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A modified method for the estimation of excess pore pressure generated by pile driving

Une méthode modifiée pour estimer l'excès de pression interstitielle provoqué par le battement des pieux

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SYNOPSIS: Due to pile driving in cohesive, low permeable soils high excess pore pressure can be induced even in greater distances from the driven pile. This excess pore pressure can reduce the stability of near situated slopes or can stress the foundations of existing buildings.

This paper deals with a method to predict the excess pore pressure due to pile driving in cohesive soils. Pile installation is modelled as the expansion of a cavity in the undrained soil. With a soil model based on the theories of Critical State Soil Mechanics the relation between deformation and stress change as well as between deformation and pore pressure are described. These theories are connected with an analysis of measurements during pile driving including all influencing parameters. For reliable estimation of excess pore pressure generated by pile driving in cohesive soils, equations are proposed using also statistical methods. Only few parameters are needed which can easily be determined by standard tests.

1 INTRODUCTION

Pile foundations usually are necessary for most of situations requiring construction of buildings on soft ground. The piles are employed to carry the building loads through the soft soil to a firmer soil below. If driving is possible and allowed, driven piles mostly are preferred.

The effects on the penetrated cohesive soil due to pile driving are more or less neglected. Some worth mentioning damages caused at buildings and slopes situated near the piling area as well as damages at piles driven before, like uplift or displacement were observed. These effects have been the reason for extensive measuring programs where partially large soil movements and excess pore pressure were measured within the penetrated cohesive soil.

On the other hand, the change of stress in the soil during and after pile driving must be known for the estimation of the shaft capacity of piles being driven in cohesive bearing strata.

The state of soil stress after loading a pile results from the addition of the following four states:

1. Initial state of stress of the soil before pile driving
2. Stress change during pile driving
3. Stress change after pile driving (reconsolidation)
4. Stress changes by pile loading.

This paper deals with the stress change and mainly with the development and distribution of excess pore pressure in cohesive soil induced during pile driving.

2 EFFECTS OF PILE DRIVING IN COHESIVE SOILS

2.1 Displacement of soil due to pile driving

The installation of a solid driven pile into soil is always combined with deformations of the soil adjacent to the pile. In non cohesive soils voids decrease due to compaction effects of driving, while the volume of cohesive soils remains constant due to low water permeability (Fig. 1).

At small penetrations, up to about ten times the radius of the pile, some heave of the ground surface occurs. At greater depths, the soil is moved predominantly outwards in radial direction. Near the pile partially high excess pore pressure arises. It decreases after the end of driving process due to reconsolidation of soil.

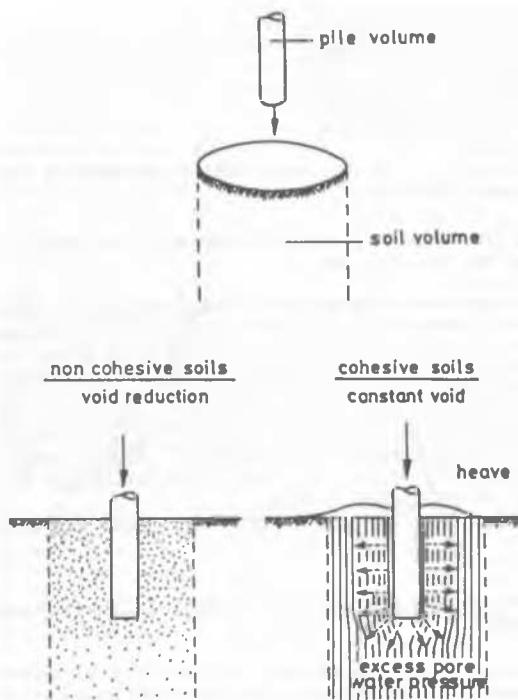


Fig. 1 Effects of pile penetration on surrounding soil

Model tests (Randolph et al., 1979) and excavations showed that the soil particles below the pile are displaced along straight lines radiating from a common source corresponding to the centre of the pile.

This is to compare with a spherical cavity being expanded, centred at this point. As the pile tip passes the current position of the soil particles, significant additional horizontal movement occurs even in a distance up to ten pile radii from the pile axis. At this distance movements of the magnitude of 0.05 times the pile radius were measured (Steenfelt et al., 1981). Thus, if a solid pile with a radius of e.g. 20 cm is installed, horizontal movements of about 1 cm can be expected at a distance of 2

m. These observations led to the pile installation process being modelled as the expansion of a cylindrical cavity with a final radius equal to that of the pile. Near the pile the soil will severely be remoulded. Cause of the irreversible deformations, this area is called "plastic zone" with the radius r_p . Beyond this plastic zone more or less reversible deformations occur, on account of which this area is called "elastic zone" (Fig. 2).

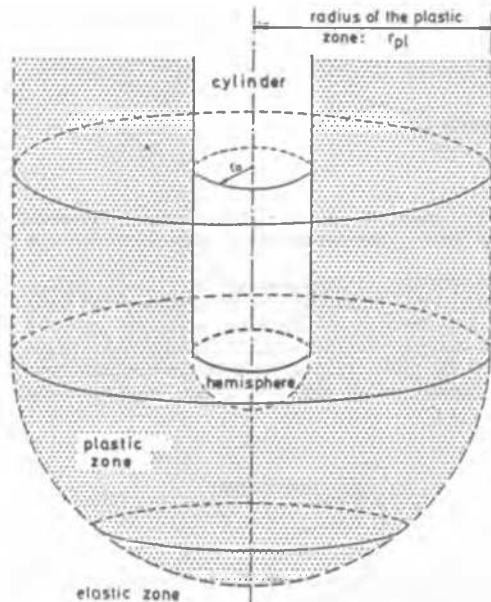


Fig. 2. Illustration of the penetration process by the model of expanding cavity (Cunze, 1985)

2.2 Methods to estimate excess pore pressure in cohesive soil due to pile driving

Due to the fact that pore pressure measurements are time intensive and expensive, different methods to estimate excess pore pressure due to pile driving were given by Ladanyi (1961, 1963), Lo and Stermac (1965), D'Appolonia and Lambe (1971), Vesic (1972), Randolph et al., (1979). Different stress-strain theories for soil are used, e.g. the stress path method (Lambe, 1967) or the theories of Critical State Soil Mechanics (Schofield, Wroth, 1968). The installation process of the pile is modelled as the expansion of a cylindrical cavity. The methods are described and compared in a study by Cunze (1985).

2.3 Comparison of measured and estimated excess pore pressures

Within the scope of researches the accuracy of these methods were verified by using the published results of 453 pore pressure measurements performed during pile driving.

In a preliminary study the expected values of excess pore pressure were estimated according to the methods mentioned above under consideration of the respective soil properties and geometrical conditions (e.g. pile radius, distance to the pile) and were compared with the corresponding results of field measurements.

The degree of approach between calculated and measured values was determined by using statistical methods. A determination of exact functional relations between the induced excess pore pressure and the soil parameters, the initial stress state as well as the geometrical conditions is not possible cause of secondary effects (e.g. different measuring methods, accuracy of determined soil parameters

etc.). However, the degree of relationship between excess pore pressure and the independent variables can be determined by correlation- and regression-analyses and thereby probability theoretical relations between these values can be found. Thus, statements about the scope of the methods mentioned above are possible.

Assuming the pile driving being modelled as the expansion of a cylindrical cavity, the calculated values Δu according to the method of Vesic (1972) are compared with the corresponding results of measurements $\text{meas } \Delta u$ within the plastic zone around the pile.

The results differ widely considering the low correlation coefficient $r^2 = 0,45$ and the relatively high standard deviation of $s = 31 \text{ kN/m}^2$.

The analyses of the other methods showed comparable results (Cunze, 1985), except the method according to Randolph et al. (1979), with which a correlation coefficient $r^2 = 0,76$ and a standard deviation of $s = 21 \text{ kN/m}^2$ were obtained.

It can be concluded from the results of the other methods that the stress and strain changes in the soil due to pile driving are not taken sufficiently into consideration by the partially idealizing assumptions contained in these methods.

3 PROPOSAL FOR AN IMPROVED METHOD TO PREDICT EXCESS PORE PRESSURE DUE TO PILE DRIVING IN COHESIVE SOILS

3.1 Preliminary remarks

The preliminary studies (ch's 2.1 and 2.3) have shown, that the driving process being modelled by the expansion of a cylindrical cavity and the theories of Critical State Soil Mechanics (Schofield, Wroth, 1968) cause of the strains large enough to reach the critical state (Kirby et al., 1977), can be used as a base for an improved prediction of excess pore pressure due to pile driving in cohesive soils. These theories were combined with an analysis of pore pressure measurements and the corresponding data of soil properties, initial stress and geometrical conditions. Cause of a great number of measurements being at disposal the evaluation of the results were supported by statistical methods.

3.2 Stress change in the soil due to the pile driving

The stress paths in q - p and e - p space of the change in effective and total stresses of an element of soil adjacent to the pile are illustrated in Fig. 3 (Esrig et al. 1977). The effective stress of a soil element initially consolidated to point 1' decreases following the effective stress path (ESP) ending at point 3' on the critical state line (CSL), while the total stress rises following the total stress path (TSP), keeping void ratio constant.

The difference in stress between points 3 and 3' is the excess pore pressure at the pile-soil interface generated by pile driving (Kirby et al., 1977; Cunze, 1985).

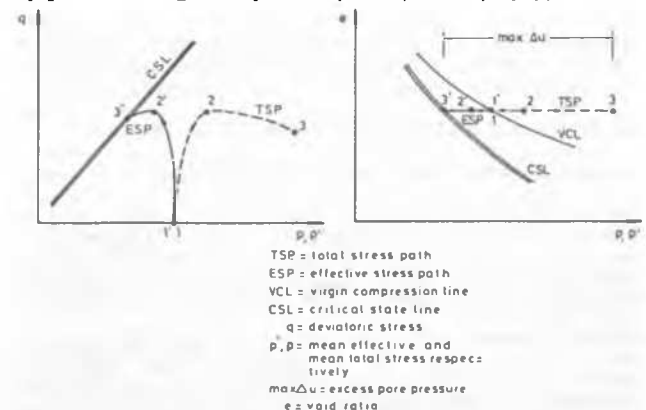


Fig. 3 Stress paths of an element of soil adjacent to the pile shaft (Esrig et al., 1977)

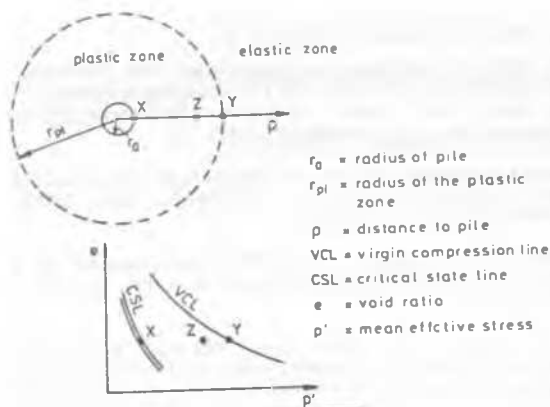


Fig. 4. Soil elements in the e-p'-space after the expansion of a cavity

For illustration of stress changes due to pile driving within the plastic zone with the radius r_{pl} , three representative soil elements are shown in Fig. 4. The element X located at the pile soil interface (normalized distance $\rho/r_o = 1$) is stressed to volume constant yielding, i.e. its stress state is characterized by the point X on the critical state line. The behaviour of an element Y lying on the boundary between plastic and elastic zone (normalized distance $\rho/r_o = r_{pl}/r_o$) can be indicated just as elastic. Hence, the effective mean normal stress of the element Y doesn't change. Elements located between X and Y, as the element Z for example in Fig. 4 don't reach critical state but their great deformations cause changes in effective stress, which depend on its relative location to the pile shaft.

Thus, for prediction of excess pore pressure within the plastic zone two magnitudes depending on the distance to the pile were introduced.

1. change of effective stress related to the distance
2. change of total stress related to the distance.

3.3 Estimation of excess pore pressure due to pile driving

As mentioned above, the excess pore pressure can be expressed as a general function of the initial stress state (A_i), geometrical conditions (B_i) and soil properties (C_i):

$$\Delta u = f \left(\sum_{i=1}^n A_i, \sum_{i=1}^{n_2} B_i, \sum_{i=1}^{n_3} C_i \right) \quad (1)$$

With the help of multidimensional, non linear regression analyses the influence of each parameter on the development of excess pore pressure as well as the degree of agreement between measured and calculated values were determined, expressed by the correlation coefficient r^2 and the standard deviation s . The best results were reached by using following equation (2):

$$\Delta u = 1,1 \cdot (p'_{nc} - p'_{cs}) \cdot \frac{r_{pl} - \rho}{r_{pl} - r_o} \cdot 1,2 \cdot c_u \cdot \sqrt{\frac{r_{pl}}{\rho}} \quad (2) \quad r_{pl} = r_o \sqrt[3]{\frac{E_u}{3c_u}} \quad (3)$$

- with: p'_{nc} = mean effective stress of normally consolidated soil
 p'_{cs} = mean effective stress of soil reaching the critical state
 c_u = undrained shear strength
 r_{pl} = radius of the plastic zone
 r_o = radius of the pile
 ρ = distance to the pile axis

The accuracy being reached with this equation is expressed by a high correlation coefficient of $r^2 = 0,90$ and a low standard deviation of $s = 19 \text{ kN/m}^2$. Thus, a reliable prediction of excess pore pressure due to pile driving in cohesive soil surrounding the pile is possible using only few parameters easily to be determined (equ. 2) such as:

- radius of the pile
- distance to the pile axis
- undrained shear strength of the undisturbed soil
- change of mean total stress
- change of mean effective stress
- stress-strain - properties of the soil.

4 THE PRACTICAL USE OF PREDICTION EQUATIONS FOR EXCESS PORE PRESSURE CAUSED BY PILE DRIVING

Compared with in situ measurements by pore pressure gauges during pile driving in cohesive soils the analytical estimation of excess pore pressure in advance represents a fast and cheap help to initiate suitable steps in time to avoid damages at buildings, at piles driven before or at slopes in the vicinity of the driving area. On the other hand a reliable estimation of the generated excess pore pressure is the base for further calculation the development of pore pressure during reconsolidation.

One reliable method to predict the excess pore pressure has been developed by Ladanyi (1961, 1963; Cunze, 1985), using the results of triaxial tests. The laboratory tests required and their evaluation are time intensive and expensive, however, and can't be carried out in each laboratory.

The different methods to predict the excess pore pressure due to pile driving mentioned in chapter 2.3 are described and compared in a study by Cunze (1985). The essential distinguishing feature is the use of different theories for description the stress-strain properties of soil. According to the methods proposed by Lo, Stermac (1965) and by D'Appolonia, Lambe (1971) the excess pore pressure is supposed to be constant within the plastic zone around the pile. The verification of both methods by a few local measurements showed a relatively wide difference between measured and calculated values.

The method according to Randolph et al. (1979) was verified by e.g. Esrig et al. (1977, 1979) and Kirby et al. (1977, 1980) for prediction of axial capacity of driven piles in clay. Combined with the Critical State Soil Mechanics (Schofield, Wroth, 1968), renders possible a more reliable prediction of excess pore pressure. It was modified by Cunze (1985) in consideration the soil properties, stress state, changes of stress and of geometrical conditions (equation 2).

The essential novelty compared with the other methods consists in introducing the member of total stress change as a radical function. Thereby the fact is taken in account that considerable excess pore pressure can occur even in distances of several pile diameters.

The proposed equation (2) can be applied on a practical problem if e.g. for an annex of an existing building a pile foundation is necessary. The soil tests required are confined to usual standard tests as e.g. liquid and plastic limits of the soil as well as to the determination of undrained shear strength by vane tests (laboratory or in situ). The radius of the plastic zone r_{pl} depends on the rigidity index E_u/c_u (Vesic, 1972), ranging between 150 and 1500, and is determined by equation (3):

The change of effective stress due to pile driving according to equation (2) $p'_{nc} - p'_{cs}$, can be estimated using equation (4):

$$p'_{nc} - p'_{cs} = p'_{nc} [0,83 - 0,51 \cdot LL] \quad (4)$$

- with $p'_{nc} = 1/3 \cdot G_{vo} \cdot (1+2K_0)$
 G_{vo} = overburden load
 LL = liquid limit
 K_0 = coefficient of earth pressure at rest.

However, the exact determination of ($p'_{nc} - p'_{cs}$) is possible in triaxial tests, only (see Fig. 3). The excess pore pressure expected due to pile driving is determined as an example as follows:

Soil: normally consolidated silty clay
 liquid limit $LL = 1,1$
 plastic limit $PL = 0,5$
 natural watercontent $w_n = 0,9$
 coeff. of earth press. at rest $K_0 = 0,6$
 undrained shear strength $c_u = 45 \text{ kN/m}^2$
 rigidity index $E_u/c_u = 400$
 overburden pressure $\sigma_{vm} = 58 \text{ kN/m}^2$

File: Radius $r_0 = 0,2 \text{ m}$
 inspection points (distance to the pile axis):
 $\rho = 0,2 \text{ m (shaft)}$
 $\phi = 1,0 \text{ m}$
 $\phi = 2,0 \text{ m}$

Equation (3): $r_{pl} = 2,31 \text{ m}$

Equation (4): $p'_{nc} - p'_{cs} = 11,4 \text{ kN/m}^2$

Equation (2):
 $= 0,2 \text{ m: } \Delta u = 196 \text{ kN/m}^2$
 $= 1,0 \text{ m: } \Delta u = 90 \text{ kN/m}^2$
 $= 2,0 \text{ m: } \Delta u = 60 \text{ kN/m}^2$

Thus the distribution of excess pore pressure to be expected within the plastic zone around a driven pile is shown in Fig. 5. Additionally in Fig. 5 the results according to other authors are shown, too.

Beyond the plastic radius r_{pl} excess pore pressure becomes negligible for practical purposes.

For each chosen depth a similar calculation can be carried out with corresponding parameters, so that a general view on the development of excess pore pressure over the pile length is obtained.

Generally, excess pore pressure generated by several driven piles will superpose each other, whereby the influence increases with decreasing distance to the inspection point.

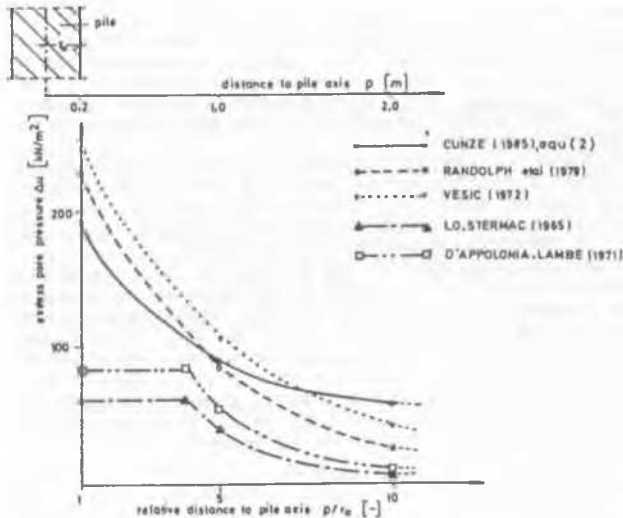


Fig. 5. Distribution of excess pore pressure due to pile driving

During driving the following piles reconsolidation for the first piles is taking place. So, with increasing distances decreasing excess pore pressure can be measured. Generally, it should be noted, that this decrease only can be expected, when driving the nearest piles at first. Hence, the absolute value of maximum excess pore pressure is lower than if the highest value (by the nearest pile) is superposed to an already existing "level of excess pore pressure". In this connection it is pointed out, that the reconsolidation rate decreases with decreasing absolute values of excess pore pressure.

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