The Theory of Elasticity will no longer be considered in the following.

3. MAGNITUDE, DURATION, REPETITION AND ALTERNATION OF TEST LOADS.

The Winkler Medium Theory presumes the elastic behaviour of soil. In reality, however, the soil is not elastic but an elasto-plastically strainhardening material. Nevertheless the assumption of elasticity may be applied approximately if the test load simulates the design load well enough. In this way a suitable secant modulus for the bedding value can be obtained. If too large a test load is applied, this secant modulus becomes too small and vice versa.

The duration of the application of the test loads is also of importance, and the more so, the more the soil creeps. The test loads must therefore be maintained in the various loading steps, as long as the deflections decrease distinctly. Should the load test step be stopped too soon, the secant modulus for the bedding value becomes too large.

It is of particular importance to investigate the reaction of test piles to repetitive and alternating loads, as if a horizontal load, which under working conditions is repetitive or alternating, suppresses a certain threshold value, the plastic components of the horizontal deflections accumulate under the repeated loadings and the plastic horizontal deflection enlarges. The difference between the design load and the threshold value must, therefore, be sufficient

and thus the horizontal deflections should not increase even under 1.5 times the design load. An example of the quasi elastic behaviour as required under repetitive and alternating loads is shown in Fig. 2 (As it is impossible to decide which load has the greater disadvantage, both repetitive and alternating loads were applied. It is seen that it should be sufficient, to apply the repetitive load only.)

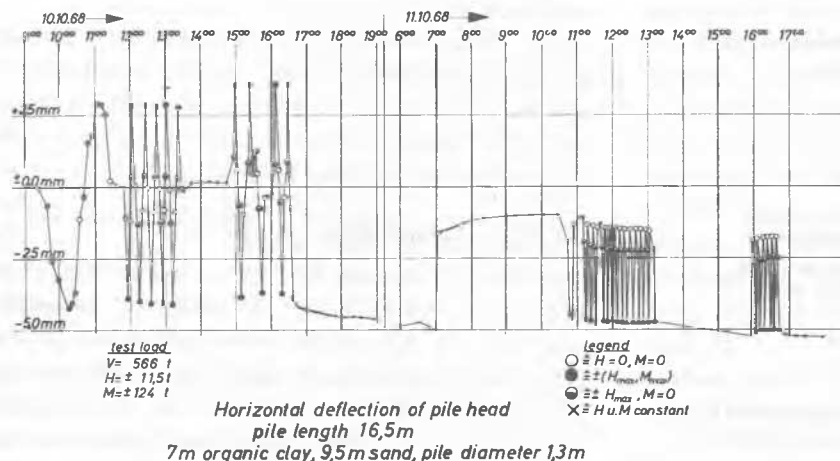


FIG.2. Horizontal deflections of pile head under repeating and alternating loads

4. POSSIBILITIES TO SIMPLIFY THE LOADING TEST

In Section 3 reasons were given as to why the test load has to simulate the design load. This design load, acting on the head of the pile, generally consists of a vertical load V , a horizontal load H and a bending moment M . Consequently, V , H and M should be properly applied as test loads. To apply these three loads simultaneously is certainly possible (Fig. 3, 4 and 7), but



FIG.3. Loading frame of Fa. Frankipfahl

very expensive. The following, therefore, shows under which conditions the loading test may be simplified:

If the piles are long enough, the vertical load V does not influence the horizontal deformations, and V may be omitted in the loading test. According to the Winkler Medium Theory (E. Titze 1970, L.C. Reese and M. Matlock 1956), this is possible with homogeneous subsoil if the pile length

is three to four times larger than the so-called elastic length L_0 (Fig.5). With layered soil, this critical length, beyond which the internal forces and deflections of the pile are no longer a function of the pile length, has to be obtained by trial and error calculations using estimated bedding values. On piles longer than the critical length, the horizontal bending load caused by H and M does not reach the end of the pile, and without fault the pile may be considered

of infinite length. The end of the pile is then fixed, and the friction force

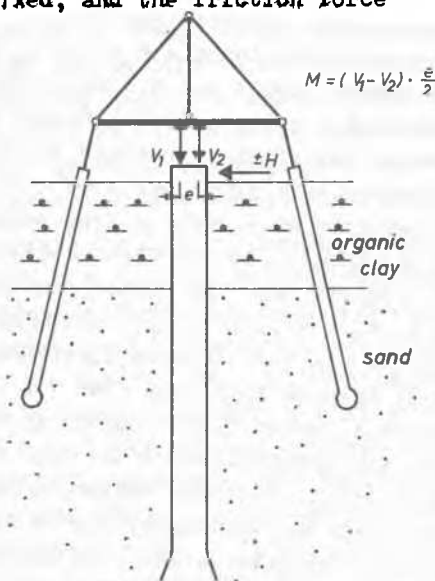


FIG.4. Scheme of loading frame

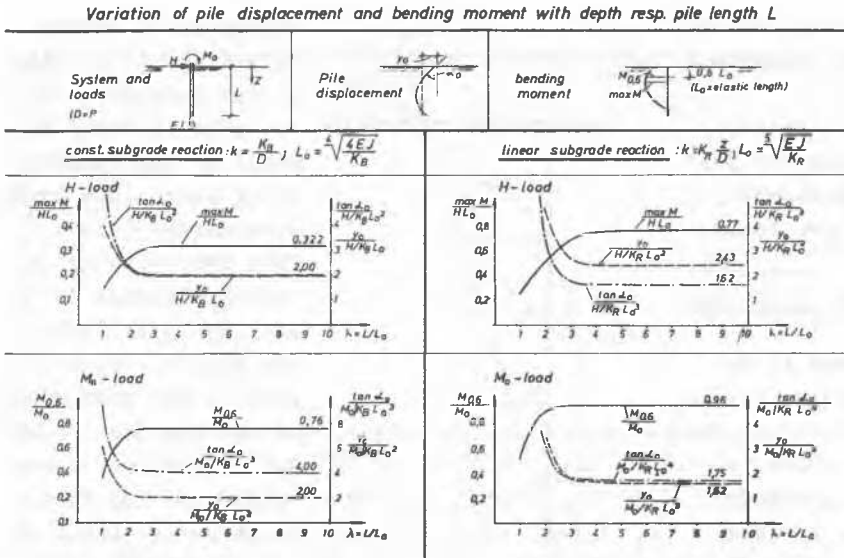


FIG.5. Dimensionless diagrams according to Titze (1970)

$R = V \cdot \tan \delta$ (Fig.6) does not affect the distribution of earth pressure along the pile nor its horizontal deflections. During a test loading, it was found, for example, that three piles, each with a diameter of 130 cm and varying length of 13.5, 16.5 and 19.5 m suffered almost equal pile-head deflections of about 6.5, 11.5 and 19.5 mm under the following loads (Table 1).

loads pile length	$V = 452 \text{ t}$ $H = \pm 6.6 \text{ t}$ $M = \pm 93 \text{ tm}$	$V = 566 \text{ t}$ $H = \pm 11.5 \text{ t}$ $M = \pm 124 \text{ tm}$	$V = 600 \text{ t}$ $H = \pm 17.25 \text{ t}$ $M = \pm 186 \text{ tm}$
13.5m	7,5 mm	11,0 mm	20,3 mm
16,5m	6,7 mm	11,8 mm	19,1 mm
19,5m	5,4 mm	11,0 mm	19,1 mm

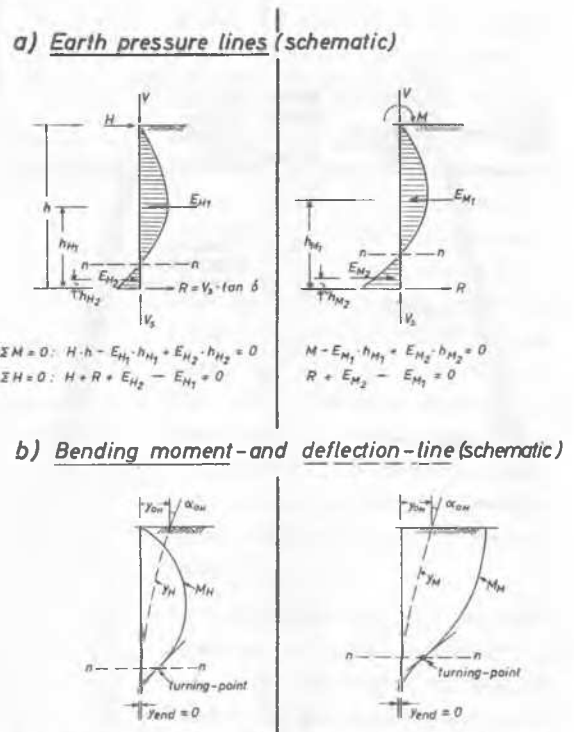
If the actual piles are shorter than the critical length, the test piles should not be longer either. In this case, however, the influence of the friction force R on the earth pressures or bedding stresses and the pile deflections has to be taken into account by the application of the vertical load V to the test piles, in addition to the horizontal loads H and M , or else the pile deflections become too large and the bedding value becomes too small as the soil actually

behaves non-elastically. This, however, may be on the safe side in many cases. If the test piles are longer than the critical length and the actual piles shorter, the loading test results in too high bedding values.

Apart from this the moment M may always be replaced approximately by an additional horizontal load ΔH , where

$$\Delta H = \frac{y_{0M}}{y_{0H}} \cdot H$$

according to Fig.6. ΔH must be calculated, before the test loading, from the values of y_{0M} and y_{0H} . These are obtainable by using pre-estimated bedding values. An error in the pre-estimated bedding values will be of little



In approximation ΔH can be used instead of M , therefore ΔH is to calculate for the condition $y_{0\Delta H} = y_{0M}$

FIG.6. Earth pressures, bending moments and deflection curves of piles under H- and M-load

consequence, as in calculation only the ratio y_{OM}/y_{OH} of the deflection of the pile head occurs.

When it is possible (as outlined) to omit the V- and M-loads, a test-loading for just an H-load may be carried out conveniently and inexpensively by tensioning two foundation piles against each other.

5. EXAMPLE FOR THE DETERMINATION OF BEDDING VALUES

The simplest and most accurate way is to measure directly the lateral bedding stress p along the shaft of the pile. With the help of the horizontal deflections y which, as shown in Fig.7 and 8, may also be measured directly, the bedding values $k = p/y$ are obtained. This method, however, will often be impracticable, as earth pressure mea-

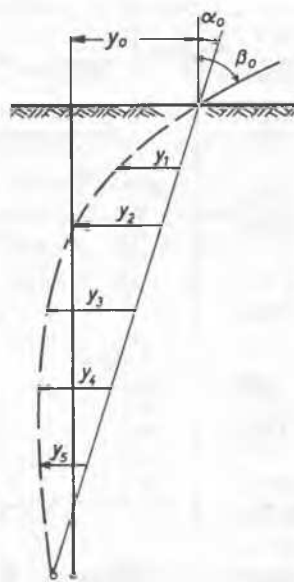


FIG.8. Complete pattern of pile deformation

suring cells cannot be set up at the side of the borehole, if the pile is bored by means of well casing or if there is a high groundwater level. This necessitates an instrumentation of the test pile (e.g. see Fig.7), which permits the measuring of the bending moment and deflection curves (Fig.9 and 10) or at least one of them. In the latter case, the deflection curves should be given preference, since they can be measured with

better accuracy, as the figures show. It is then theoretically possible to determine the earth pressure distribution by differentiating the deflection curve four times and the bending moment curve twice. The results, however, are much too inaccurate for practical purposes. A more practicable way to find out suitable bedding values is to assume various bedding values by way of trial and to calculate deflection and bending moment curves until the results of calculation and measurements coincide. Fig. 11 shows an example for a case with two soil layers. In this way sufficiently accurate bedding values are obtained.

The very least which should be done is to measure y_0 and β_0 (see Fig.8). The bedding value for a homogeneous foundation soil may then be read off directly from Fig.5. It is true, that the bedding value for a layered subsoil cannot be determined uniquely in this way, but in many cases it is possible to estimate it with sufficient accuracy by trial and error calculations (H.G. Schmidt 1971).

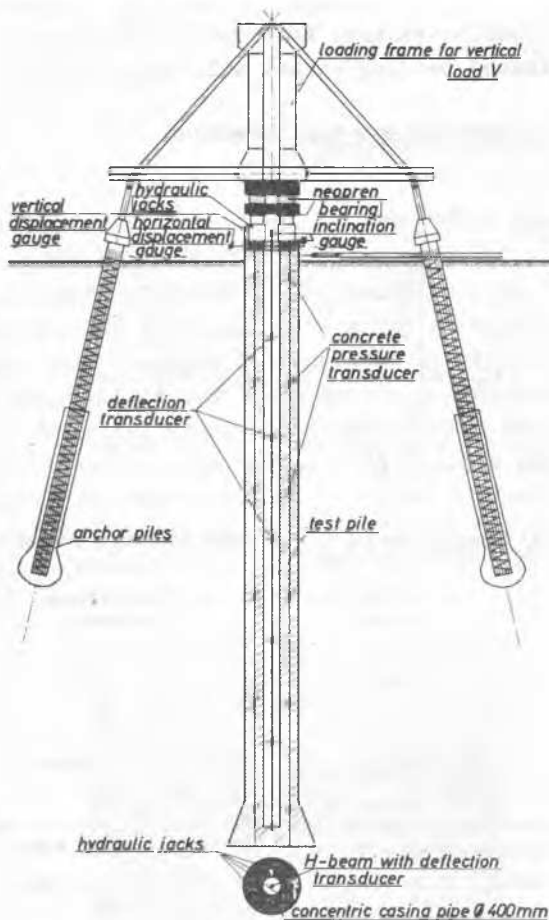


FIG.7. Instrumentation of test pile

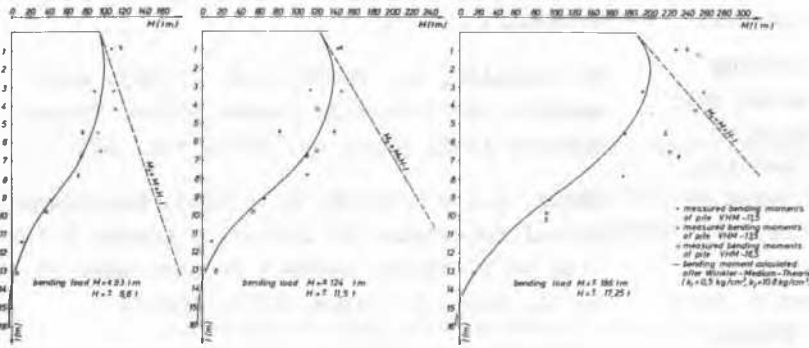


FIG.9. Bending-moments. Points given by measured concrete strains, curves given by measured deflection lines

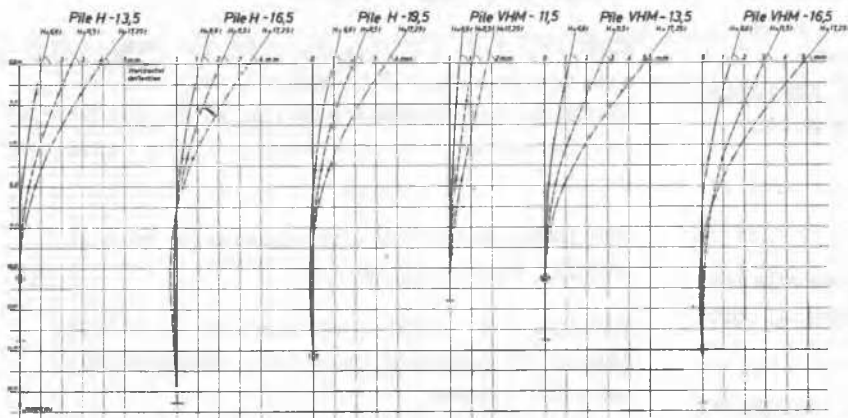


FIG.10. Measured deflection lines

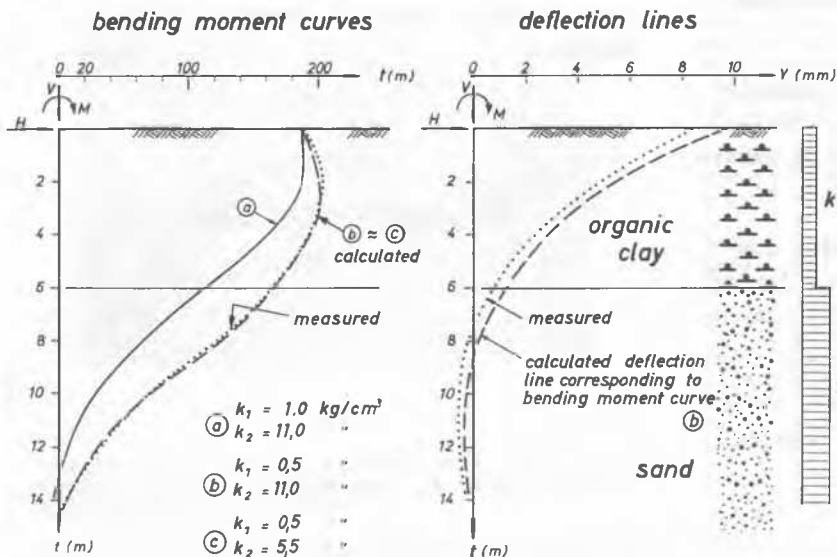


FIG.11. Calculation of bedding values by trial and error

CONCLUSIONS:

a) To obtain an accurate no-rizontal force-deflection law, a loading test is unavoidable. All other methods are insufficiently accurate.

b) The best method for analyzing loading tests is the Winkler Medium Theory. In determining bedding values from loading tests the influence of stratifications of the subsoil is very accurately accounted for, but not the stress distribution across the pile. Bedding values, therefore, should be determined by using test piles with the same diameter as the piles to which the bedding values are to be applied.

c) Since in contrast to the theoretical assumptions the foundation soil is non-elastic and, moreover, often creeps, magnitude and duration of the test load must simulate the design load. In addition to this, the design load, as well as 1.5 times its value, must be applied in the form of repetitive loads, in order to prevent plastic horizontal deflection components accumulating by repeating the load.

d) Test loadings may be made simpler and less expensive by replacing the bending moment load M by an equivalent additional horizontal force ΔH . If, furthermore, the pile length exceeds a certain critical value, the vertical load V may also be omitted

Omitting the vertical load with shorter piles results in too low a bedding value, which is on the safe side in most cases.

e) The best way to determine the bedding values is by measuring the deformation pattern of the test pile and by calculating deflection curves using estimated bedding values until the measured and the calculated curves coincide. In order to simplify this, the movement and the inclination of the pile head should only be measured. Some accuracy, however, is lost if the foundation soil is layered.

The same procedure may be applied to the moment curves, but the accuracy is much less than with the deflection curves, since concrete stresses, as a result of deviation from exact elastic behaviour, are mostly more or less wide-spread.

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