Grid Mats—A New Foundation Method

Grid Mats—Une Nouvelle Méthode de Fondation

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SYNOPSIS A new foundation method, the grid mat method, is described which appears to be well suited for different offshore structures such as drilling platforms and lighthouses. The foundation elements which are used in this method are composed of open triangular or square cells which are joined together to form a grid. The grid mats can be adjusted to fit different bottom conditions. The bearing capacity, the lateral and the tensile resistance of the grid mats in fine sand have been investigated with model tests. The agreement between measured and calculated values was satisfactory.

INTRODUCTION

A new foundation method has been developed which appears to be well suited for different offshore structures such as drilling platforms, light houses etc. The grid elements used in this method are constructed of vertical thin steel plates, which are joined together in the form of open triangular or rectangular cells as shown in Fig. 1.

When the soil consists of dense sand or of stiff to hard clay and it is not possible to push the grid into the soil, they can be placed directly on the bottom as illustrated in Fig. 2a. The open cells are then filled with sand, gravel or rockfill. In soft clay or in loose sand the grids are pushed into the soil as shown in Fig. 2b. If the bearing capacity of the soil is very low the grids are combined with piles as illustrated in Fig. 2c.

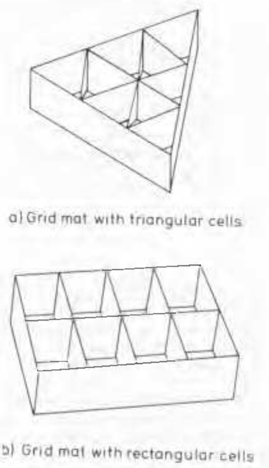

Fig. 1 Grid mat elements

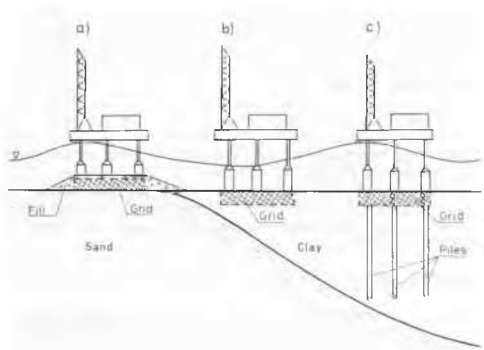

Fig. 2 Application of foundation grids in different bottom conditions

The flexural strength of the grid is high due to the large height of the elements. The lateral support provided by the soil enclosed by the cells is generally sufficient to prevent lateral buckling of the thin plates. At the top edge above the surface of the soil it may be necessary to increase the buckling strength of the thin plates with ribs.

The bearing capacity, lateral and pull-out resistance of the grid units is analyzed in this article and compared with results from model tests. A large number of load, direct shear and extension tests have been carried out on models composed of triangular or rectangular cells. The shape of the models has been varied as well as the relative density of the sand.

BEARING CAPACITY

Cohesive Soils

Failure of a grid mat unit in clay can be caused by two different mechanisms. The first failure mode, penetration failure, governs when the height of the cells is relatively small in comparison with the circumference of the individual cells. The second failure mode, bearing capacity failure, governs when the height of the cells is relatively large. Then the friction or the adhesion of the soil along the vertical plates is sufficient to prevent the extrusion of the soil through the cells.

The ultimate bearing capacity of the grid (Q_{ult}) at penetration failure is dependent on the total surface area A_m of the individual cells in contact with the soil and on the adhesion c_a between the clay and the cell walls

$$Q_{ult} = c_a A_m \tag{1}$$

The adhesion c_a is dependent on the undrained shear strength c_u of the soil and on the material of the grids. Experience from load tests with steel piles indicates that c_a can be 0.5 c_u when c_u <50 kPa and as low as 10 kPa when c_u >50 kPa. The scatter in the test results is large particularly when c_u >50 kPa.

Failure by exceeding the bearing capacity of the soil occurs when the cells are relatively high in comparison to the width. The ultimate bearing capacity of a square, triangular or circular grid unit can be calculated from

$$Q_{ult} = (7.5\ c_u + q_o)\ A_b \tag{2}$$

where q_o is the total overburden pressure at the bottom of the grid and A_b is the total bottom area. The adhesion along the outside perimeter of the foundation elements has been neglected in the derivation of this equation since the adhesion generally is relatively small.

Cohesionless Soils

Also for cohesionless soils the ultimate bearing capacity is either governed by the penetration resistance of the grid or by the bearing capacity of the soil. The bearing capacity at penetration failure can be analyzed by considering the forces acting on a slice with the thickness dh located at a distance h below the surface of the soil as indicated in Fig. 3.

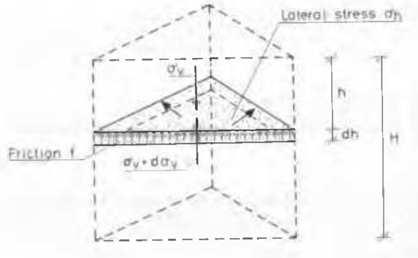

Fig. 3 Stress distribution within a cell

It has been assumed that the earth pressure distribution within the cells can be calculated by the same method as that used for silos. The pressure distribution and the penetration resistance are thus affected by the friction along the walls of the cells which increases with the overburden pressure and with increasing wall friction. The friction f along the perimeter of the slice can be calculated in terms of effective stress from

$$f = K\ \sigma_v\ tg\ \phi_a \tag{3}$$

where $K = \sigma_h/\sigma_v$ and ϕ_a is the wall friction. The stress increase $d\sigma_v$ can then be evaluated from $d\ \sigma_v\ A_b = \gamma g\ dh + f\ \theta\ dh$ where γ is the density of the soil, θ is the perimeter of a cell, A_b is the area of a cell and g is the acceleration due to gravity.

This equation can be simplified to

$$d\sigma_v = \left[\gamma g + \frac{K\sigma_v\ \theta\ tg\ \phi_a}{A_b}\right]dh \tag{4}$$

The solution of this differential equation is

$$\sigma_v = \frac{\gamma g\ A_b}{K\ \theta\ tg\ \phi_a}\left[e^{\frac{K\ \theta\ h\ tg\ \phi_a}{A_b}} - 1\right] \tag{5}$$

The penetration resistance has been calculated in Fig. 4 for cells with triangular and rectangular shap. It has been assumed that ϕ_a = 25 degrees and that the density of the soil within the cells is either loose (K=0.3) or dense (K=0.9).

It can be seen that the penetration resistance increases rapidly with increasing depth. The bearing capacity for cells with triangular shape is larger than that of the rectangular cells at the same penetration depth. The difference increases with increasing depth.

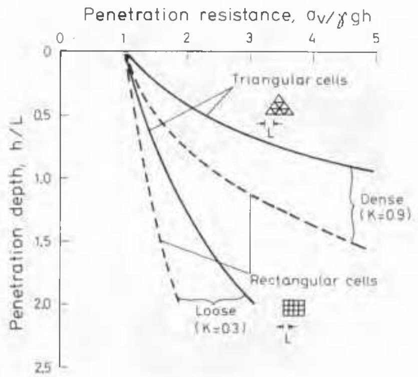

Fig. 4 Bearing capacity of a single cell at penetration failure in sand (ϕ_a = 25°).

The ultimate bearing capacity for cohesionless soils can be calculated from the general bearing capacity equation

$$q_c = 0.6\ B\ \gamma g\ N_\gamma + q_o\ N_q \qquad (6)$$

where N_γ and N_q are bearing capacity factors, B is the total width of the foundation grid, γ is the density of the soil and q_o is the overburden pressure at the foundation level.

The bearing capacity factors N_γ and N_q which depend on the angle of internal friction ϕ are approximately equal to 20 at ϕ = 30°. The value of N_γ and N_q increases rapidly with increasing ϕ.

The transition from penetration failure to soil failure is independent of the size of the grid and of the size of the individual cells. It is only affected by the number of rows of cells (n) and by the angle of internal friction of the soil. Normally the bearing capacity of the grid foundation is governed by the penetration resistance except when the height of the cells (H) is relatively large in comparison with the width (L).

LATERAL RESISTANCE

Cohesive Soils

Failure occurs when the shear strength of soil along the bottom of the grid is exceeded. The lateral resistance is not only a function of the shear strength of the soil along this failure surface but also of the lateral earth pressure acting at the front face of the grid. The deformation required to mobilize the shear resistance of the soil along the bottom face of the grid is small compared with the deformation required to mobilize full passive earth pressure along the front face. It is therefore questionable to utilize full passive earth pressure in the calculations. Therefore the lateral resistance should be evaluated from

$$Q_L = c_u\ A_b \qquad (7)$$

where A_b is the total bottom area of the grid and c_u the undrained shear strength of the clay. It should, however, be possible to include in the calculations the resistance of the soil along the sides of the grid which are parallel with the applied load.

The lateral resistance of a grid can be increased with piles driven through the grid into the underlying soil. A relatively large deflection is, however, required to mobilize the maximum lateral resistance of a pile.

Cohesionless Soils

Failure of a grid in sand will take place along the bottom surface of the grid. The shear resistance of the soil will in this case be proportional to the weight of the soil enclosed in the grid and to the weight of the structure (including the weight of the grid).

It is proposed to neglect passive earth pressure at the front face of the grid since the lateral deformation required to develop passive earth pressure is large. The lateral resistance Q_L will then be equal to

$$Q_L = HA_B\ \gamma g\ tg\ \phi \qquad (8)$$

where ($HA_b\ \gamma g$) is the effective weight of the soil enclosed in the grid and ϕ is the angle of internal friction of the granular soil. The lateral resistance depends on the weight of the soil enclosed in the grid and can be increased by increasing the height of the cells or the size of the grid.

PULL-OUT RESISTANCE

Cohesive Soils

When the height of the cells is relatively small the pull-out resistance is dependent on the total contact area of the grid plates with the soil. However, the pull-out resistance should not exceed the total weight of the soil within the cells. The pull-out resistance Q_T can be calculated from the equation

$$Q_T = c_a\ A_m \qquad (9)$$

where A_m is the surface area of the grid plates in contact with the soil, and c_a is the adhesion along the grid plates. This adhesion is a function of the material in the grid plates and of the shear strength of the clay. The adhesion c_a can be assumed to be 0.5 c_u when c_u <50 kPa and as 10 kPa when c_u >50 kPa. These recommended values are conservative.

The pull-out resistance can be increased with driven piles joined with the grid plates. The length and the spacing of the piles can be chosen to correspond to the loads acting on the structure.

Cohesionless Soils

The pull-out resistance of a grid filled with a coarse material such as sand, gravel or rock fill depends on the friction angle of the soil in the cells and of the material in the cell walls. Test data indicate that the maximum pull-out resistance corresponds to the total weight of the soil within the cells.

The pull-out resistance can be increased by increasing the height of the cells or by attaching ribs to the bottom of the grid. When piles are used to increase the pull-out resistance, the interaction of the grid and the piles can, however, be reduced due to progressive failure.

MODEL TESTS

Description of Tests

The analysis presented in the previous sections has been checked by model tests in dry G 12 sand, which has been used in numerous investigations at the Danish and the Swedish Geotechnical Institutes. This sand is a beach sand of marine origin with rounded particles. The average grain size is 0.24 mm. The sand has a low coefficient of uniformity (C_u = 2.08). The angle of internal friction of the G 12 sand as determined from triaxial tests is shown in Fig. 5.

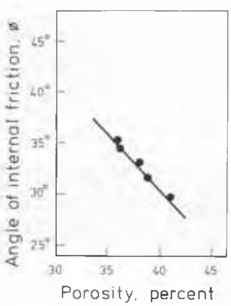

Fig. 5 Results from triaxial tests on G 12 sand

Foundation grids with a height of 100 mm were constructed of 0.2 mm thick brass sheets. The cells were triangular or rectangular. A photograph of the model "Hexagon" with triangular cells is shown in Fig. 6.

All tests were carried out in a rectangular wooden box (1.3 x 1.3 x 0.5 m). For the test series in loose sand the dry soil was poured through a funnel which was held about 5 cm above the sand surface. For the tests on dense sand the soil was compacted in layers. The layer thickness was varied to achieve a uniform compaction of the sand. The density of the soil was checked at each test series by the drive cylinder method.

Axial Load Tests

The bearing capacity of four models with triangular or square cells and of triangular and rectangular mono cells were investigated as well as the bearing capacity of plates of the same shape and size as the models. The tests were carried out in both loose and dense sand. The height of the sand fill within and around the models was changed as well as the penetration depth of the models. The deformation rate was kept constant during each test (about 2 cm/min). In some of the tests the sand in the cells was compacted. The shape of the load-displacement relationships when the grids were placed directly on the surface is illustrated in Fig. 7. It can be seen that the relative density of the soil below the grid has large effect on the load-deformation relationship. The resistance increased expotentially with increasing penetration depth.

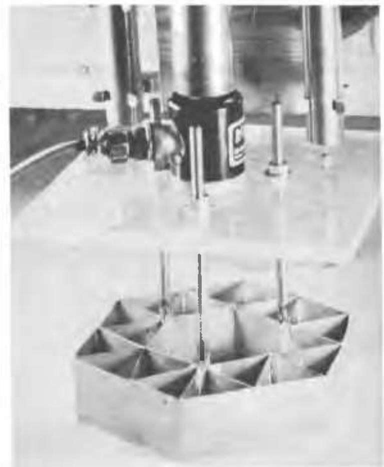

Fig. 6 Load test arrangement with the model "Hexagon"

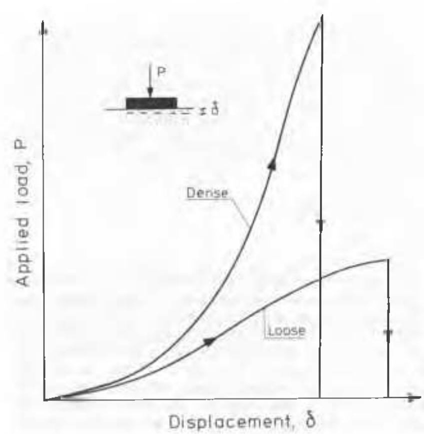

Fig. 7 Load-displacement relationships for grid placed at the surface

The soil penetrated at first into the cells. The friction resistance along the cell walls increased gradually until the surface area of the cells in contact with the soil was large enough to resist the relative movement of the soil. The grid behaved then as a solid plate and the grid with the enclosed soil moved down as a unit.

The penetration depth required to reach the ultimate bearing capacity of the soil was approximately twice the cell width when the cells were square and approximately the cells width when the cells were triangular.

Typical load-displacement relationships when the cells were filled with sand or when the grid was pushed into the underlying soil are shown in Fig. 8. The grid and the soil within the cells moved down together as a unit. The axial displacement required to reach the ultimate bearing capacity of the soil was small compared to the case when the grid was placed directly on the surface. The penetration resistance increased rapidly with increasing displacement.

It can be seen from Fig. 8 that the relative density of the soil had a large effect on the load-displacement relationship. The ultimate bearing capacity increased rapidly as the density of the soil increased.

The penetration is affected considerably by the value of the coefficient of lateral earth pressure K. This coefficient varied between 0.75 and 0.85 for the grids with rectangular cells when the soil in the cell was dense. The corresponding variation for the grids with triangular cells was between 0.55 and 0.65 when the soil was loose, and 0.65 and 0.75, when the soil was dense. The value of K was thus less for the triangular cells than for the rectangular cells.

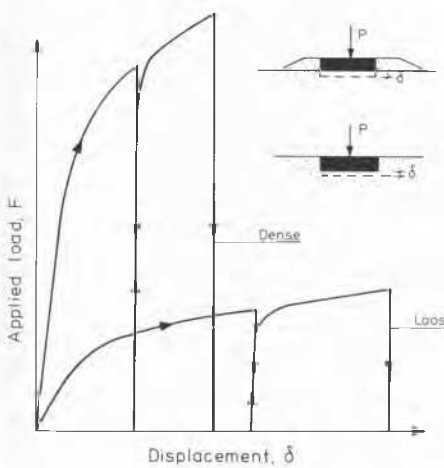

Fig. 8 Load-displacement relationships when fill has been placed around the grid or when the grid has been pushed into the underlying soil

Test results indicate furthermore that cyclic loading has a large influence on the settlements, while the ultimate bearing capacity is hardly affected. The settlements increased with increasing load level. The increase was two to four times after 1000 load cycles when the maximum level of the cyclic loading increased from 50 to 90% of the static failure load.

Lateral Load Tests

The lateral resistance of grids which were either placed on the surface and filled with sand or pushed into the underlying sand was investigated. The height of the sand fill in the cells was varied as well as the relative density of the sand.

The measured ultimate lateral resistance was approximately equal to or exceeded the sum of the calculated resistance along the base of the grid and passive Rankine earth pressure in front of the grid. The proposed design procedure will thus give results which are on the safe side.

Pull-Out Tests

The pull-out resistance was also investigated. The height of the sand fill within and around the models was varied as well as the relative density of the sand.

Typical load displacement relationships from the pull-out tests are shown in Fig. 9. The height of fill in the cells was 10 cm. It can be seen that a very small displacement less than 1 mm was required to mobilize the maximum resistance. The resistance decreased approximately linearly with increasing displacement as the contact area of the cell walls with the soil decreased. The pull-out resistance was in most cases approximately equal to the weight of the soil enclosed in the grid.

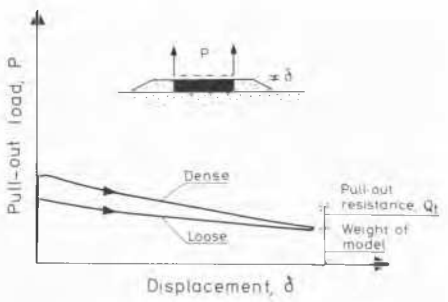

Fig. 9 Load-displacement relationships at pull-out tests after the grid has been pushed into the underlying soil

The pull-out resistance increased in general with increasing total mantel area (A_m) in contact with the soil and the total bottom area (A_b). The pull-out resistance was approximately equal to the weight of the soil enclosed by the grid.

The tension tests indicate that the behaviour of the grids with triangular cells is superior to the grids with rectangular cells. The behaviour of the rectangular cells can be improved by attaching ribs to the lower edge of the grid. The tension tests show furthermore that the pull-out resistance of a grid with triangular cells is equal to the weight of the soil enclosed within the cells when the height (H) of the soil within the cells is at least equal to the width (L) of the cells.

SUMMARY AND CONCLUSIONS

A theoretical analysis and model tests indicate that the proposed new foundation grid which consists of thin-walled vertical plates has a high bearing capacity and a high lateral resistance. The bearing capacity was equal to that of a solid plate when the cells were filled with sand or had been pushed into the underlying soil. The lateral resistance of the grid corresponded to the sum of the resistance along the bottom of the grid and the passive Rankine earth pressure at the front face. The pull-out resistance was approximately equal to the weight of the soil enclosed within the grid except for the grids with square cells and when the height of the fill was small.
The model tests also indicate that the behaviour of the grids with triangular cells was superior to the grids with rectangular or square cells both with respect to the load carrying capacity and the rigidity of the grid.

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