MODEL GROUND ANCHORS UNDER GRAVITATIONAL AND CENTRIFUGAL ACCELERATIONS

Modèles réduits d'ancrage au sol en gravité normale ou en centrifugeuse

by

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SOMMAIRE

On traite de deux séries d'essais dans lesquels des plaques circulaires d'ancrage de 25 mm de diamètre, enfouies dans des couches de sable sec à l'intérieur d'un conteneur de 0.770 × 0.770 × 0.500 m, ont été testées sous un régime de contraintes correspondant aux ancrages in situ.

Les niveaux des contraintes ont été obtenus, soit par un vide à l'intérieur de la maquette dont la surface supérieure était scellée par une membrane en caoutchouc, soit par des forces centrifuges.

On présente des courbes efforts-déplacements pour des plaques d'ancrage verticales, tirées vers la paroi du conteneur, ainsi que le changement de la distribution de la contrainte normale sur ces parois pour des valeurs différentes de la position de l'ancrage.

On trouve que la flexibilité du conteneur est critique pour le résultat des essais sous vide. Par contre, les modèles en centrifugeuse où les mouvements latéraux sont bloqués, donnent des résultats plus réalistes.

En utilisant cette technique, on a mesuré des variations importantes de la force d'arrachement, au fur et à mesure que l'ancrage passe d'une position horizontale à une position verticale. Les forces d'arrachement sont inférieures à celles présentées normalement par d'autres auteurs.

SUMMARY

Two series of model experiments are reported in which circular plate anchors, 25 mm diameter, buried in beds of dense dry sand within a container 0.770 × 0.770 × 0.500 m, have been tested at effective stress levels appropriate to field anchors.

These stress levels have been obtained by evacuating the void space within the container which was sealed at the surface by a flexible membrane and exposed to external atmospheric pressure or by the action of inertial accelerations generated within a centrifuge.

Load-deflection data are presented for vertical anchor plates pulled towards the boundaries of the container together with changes in normal pressure distribution at these boundaries for a range of initial anchor positions.

Flexibility of the container is shown to have a critical effect on the results from the evacuated models.

The centrifuge models in which boundary deflection is restrained are shown to give more realistic results and using this technique significant changes in anchor pull-out load have been measured for variations in anchor inclination from horizontal to vertical. The pull-out loads have generally been lower than those predicted by other researchers.

INTRODUCTION

The ultimate resistance to tensile loading of buried plate anchors in sand has been studied by many authors and of the design methods proposed, that developed by Meyerhof and Adams (1968) and Meyerhof (1973) has the widest use, being applicable to anchors of any shape at any inclination from horizontal to vertical.

Most of the data which have been used to justify this or any other design method of general application have been provided by small scale laboratory models. However, scale effects in model work on cohesionless soils give rise to uncertainty in the extrapolation of results to field situations. The reduction of the mobilised angle of friction ∅ under increasing mean principal stress levels is well known — typically for a dense sand a reduction of the order of 5 degrees in ∅ per log cycle of effective stress. Associated with this reduction is a transition from brittle to plastic failure in soil elements and a trend towards increased displacements at failure, relative to model size.

De Beer (1970), Graham (1974) and Aboshi (1975) among others have reported a change from overall shear failure in small models of foundations under compressive loading, to punching shear at larger sizes and higher stresses. Mikasa and Takada (1973) have performed centrifugal model tests on both shallow and deep foundations under compressive loads and have presented visual evidence of the difference in failure mode of the same model between tests at unit gravity and others at 60 g. Krebs Ovesen (1975) has summarised the findings of his own centrifuge experiments along with those of Mikasa and Takada and of Cherkasov et al. (1970) and has shown that the variation in model failure loads associated with the different modes of failure at different accelerations is consistent with substantial reductions in ∅ with stress level increases. The results of centrifuge tests by Yamaguchi et al. (1976) on surface and shallow foundations show similar effects.

The implication is that more realistic design information for tension carrying foundations may be obtained from model experiments carried out at or close to field stress levels. In this context the centrifuge model is an attractive alternative to full scale experimentation.

The S.E.L. centrifuge has a capacity to accelerate upto 2,000 kg of soil to 140 g, i.e. an acceleration factor N = 140, and has been used well within this limit in a programme of testing model anchors in sand at inclinations from horizontal to vertical. A bolted aluminium container 0.770 m square × 0.500 m deep, with 16 mm walls was used for most of the experiments. The container was filled with air dry Mersey River sand deposited from a roller spreader. The range of porosities measured after deposition was 0.353 — 0.359 corresponding to a relative density of approximately 95%. The anchor plates were 25 mm diameter, 8 mm thick, attached to steel rods 4.75 mm diameter and were placed in every case at a depth 300 mm, below the upper, level soil surface at an inclination which varied from test to test but always coaxial with the load to be applied. Full details of the experimental techniques are given by Boon (1975).

TESTS AT UNIT GRAVITY

In order to carry out preliminary experiments at field stress levels without using the centrifuge the upper sand surface was covered by a thin rubber membrane and the void space of the soil mass was subjected to a partial vacuum.

Horizontal anchors were pulled by a pneumatic jack towards a wall of the container instrumented with total stress transducers. The anchor itself passed through a lubricated sleeving at the wall and the jack reaction was taken by a mounting frame of steel sections. Fig. 1 shows load-deflection results for a number of plate anchors initially located at different distances from the wall with a suction of 66 kN/m² applied in each case. The anchor shaft load in the absence of a plate was found to be consistently less than 0.08 kN. Defining failure arbitrarily at a deflection of 30% of the plate diameter the failure load is seen, fig. 2, to be sensibly independent of location relative to the wall in the range 6 - 12 plate diameters.

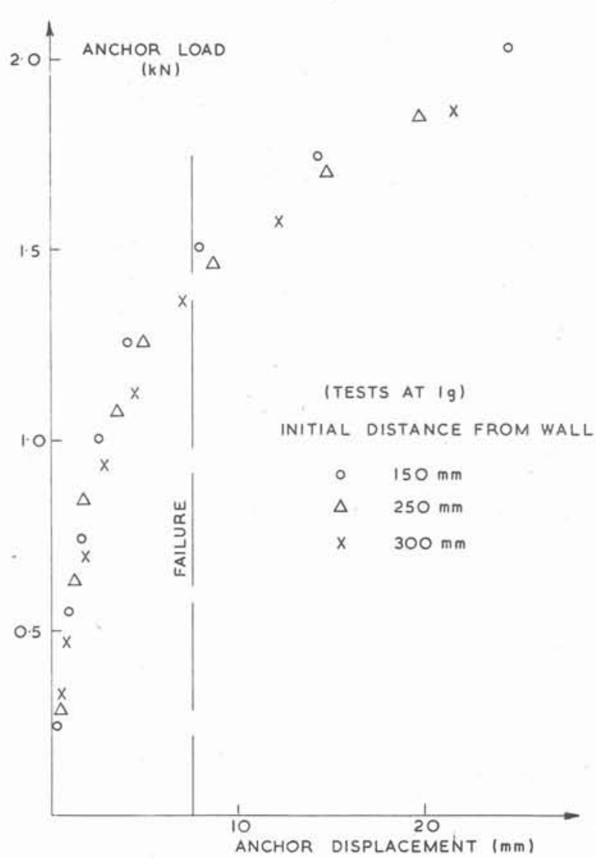


Fig. 1.

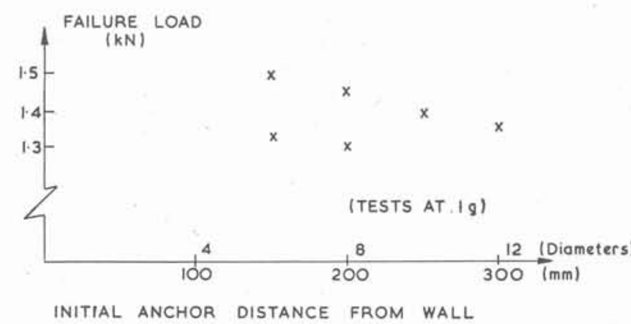


Fig. 2.

In a further series of tests on inclined anchors the applied suction was lowered to 57 kN/m² and the pneumatic jack, suitably mounted on the reaction frame, pulled the anchor rod either through a sleeve in the metal wall or through the rubber membrane. Results, fig. 3, show that the failure load increased as the inclination from the horizontal increased. The test arrangement is shown in fig. 4.

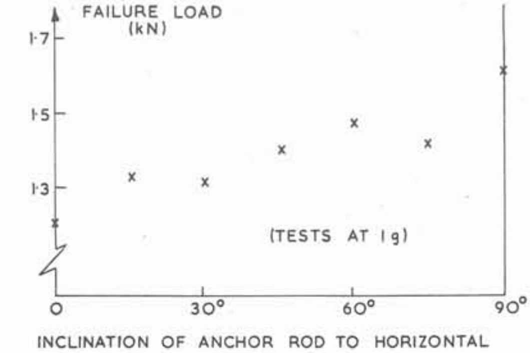


Fig. 3.

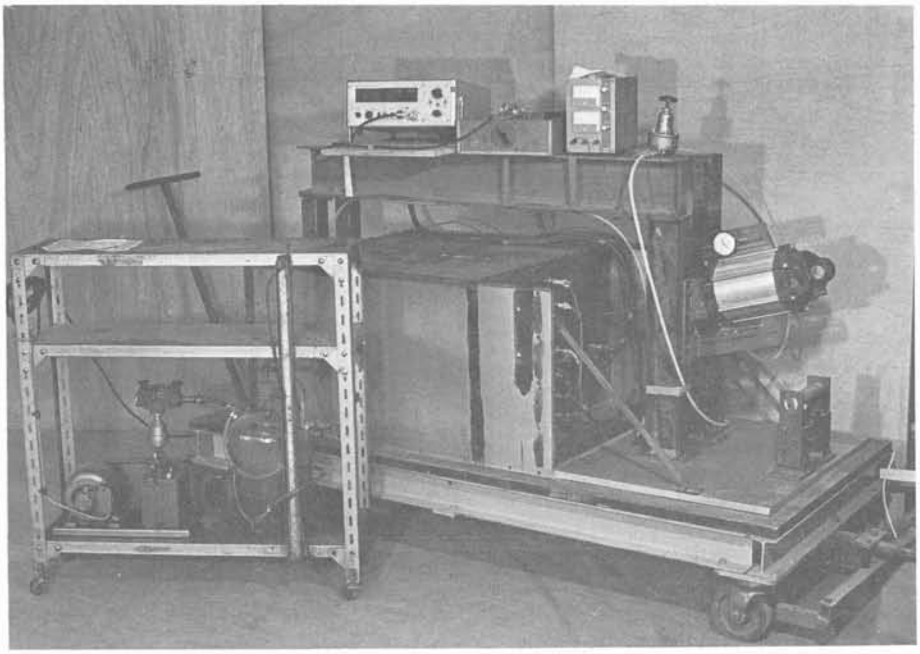
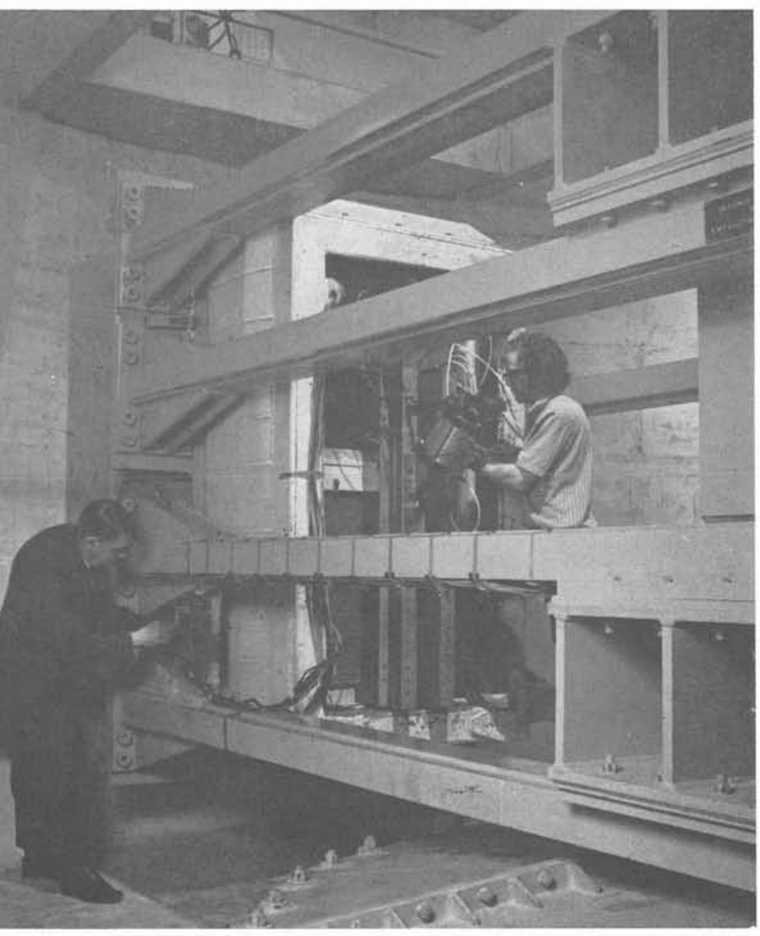


Fig. 4.

Under the action of the applied suction the box walls deflected inwards by upto 0.4 mm and the total stresses measured on the boundaries indicated initial K values ($K = \sigma'_H/\sigma'_V$) of approximately unity. The results of the pull-out tests are consistent with an initial hydrostatic pressure distribution yielding a bed of essentially uniform strength at all depths and the higher loads on vertical anchors are associated with increased gravity effects in this direction.

TESTS UNDER INCREASED ACCELERATIONS



The SEL centrifuge has a rigid rotor 7.32 m in diameter which moves in a horizontal plane, generating a radial acceleration. In order to keep the free soil surface perpendicular to the acceleration, as in the field, this surface must be in a vertical plane and to achieve this with minimal disturbance it is necessary to fit a thin membrane over the surface and to apply a small suction to the sand mass until sufficient radial acceleration has been generated to hold the soil in place.

The model box was packed into a rigid container and with all four walls fully supported internally the suction was applied before the whole assembly was lowered into the test position, fig. 5. The suction was released when accelerations reached 5 g and the anchors tested under a steady accelerations of 26 g at the radius of the anchor plate, 2.94 m. Changes in wall pressure over the acceleration increment after

Fig. 5.

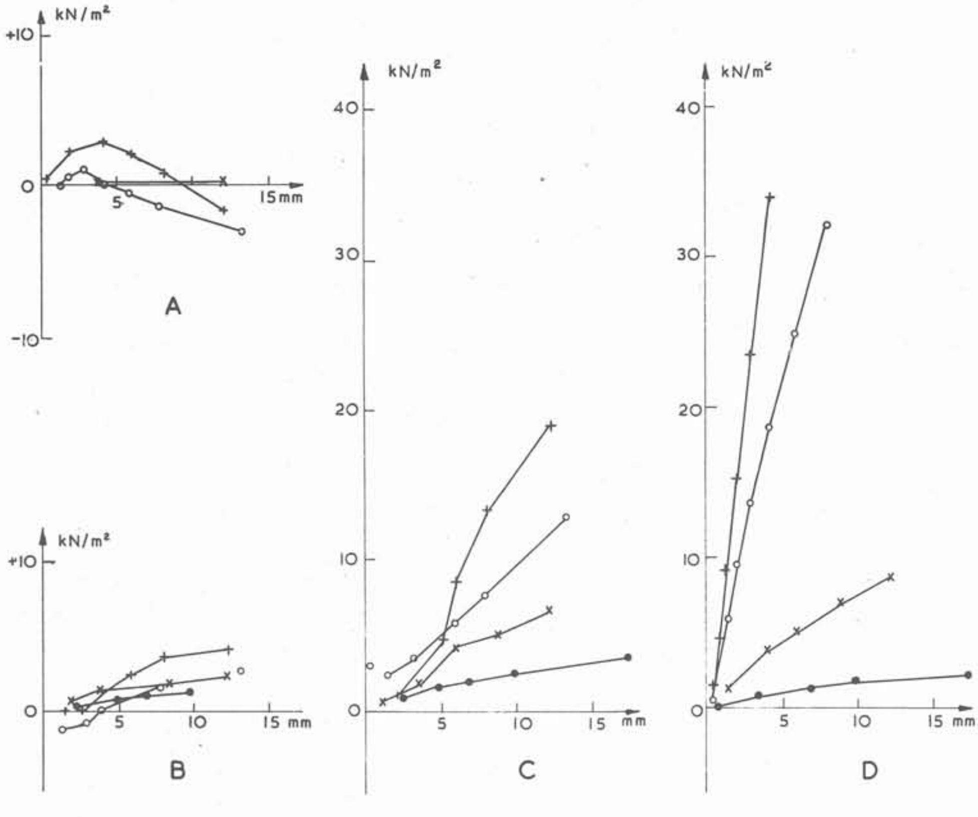
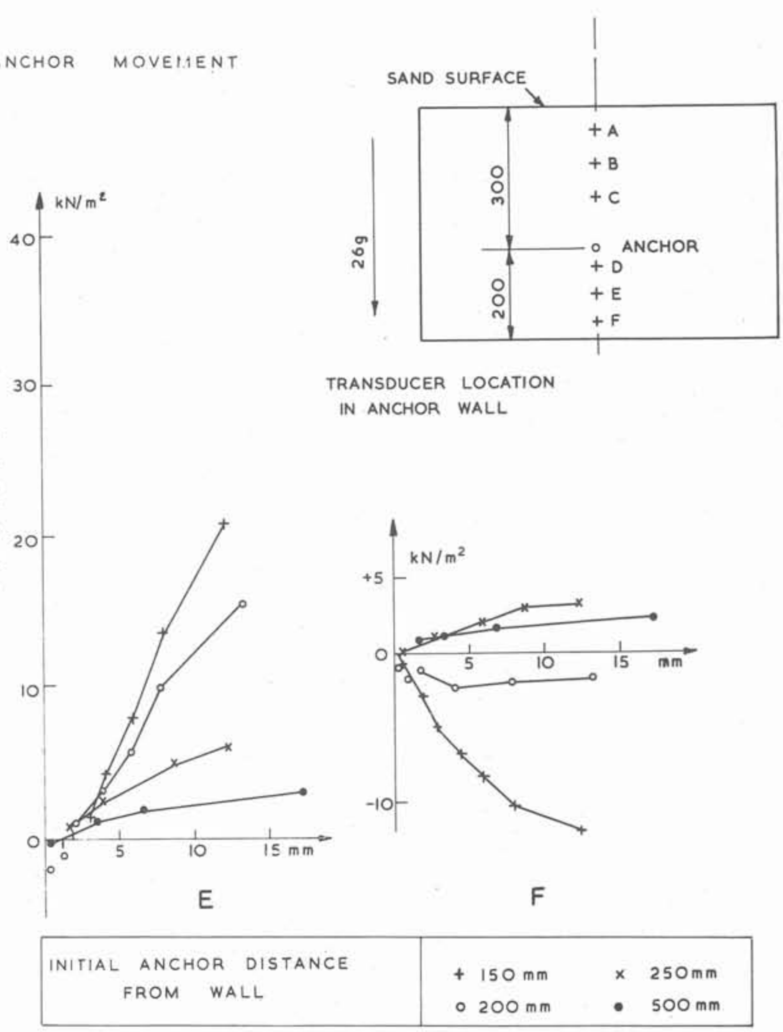


Fig. 7.

WALL PRESSURE CHANGES V ANCHOR MOVEMENT



releasing the suction were consistent with K = 0.25. At 26 g the models simulated field anchors 0.65 m in diameter at depths of 7.4 m.

Failure loads for a series of 'horizontal' anchors were again sensibly independent of initial position within the range tested, fig. 6, but the changes in measured wall pressure were greatly influenced by this variable, fig. 7. Detailed study of a single test with the anchor plate initially 8 diameters from the wall shows the development of pressure changes across and

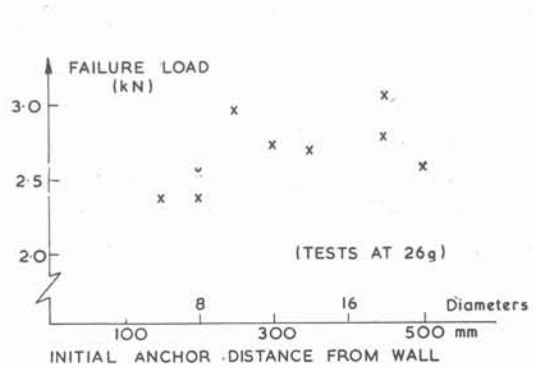


Fig. 6.

down the wall, fig. 8. The changes are symmetrical across the wall at the anchor level but are substantially higher below the anchor than above.

Limited results for tests on inclined anchors also carried out with N = 26, fig. 9, show a significant reduction in pull-out loads at inclinations of 45° and 90° from those measured on horizontal anchors. This figure also shows the failure loads predicted by the method of Meyerhof (1973) for a mean unit weight under centrifugal acceleration of 415 kN/m³ and a unique angle of friction of 41° measured in triaxial compression, for Mersey River sand at an appropriate mean stress level. In every case the prediction exceeds the observed failure load and while the difference can be reduced by considering anchor loads at displacements greater than the plate diameter a considerable discrepançy remains.

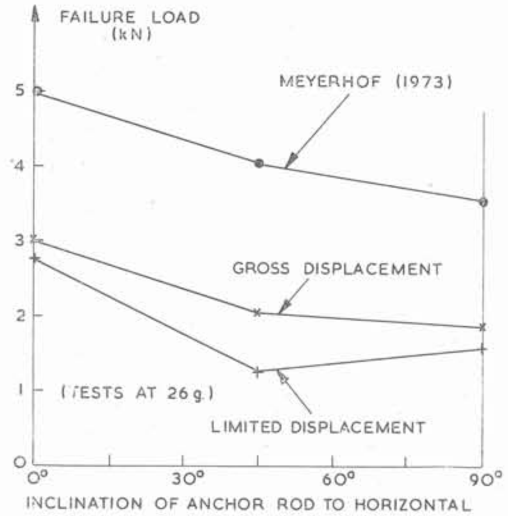


Fig. 9.

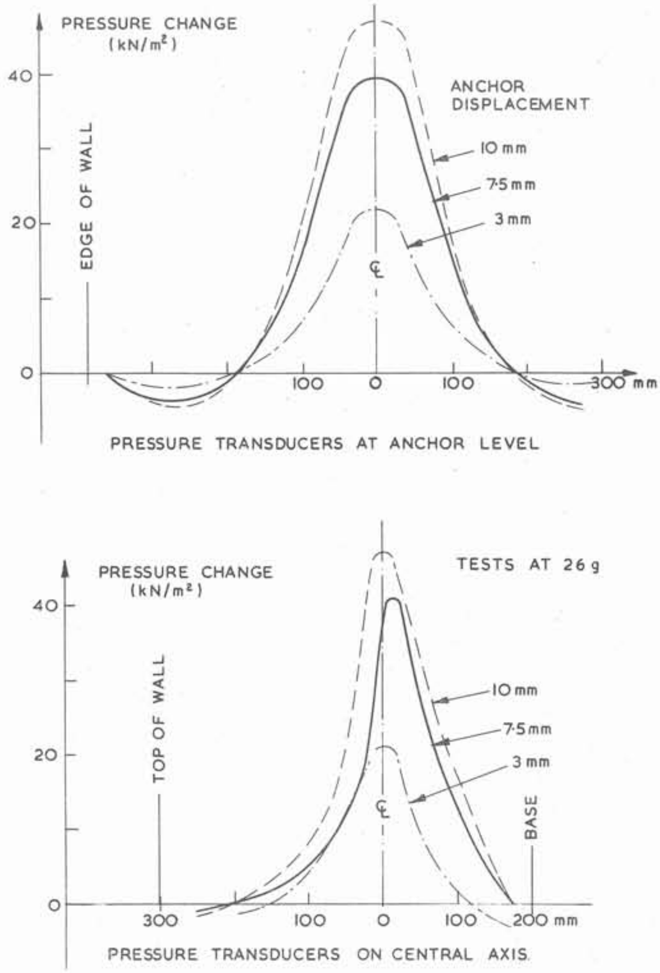


Fig. 8.

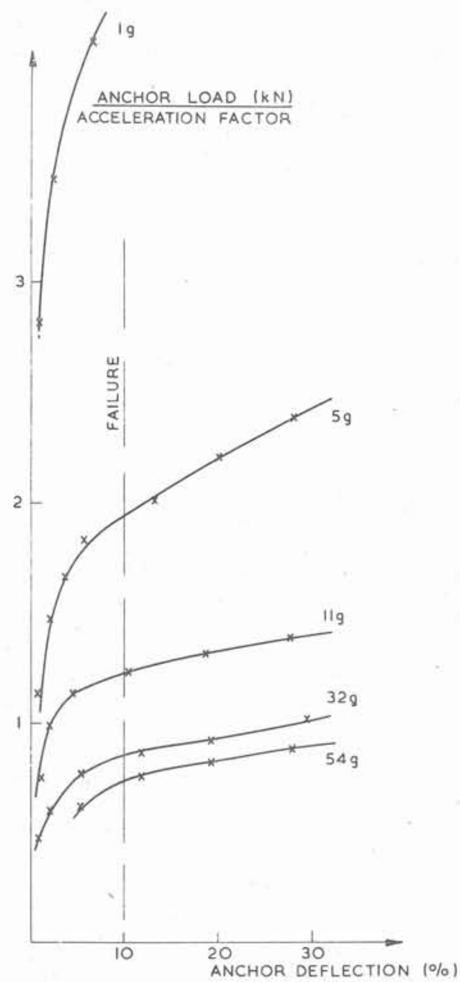


Fig. 10.

The prediction, developed from the results of Meyerhof and Adams (1968) assumes implicitly a limit to the zone of soil involved in the failure, based on observation of model tests at low stresses under unit gravity. However, this zone may be significantly reduced in size at higher stress levels with a subsequent lowering of the failure loads. No direct observation of the size of the 3-D zone of soil movement around circular plate anchors in the centrifuge has been possible, but observations on identical strip anchor models, pulled vertically in a plane strain configuration under different accelerations confirm that this zone is considerably reduced in the same manner as observed by Mikasa and Takada (1973) for the compressive loading situation.

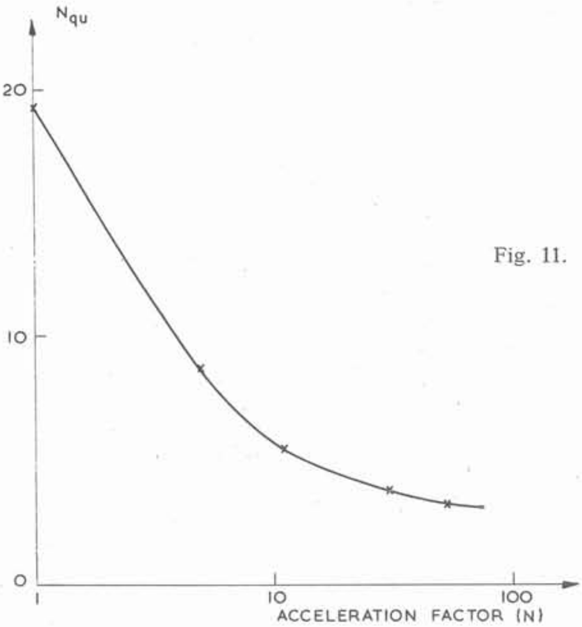


Fig. 11.

In order to assess directly the effect of changes in stress level on the failure of an anchor a 25 mm bar 152 mm long was pulled vertically, in a plane strain configuration in a box also 152 mm wide, from a depth of 340 mm towards the surface of a bed of River Mersey sand at the same initial density as used previously. The test was repeated at a number of different accelerations in the range 1 — 54 g. For ease of comparison fig. 10 shows the measured anchor loads divided by the acceleration factor as a function of the anchor deflection. Defining failure at a deflection of 10% of the width in these tests the dependence of the parameter N_{qu} and associated values of $\varnothing$, given by the analysis of Meyerhof (1973), on acceleration factor N is clear, fig. 11 and table I.

TABLE I

Acceleration Factor	Mean σ_v (kN/m^2)	N_{qu} (Observed)	$\varnothing$ (Deduced Meyerhof)	$\varnothing_{p.s.}$ (Tong)
1	3	19.4	50.0	51.5
5	15	8.7	39.0	48.0
11	32	5.5	32.5	46.0
32	93	3.8	26.5	43.5
54	157	3.3	23.0	42.5

Table I shows the mean vertical stress in the sand in each test before loading the anchors and the values of $\varnothing$ indicated for this material at the appropriate relative density from the plane strain element tests of Tong (1970) with minor principal stress of this magnitude. Allowing for this variation in friction angle the range of N_{qu} values predicted would be only one third of that observed. The difference appears to arise from the fact that the factors given by Meyerhof are based upon failure modes observed only in small model tests at unity gravity, i.e. low stresses. As Mikasa and Takada (1973) have shown, these will exaggerate the volumes of soil in the failure zone associated with geometrically similar models at higher accelerations and stress levels.

CONCLUSIONS

The design of field anchors in sand, based on data obtained from laboratory model experiments at low stress levels will be in error on account of the difference in stress level between the two situations. Adjustment of the design for changes in the angle of friction assessed in element tests at appropriate stress levels may partly eliminate the error but this will not necessarily take account of differences in failure mode if the design is still based on model test results with correct friction angles but incorrect stress levels. The centrifuge modelling technique provides a means of obtaining design data from models subjected to the failure modes appropriate to the correct stress levels.

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