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A finite element analysis of a cohesionless soil under the pullout loading of a plate anchor

Analyse par éléments finis d'un sol pulvérulent sous l'action d'une plaque d'ancrage arrachée

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ABSTRACT : Anchors are used in order to sustain structures subjected to considerable tensile forces such as suspension bridges, transmission towers, etc...

An axisymmetric finite element analysis of the behaviour of plate anchors embedded in cohesionless soils is carried out. Shallow and deep circular anchors loaded by a vertical pullout force are considered.

First, the behaviour of the soil was observed under such a loading using a Mohr-Coulomb yield criterion for the stress-strain relationship. The deformation of the soil mass and the expansion of the plastic zone are shown. Finally, the results are compared to those obtained by other authors on small scale models.

RESUME : Les ancrages sont utilisés pour les structures sollicitées par des forces de traction considérables telles que les ponts arcs et suspendus, les tours de transmission, etc...

Une analyse par la méthode des éléments finis du comportement de plaques d'ancrage à symétrie axiale enterrées dans des sols pulvérulents est effectuée. On considère des plaques circulaires enterrées à faible et grande profondeurs sous l'action de forces verticales. D'abord, le comportement du sol est observé en utilisant le critère de plasticité de Mohr-Coulomb. La déformation de la masse de sol et l'expansion de la zone de plastique sont montrées. Enfin, ces résultats sont comparés à ceux obtenus par d'autres auteurs sur des modèles réduits.

1 INTRODUCTION

Ground anchors are used for anchoring structures that transmit considerable tensile forces to their foundations. Such structures are high-mast transmission towers, suspended or arch bridges, off-shore structures, structures supporting excavations, and many others. A detailed description of ground anchors has been given by Hanna(1982).

A plate anchor consists of a plate, usually made of metal or concrete, connected to the anchored structure by means of a tie rod or cable. With respect to figure 1, we consider anchor plates of diameter D buried at depth H in sand. The soil properties are the Young's modulus of elasticity E, Poisson's ratio ν, the angle of internal friction ϕ , the relative density D_r and the unit weight γ. The anchor is loaded by an uplift force P.

The main objectives is to attempt to predict the the effect of the friction angle and the embedment depth, the load displacement relation for anchor up to collapse and their failure mechanisms.

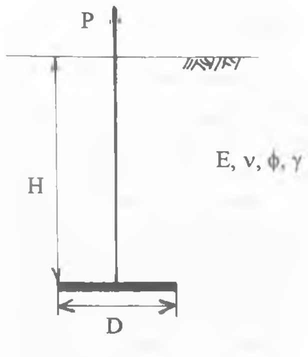

Figure 1 Soil-anchor model

2 BACKGROUND

For over thirty years, experimental and theoretical studies have been carried out by many authors in order to predict the behaviour of plate anchors in soils. The experimental studies consist of model and field tests while most of the numerical studies use analytical and finite element techniques.

2.1 *Model and field tests*

Balla (1961) was the first to establish a systematic method to design ground anchors in sands based on insitu and laboratory model tests. This work was continued by Matsuo (1968), Meyerhof and Adams (1968), Fadl (1981), Bouazza (1991), Ghaly and Hanna (1994) and many others in order to establish a general method for calculating the soil uplift resistance to tensile forces transmitted to buried plates. However, before such methods can be established, an increased understanding is required of the relative importance of the many variables associated with uplift resistance and of the nature of the failure mechanism.

Some small scale model studies were carried out on centrifuges, Dickin and Leung (1983). These studies take into account the mass forces which have an important effect on the anchor behaviour.

2.2 *Semi-empirical theories*

Since the early sixties many authors attempted to develop a general theory to determine the uplift capacity of anchors based on the shape of the failure surface.

Balla (1961) and Matsuo (1968) took into account the effect of the friction angle ϕ in their calculations without considering other material parameters. Later, Fadl (1981) considered the effect of the relative density. However since he used only one type of sand in his experiments, it was thus impossible to separate the effect of relative density from that of friction angle. Results obtained by Bouazza (1991) show clearly that different sands having the same friction angle give different responses and different sands having the same relative density give different responses too. These results show that characterisation of sand in terms of ϕ alone or D_r alone is inadequate.

2.3 *Numerical studies*

Several linear analytical techniques to study the elastic behaviour of soils under anchor loading have been reported ; Fox (1948), Rowe and Booker (1979, 1981), Selvadurai (1981). However, the behaviour of soil in general and that of sand in particular is not elastic and, consequently such methods cannot give reliable results even at working loads. The finite element method has been used more recently, Rowe and Davis (1982), Ito and Kitahara (1982), Vermeer and Sutjiadi (1985), Desai et al (1986). The major difficulties in their use arise from the determination of appropriate stress-strain relations for sand.

3. SOIL-ANCHOR MODEL

3.1 *The axisymmetric problem*

For a three-dimensional soil mass which is symmetrical about its centreline axis (which coincides with the z-axis) and which is subjected to loads and boundary conditions that are symmetrical about this axis, the behaviour is independant of the circumferential coordinate θ. Figure 2 shows the axisymmetric anchor problem. The circular anchor is assumed to be rigid and very thin. A typical mesh giving reasonably accurate results is shown in figure 11 after deformation.

3.2 *The boundary conditions*

In the soil-anchor model the boundaries should be at sufficient distance from the anchor so that they do not affect the anchor response.

Two types of boundary conditions were considered as shown in figure 3. The conditions along the centreline (which is the axisymmetric axis) imply no horizontal displacements. The lower and lateral boundary conditions can either be smooth (a) or rigid (b). The slight effect of these two boundary conditions on the pull-out capacity was analysed and shown in figure 4.

4. FINITE ELEMENT ANALYSIS

The axisymmetric finite element program used in this study considers four-, eight- and nine-node isoparametric quadrilateral elements. Point loads, gravity and distributed edge loadings can be handled by the program as well as loading due to initial stresses and non-zero prescribed displacements.

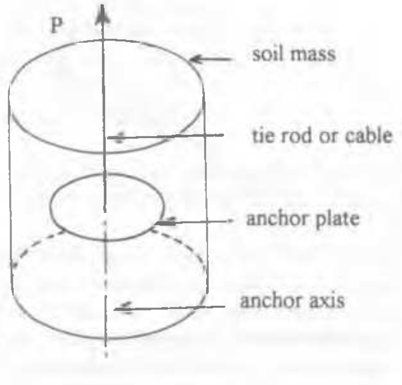

Figure 2. Axisymmetric anchor problem.

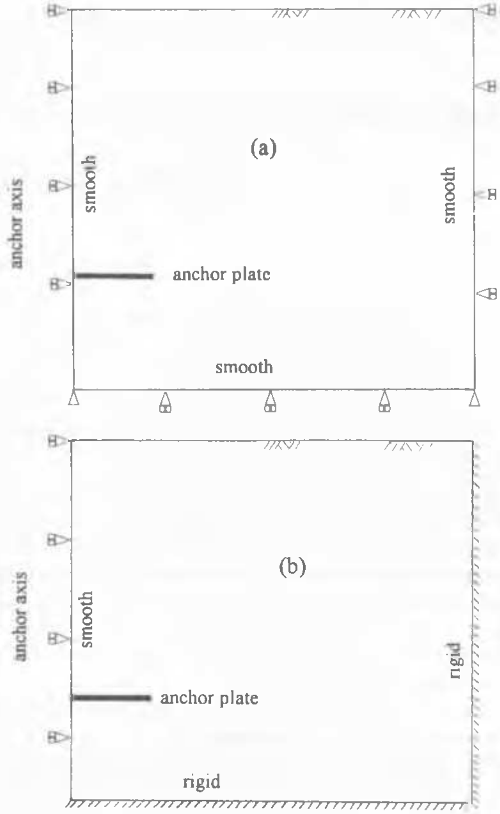

Figure 3. Smooth (a) and rigid (b) boundary conditions.

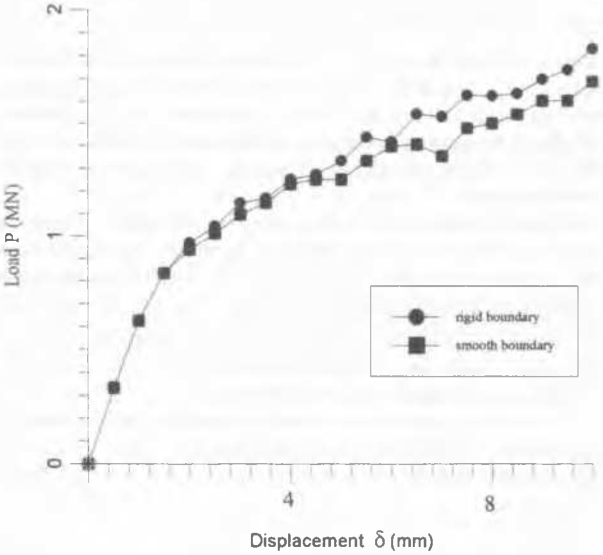

Figure 4 Effect of boundary conditions

4.1 *Finite element mesh and quadrilateral element*

A typical mesh giving reasonably accurate results but without unreasonable number of elements is shown in figure 10. To determine the optimum pattern, a detailed convergence study was done. For a shallow anchor embedded at H/D=2.5 four meshes with 16, 30, 49 and 100 elements were studied. The curves of figure 5 show that, as expected, meshes with lesser number of elements give a stiffer response. Meshes with larger number of elements give naturally more accurate results but more cpu-time. From δ=8mm onwards the curves converge with less than 6% difference. For major problems involving shallow anchors, a 30-element mesh is adopted since the major

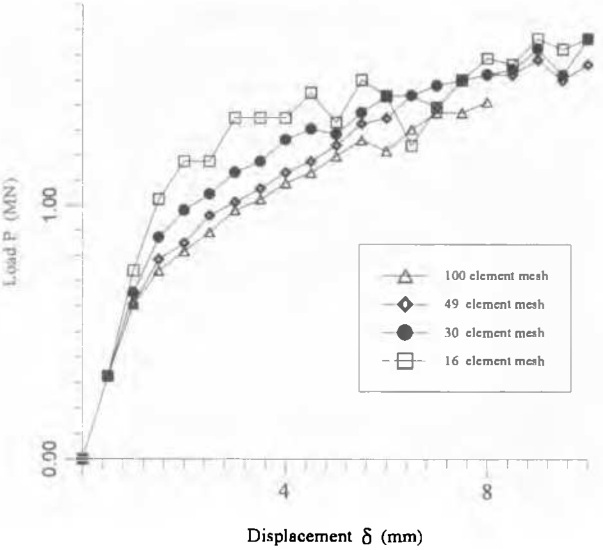

Figure 5 Effect of mesh size.

objective is to determine the collapse load.

The finite element used in this study is an eight-node isoparametric quadrilateral called Serendipity element (figure11).

4.2 *Constitutive law*

Four yield criteria are available in the program : Von Mises, Tresca, Drucker-Prager and Mohr-Coulomb. The Mohr-Coulomb criterion was employed in this study with an associated flow rule.

4.3 *Failure load*

Rowe and Davis(1982) reported that at greater depths of embedment, the deformations before collapse are so large that practical failure may be deemed to have occurred at a load less than the collapse load. The authors used finally the so-called k_4 failure load concept. The k_4 failure load is the load which produces four times the displacement that would have occurred if the soil remained elastic. This k_4 failure load concept is used in this study for both shallow and deep anchors.

5 RESULTS

After choosing suitable numerical parameters for a good convergence process, results concerning some geometry and material parameters are presented in this paragraph. Attention is foccussed on the effects of the friction angle and the embedment depth, the yield propagation and the soil deformation. Some results are given in terms of Nq (break-out factor) $N_q=4P/\pi D^2\gamma H$ and $\xi=\delta E/\pi D^2\gamma H$ which are load and displacement dimensionless parameters, respectively.

5.1 *Effect of friction angle*

The effect of the friction angle was investigated on both shallow and deep anchors.

Shallow anchors

Figure 6 shows the load-displacement curves for a shallow anchor using four types of sand (ϕ=30°, 35°, 40°, 45°). The plots show that the angle of friction has no effect on the soil-response on the linear part of the curve. However, when the material behaviour is elasto-plastic the effect of the friction angle becomes sgnificant and has a major influence on the anchor pull-out capacity.

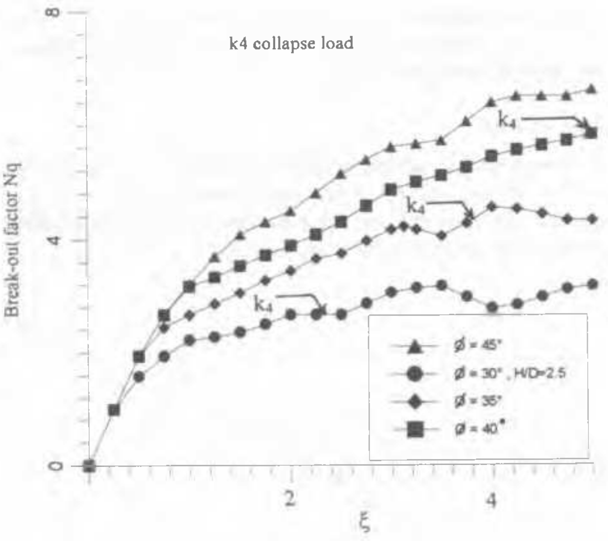

Figure 6. Effect of ϕ on shallow anchors

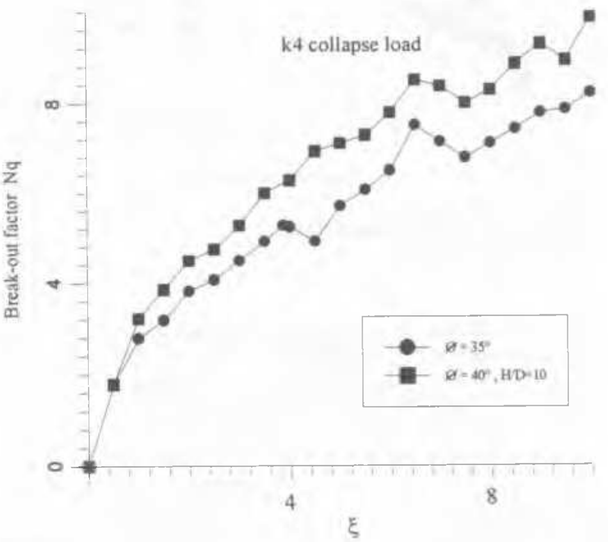

Figure 7. Effect of ϕ on deep anchors.

Deep anchors

Figure 7 shows an identical anchor response at an embedment depth H/D=10 for two types of sand (ϕ=35° and 40°).

5.2 *Effect of embedment depth*

The effect of embedment depth has been investigated on plates embedded at H/D=2.5, H/D=5 and H/D=10. Figure 8 shows that the uplift capacity of the anchor increases when the ration H/D increases.

5.3 *Yielding propagation*

Initiation and propagation of yielding in the sand around anchors at H/D=2.5 and H/D=10 is examined. The friction angle of sand is 35° for both shallow and deep anchors.

Shallow anchors

For shallow anchors yielding initiates from the anchor edge and the ground surface near the anchor axis at 20% of the ultimate uplift load (figure 9). These two small zones expand and propagate towards each other until they meet at a load equal to

60% of the ultimate anchor force. At the ultimate load, the shape of the plastic zone limit is reminiscent of the slip surfaces proposed by Balla and Matsuo.

Deep anchors

For deep anchors yielding initiates near the edge of the anchor at 40% of the ultimate uplift load. When the pullout force reaches 90% of its ultimate value another yielding zone initiates at the ground surface near the anchor axis (figure 10).

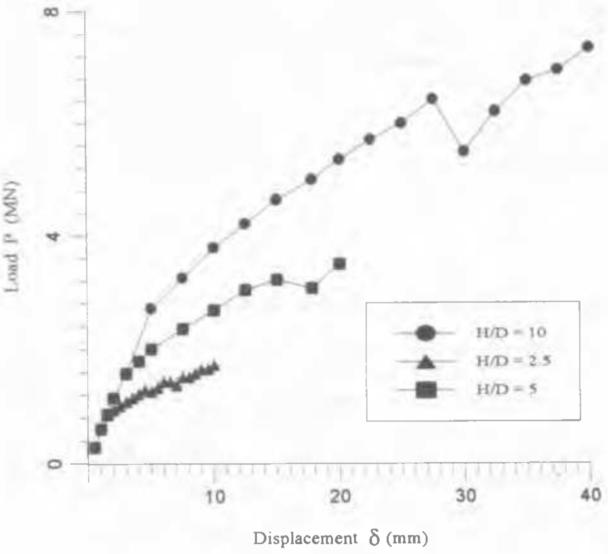

Figure 8 Effect of embedment depth.

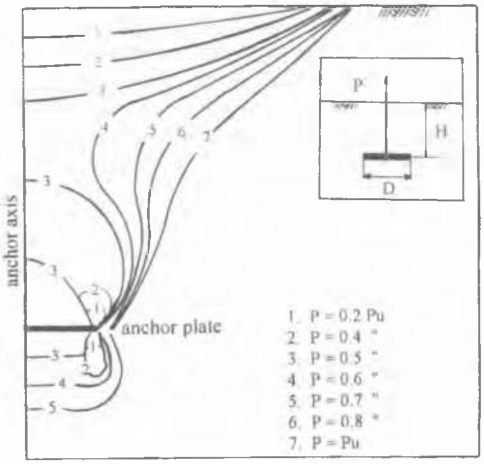

Figure 9. Propagation of yielding for shallow anchor. (Pu=1.4 MN, γ=20kN/m^3, H/D=2.5)

5.4 *Mesh deformation*

Figure 11 shows the deformation of the sand around an anchor plate buried at shallow depth (H/D=2.5). The region close to the anchor plate is most affected by the loading, more particularly points near the edge of the plate. Mesh elements located near the anchor edge undergo large displacements and necking occurs in the elements situated below the anchor plate. However, the elements which are remote from the anchor axis retain their initial form and are relatively unaffected by the anchor loading.

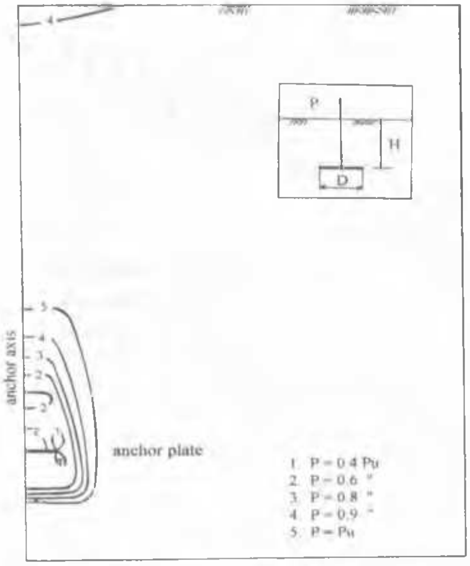

Figure 10. Propagation of yielding for deep anchor. (Pu=8.8 MN, γ=20kN/m^3, H/D=10)

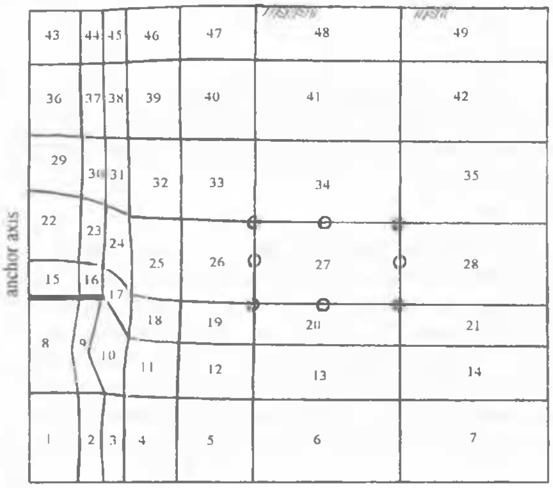

Figure 11. Deformation of soil for shallow anchor (displ.x100).

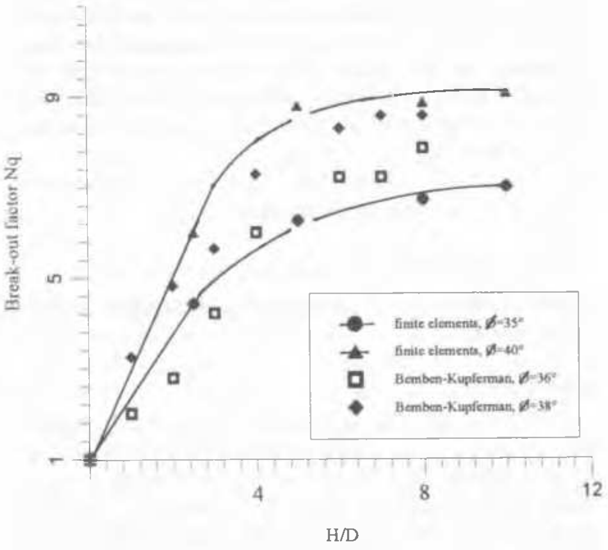

Figure 12. Comparison with experimental results

5.5 *Comparison with experimental results*

Figure 12 shows the variation of the uplift capacity of plate anchors with depth of embedment at various values of friction angle. The results from the finite element study are compared with the experimental results of Bemben and Kupferman (1975). These tests were carried out on two sands in a loose state. The first is a silty sand known as BBY sand (ϕ=36°) and the second is a medium to fine sand known as Sunderland sand (ϕ=38°). The finite element results appear to be in general in good agreement with these experimental results.

6 CONCLUSIONS

1. The pull-out factor N_q increases with the embedment depth ratio H/D.
2. The pull-out factor N_q increases with increasing angle of internal friction ϕ
3. At ultimate load, yielding affects all the soil located between the anchor plate and the ground surface at shallow depths while it affects only the soil close to the anchor plate at greater depths.

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