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REVIEW OF MEASURED NEGATIVE PILE FRICTION IN TERMS OF EFFECTIVE STRESS

UNE REVUE DU FROTTEMENT NEGATIVE D'UN PIEU EN FONCTION DES CONTRAINTES EFFECTIVES

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SYNOPSIS The paper describes a review of published measurements of negative friction on driven piles in soft clay. Altogether ten case records are analysed in which negative friction has been measured over localised lengths of pile, together with the vertical distribution of pore water pressure in the surrounding ground. The results have been analysed in terms of the ratio τ_{sf}/σ'_v $(=\beta)$. The case records cover a wide range of pile types, causes of negative friction and length of period of measurement. It is shown that for most normally consolidated sediments β lies in the range -0.2 to -0.35 which is consistent with driven piles in these materials. However, for low plasticity sensitive marine clays, lower values in the range -0.15 to -0.25 are obtained. Negative friction is shown to mobilize at relative displacements of about 10mm. It is concluded that the effective stress β approach is both simple and reliable.

INTRODUCTION

Johanneson and Bjerrum (1965) made measurements of the compression of a steel pile driven through soft marine clay to rock. The compression was caused by negative shaft friction from consolidation of the surrounding clay under a surcharge. The deduced shaft friction down the pile was approximately distributed as the effective vertical stress during consolidation. A reasonably good agreement was obtained between the observed and computed distribution of compression of the pile when the negative shaft friction at any depth was assumed equal to σ'_v.K.tan ϕ'_a where σ'_v is the vertical effective stress at that depth and K.tan ϕ'_a was assumed to be constant along the pile. This approach gave considerably better agreement than a distribution of shaft friction based on the variation of undrained strength down the pile.

The above paper was one of the first to treat the shaft friction of piles in clay in terms of effective stress. Much research since then has shown that the shaft friction is governed by the Coulomb equation

$$\tau_{sf} = \sigma'_{rf}.\tan\delta' \quad\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where σ'_{rf} is the effective radial stress acting on the shaft at failure and δ' is the angle of interface friction. The magnitude of σ'_{rf} is a function of the effective vertical stress σ'_v, the initial at rest horizontal effective stress σ'_{ho}, installation effects and loading effects. Dividing through by σ'_v, equation (1) can be re-written as

$$\tau_{sf}/\sigma'_v = \beta = K_{sf}.\tan\delta' \quad\ldots\ldots\ldots\ldots\ldots(2)$$

The parameter β is the shaft friction factor defined by Burland (1973). It may be obtained purely empirically from pile tests or by soil mechanics methods through the expression K_{sf}.tan δ', where K_{sf} is the earth pressure coefficient for the shaft at failure. Bond et al (1992) have recently set out a procedure for analysing driven piles in terms of effective stresses. The empirical effective stress approach usually involves evaluating the mean shaft friction $\bar{\tau}_{sf}$ and mean vertical effective stress $\bar{\sigma}'_v$ giving the mean shaft friction factor $\bar{\beta}$. The results of numerous tests on driven piles in normally consolidated sediments generally give values of β between about 0.25 and 0.35 (Burland 1973 and Flaate and Selnes 1977).

In the time since Johanneson and Bjerrum published their classic paper on negative friction, a number of experimental studies have been published. The purpose of this paper is to review the results in terms of the simple effective stress equation (2) so as to assess its relevance and derive the range of β values.

CASE RECORDS

Johanneson and Bjerrum (1965)

As mentioned in the Introduction, measurements were made on a 53m long hollow steel pile driven through soft, low plasticity marine clay to rock at Sorenga in Oslo harbour. The local compression of the pile was measured by means of telltales consisting of a series of guided steel rods leading from the top of the pile to various measuring points. Settlement points and piezometers were installed in the surrounding clay at various depths. A ten metre thickness of fill was then placed around the pile so as to induce consolidation of the clay.

Fig. 1 shows the deduced distribution of local negative shaft friction with depth some two years after commencement of the experiment when the surface settlement was about 1.7m. Also shown are the local values of β derived from a knowledge of the vertical distribution of σ'_v. It can be seen that over most of the pile in the clay the values of β lie between about -0.15 and -0.25. Near the bottom the value is higher, being -0.37. This may be due to the presence of sand layers near the bottom of the profile. It should

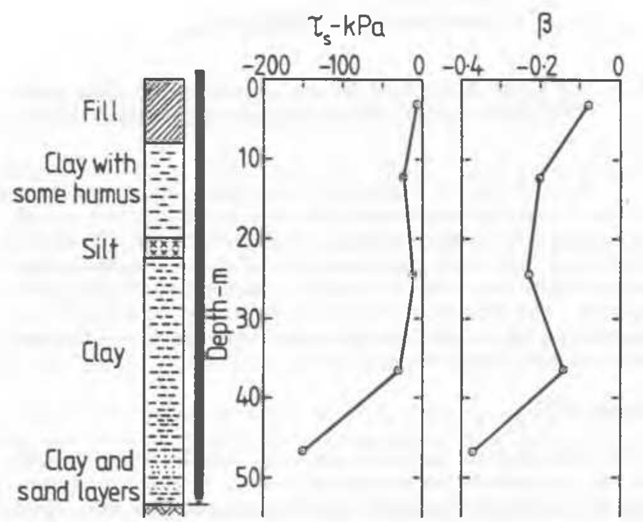

Fig. 1. Steel tubular pile driven through marine clay to rock. Consolidation caused by fill. (Johanneson and Bjerrum 1965)

also be borne in mind that the interpretation of telltale measurements is difficult as they are sensitive to the effects of eccentricity (known to be present here). Johanneson and Bjerrum found that an average value of β= -0.2 gave satisfactory agreement between the measured and computed distribution of compression for the two year measurements.

Bjerrum, Johanneson and Eide (1969)

These authors report the results of a number of additional tests on tubular steel piles driven to rock through deposits of soft clay. Two additional piles at Sorenga gave average values of β equal to -0.2 and -0.23. A pile at Heroya gave a higher average value of -0.26 which was thought to reflect the more silty nature of the clay.

Endo et al (1969)

These tests were carried out on tubular piles instrumented with local LVDT strain gauges which allow a more precise determination of the load distribution down the pile. Most of the piles were driven through soft clayey and silty alluvium onto dense fine sand as shown by the soil profile in Fig. 2(a). A large number of piezometers and settlement gauges were installed in the surrounding ground. The consolidation of the alluvium was due to a depressed piezometric head in the underlying sand. The loads took about three years to fully develop during which time the settlement of the ground surface was about 120mm. Fig. 2(b) shows the distribution of shaft friction for two closed ended piles (one of them battered). It can be seen that the agreement between them is excellent. At a depth of about 28m the negative shaft friction reaches a maximum and begins to reduce eventually becoming positive. The downdrag forces were carried by a combination of shaft friction over the bottom 10m and end bearing. Also shown are the results of a shorter closed ended 'floating' pile.

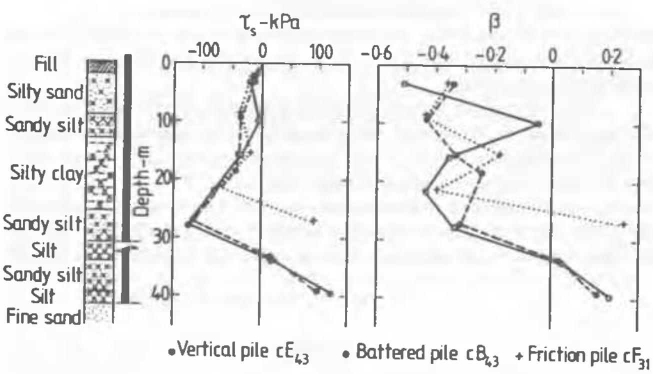

Fig. 2. Steel tubular piles driven through silty alluvium to dense sand. Consolidation caused by under-drainage from sand. (Endo et al 1969)

The local values of β are shown in Fig. 2(c) and lie between about -0.2 and -0.4 over the fully developed zone with an average value of -0.32 (measurements on a single open ended pile gave a lower average value of β=-0.21). It can be seen that there is a relatively short transition zone between fully developed negative values of β and positive values of similar magnitude. Measurements of the relative displacement between pile and adjacent soil above and below the neutral point suggest that about 10mm was required to fully mobilize the shaft friction.

Bozozuk (1972)

A 49m tubular steel pile was driven open ended through a 9m high test fill into soft, low plasticity Berthierville marine clay. Relative compressions along the pile were measured with carefully machined push rods. Four piezometers were installed between 6m and 27m depth. Analysis of the results at 5 years after installation show that within the fully developed zone of negative friction the values of β varied from -0.12 to -0.2 with an average of -0.16.

Walker and Darvall (1973)

A closed ended tubular steel pile was driven through 2m of recent fill, 7m of medium sand, 15m of firm silty clay, 3m of sandy silt into dense sand and gravel. The pile was instrumented with electrical resistance strain gauges at selected levels. The surrounding ground was instrumented with settlement gauges and piezometers. After installation of the pile, 3m of fill was placed over the site. Over the period of 4 months of measurements the ground surface settled about 35mm. Within the medium sand layer local values of β=-0.74 to -0.96 were measured. Within the firm silty clay β reduced from -0.51 at the top to -0.15 lower down. It seems probable that shaft friction was fully mobilized only in the top 2m or 3m of this layer.

Garlanger (1974)

A steel H-pile for a bridge abutment was driven through 7.6m of fill, 4m of sand and 15.2m of soft low plasticity clay into a dense glacial till. Seventeen years after the bridge was completed, the distribution of local shaft friction was determined by measuring the rebound of the pile as it was cut free from the abutment and after using electro-osmosis. Values of β between -0.2 and -0.25 were deduced for the soft clay.

Auvinet and Hanell (1981)

The effect of negative friction on two precast concrete piles driven into highly plastic Mexico City clay was investigated at a location where intense pumping was inducing consolidation. The piles were triangular in cross section and load cells were installed at intervals down the pile. Piezometers and settlement gauges were installed in the surrounding ground. During the ten month period after installation, the ground surface settled about 100mm whereas at the tip of the pile the corresponding settlement was about 20mm. The deduced local values of β ranged from -0.26 to -0.38 with an average value from the two piles of -0.30. Auvinet and Hanell concluded that a relative displacement between shaft and soil of about 20mm was required to fully mobilize the shaft friction. The precise reasoning behind this conclusion is not clear and the figure is believed to be an upper limit.

Keenan and Bozozuk (1985)

The development of negative friction on a group of three piles was observed over a period of 6.5 years. The piles were closed ended tubular steel, 32m long and driven through a 12m thick granular fill into a deep deposit of soft clayey silt - see Fig. 3(a). The piles were instrumented with telltales. Fig. 3(b) shows the measured distribution of shaft friction for two of the piles. The agreement between them is good. The distribution of β for the two piles is shown in Fig. 3(c). A striking feature is the sharp transition from fully developed negative values to positive values over a distance of about 3m. Within the zone of negative friction the values of β for the clayey silt lie between -0.25 to -0.4. The range is much larger for the granular fill.

Leung, Radhakrihnan and Tan (1991)

This case study involved the measurement of downdrag on two precast reinforced concrete piles driven through soft highly plastic Singapore marine clay into residual soil and weathered rock - see Fig 4(a). Of particular interest is the fact that the piles formed part of the foundations for the reinforced concrete deck of a stacking area and their performance under long-term loading was observed. The piles were instrumented with vibrating wire strain gauges welded onto the steel reinforcement at a number of locations along each pile.

Fig. 4(b) shows the distribution of shaft friction down the two piles about two years after commencement of construction. It can be seen that both piles were subject to downdrag from the soft marine clay - probably as a result of dissipation of pore water pressures set up during pile driving. The corresponding values of β are plotted in Fig. 4(c). It is evident that the magnitudes steadily reduce from about -0.35 near the top of the clay to zero at the neutral point. This is indicative that the zone of negative friction had

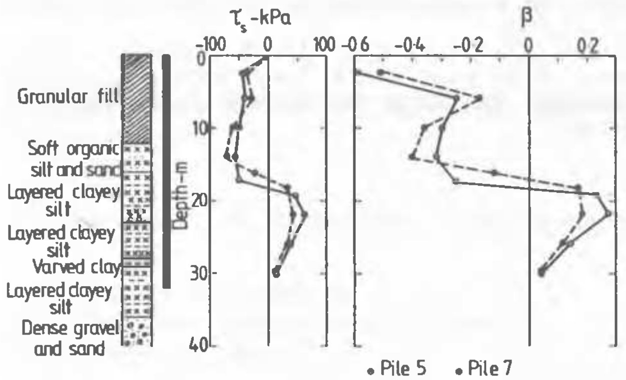

Fig. 3. Floating steel tubular piles beneath test embankment. (Keenan and Bozozuk 1985)

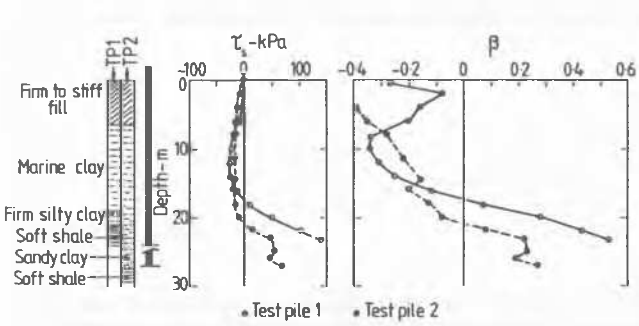

Fig. 4. Precast concrete piles driven through soft marine clay into stiff residual soil. Consolidation due to disturbance during driving. (Leung et al 1991)

only fully developed near the top of the piles and that further down the relative displacements between ground and pile were insufficient to mobilize full negative friction.

Indraratna et al (1992)

Short-term pullout tests and long-term measurements of negative friction were made on a hollow cylindrical prestressed concrete pile driven through soft highly plastic Bangkok marine clay into stiff clay. The pile was instrumented with load cells and telltales. The surrounding soil was instrumented with piezometers and settlement gauges. Negative friction was induced by placing a 2m thick fill on the surface.

After a period of about 9 months, negative friction had fully developed over much of the length of pile embedded in the soft clay. An average value of $\beta = -0.2$ was determined. This value was almost identical with the average value obtained from the short-term pull-out tests. It would appear from the measured distribution of settlement with depth that the relative displacement between pile and soil required to fully mobilize the negative friction was less than 10mm.

DISCUSSION AND CONCLUSIONS

In this paper ten case records of measured negative shaft friction have been briefly reviewed and analysed in terms of the shaft friction factor β. The case records cover a wide range of conditions. The types of pile vary from point bearing through friction plus end bearing to 'floating'. Both steel and concrete driven piles are considered. The causes of negative friction include surface surcharge, underdrainage and disturbance during pile driving. For one of the cases the piles were subjected to significant working loads. The periods of measurement varied from a few months up to seventeen years. Inspite of the wide range of conditions, average values of β for soft compressible sediments are found to lie within relatively narrow limits of -0.15 to -0.35.

A careful study of the soil types reveals that for low plasticity marine clays the values of β are generally in the range -0.15 to -0.25 whereas for higher plasticity clays and silty clays β tends to lie between -0.2 to -0.35. It is of considerable interest to note that values of β deduced from pile loading tests on normally consolidated sediments tend to lie in the range 0.25 to 0.35 (Flaate and Selnes 1977). However recent research has shown that for sensitive low plasticity materials, significantly lower values can be obtained (Karlsrud et al 1992). Therefore, it would appear that the values of β operating for negative friction are very similar to those associated with driven friction piles.

For fill materials the values of β are very variable and can be as high as 1. The single result for negative friction in firm clay indicates that, provided sufficient relative displacement is generated, the magnitude of β may exceed -0.5.

The pull-out test described by Indraratna et al (1992) suggests that β is not significantly rate dependent and can be evaluated from pile tests even though negative friction may take a much longer period to develop.

Direct evidence for the magnitude of the relative displacement required to fully mobilize negative friction is not easy to come by and loading or pull-out tests can be misleading. A study has been undertaken of those case histories where the vertical distribution of settlement in the ground adjacent to a pile can be compared with the length of the transition zone around the neutral point. It appears from this that such relative displacements are of the order of 10mm. Further research is required on this matter.

It can be concluded that the effective stress β approach to the analysis of negative friction in piles is both simple and reliable.

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