Tubular Elements as Foundation for Structures

Les Elements Tubulaires pour Fondations des Ouvrages

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SYNOPSIS A new shallow foundation method where short open large diameter tubular members with 1 to 2 m length and 1 m diameter are used, is described in the paper. This method can primarily be used in granular soils where heavy concentrated loads occur. A large number of model tests have been carried out to investigate the behaviour when the soil inside the cylinders is loaded. The cylinders and the enclosed soil behaved essentially as a unit. The displacements were about the same when the depth of the granular layer in the cylinder was equal to the diameter. The compression of the soil in the cylinders was negligible.

INTRODUCTION

A new shallow foundation method has been proposed by Mr Arne Mattson, Paul Andersson Industries, Västerås, Sweden. At this method 1.0 to 2.0 m long steel or concrete cylinders with about 1 m diameter are used which are driven down into the soil or placed in excavated trenches. The cylinders are filled with sand or gravel. The soil inside the cylinders is loaded as illustrated in Fig. 1. The bearing capacity of the new foundation method will be high since the load is transferred to the bottom of the cylinders. The settlements will be small since the soil is confined by the cylinders.

The proposed new method can be used

(a) as foundation for small buildings. In clay the method can be combined with lime columns,

(b) as support for industrial floors on clay, sand or till. The bearing capacity will be high since the load is transferred to the bottom of the cylinders. It is not necessary that the floor is supported directly on the cylinders,

(c) as foundation for storage tanks, grain silos and industrial chimneys in sand, gravel or till, since the cylinders can carry high concentrated loads without excessive settlements.

Krsmanoviç and Balla (1970) have investigated the bearing capacity and settlement of granular soils reinforced with vertical steel cylinders. The ultimate bearing capacity of the cylinders was calculated using a similar method as that proposed in this paper.

The allowable load on the cylinders is governed by the requirements

(a) that the factor of safety with respect to the ultimate bearing capacity should be sufficiently high (2.0 to 3.0)

(b) that the total and the differential settlements should be less than those that the supported structure can tolerate without affecting the function of the structure and to avoid excessive cracking.

Ultimate bearing capacity

The ultimate bearing capacity of a cylinder buried in soil depends to a large extent on the depth of embedment and how the cylinder is loaded. When the soil inside a cylinder is loaded the ultimate bearing capacity will depend on the skin friction along the outside (Q_{skin}) and on the point resistance(Q_{point})according to the equation

$$Q_{ult} = Q_{skin} + Q_{point} \qquad (1)$$

It has been assumed that the length is sufficient so that the soil plug in the cylinder can force it down when the soil is loaded. This will occur in cohesionless soil when the height of the sand column inside the cylinder corresponds approximately to the diameter. The cylinder will then function as a short pile.

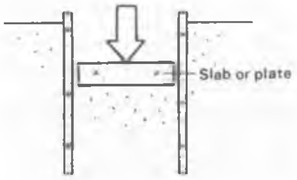

Fig.1 Proposed foundation methoa

The friction resistance along the inside of a cylinder has been calculated in the same way as in a silo. The vertical stress σ_v has been evaluated by analyzing the forces acting as a slice of soil with the thickness dz in the cylinder. The solution of the resulting differential equation is

$$\frac{\sigma_v}{\rho\, gD} = \frac{1}{4\, K\, tg\, \phi_a}\left[e^{\frac{4\, Kz\, tg\, \phi_a}{D}} -1 \right] \quad (2)$$

where D is the diameter of the cylinder, K is the coefficient of lateral earth pressure, ϕ is the friction angle of soil in the cylinder with respect to the wall in the cylinder and ρ is the unit weight of the soil.

This equation can be simplified

$$\frac{\sigma_v}{\rho\, gD} = \frac{1}{B}\left[e^{\frac{Bz}{D}} -1 \right] \quad (3)$$

It has been assumed in the analysis that the vertical pressure σ_v is uniformly distributed over the cross-section and that the lateral normal pressure is proportional to the vertical overburden pressure.

The ultimate bearing capacity of the soil below the driven or buried cylinders has been calculated by a conventional method using the bearing capacity factors N_c, N_γ and N_q. In cohesionless soils the bearing capacity will increase rapidly with depth, but not as fast as the friction resistance of the soil plug in the cylinder. At a depth equal to the diameter of the cylinder the resistance of the soil plug will exceed the bearing capacity of the underlying soil and the cylinder will behave as a closed-ended short pile with the same diameter even when the load is applied along the rim of cylinder. The bearing capacity will in that case be independent of the level of the soil in the cylinder.

The load that can be allowed will in that case correspond at least to that on a slab or a spread footing founded at the same depth. Also the skin friction along the outside of the cylinder will contribute. For a cylinder which has been driven down into the soil, the bearing capacity of the soil will be high due to the compaction and the preloading of the soil during the driving of the cylinder.

The outside skin friction resistance can be calculated in the same way as for a short pile and depends on the lateral pressure acting on the cylinder $\sigma_v = K\, \sigma_v$ where K is an earth pressure coefficient. The arch action in the soil should be small since the soil is not confined. The outside skin friction resistance is normally 10% to 20% of the point resistance of the cylinders. It is generally sufficient to increase the point resistance by 10% to take into account the outside skin friction. The skin friction resistance affects also the point resistance since the effective overburden pressure is increased. This increase is normally small compared with the total bearing capacity and is usually neglected.

A high radial pressure will develop in a cylinder which is pushed or driven down into the soil, which can cause the cylinder to rupture longitudinally. The radial pressure increases with increasing depth. When a soil plug is formed in the cylinder which prevents the soil from entering the lateral pressure will be proportional to the point resistance. The cylinder had to resist a lateral pressure of K σ_v and a circumferential total force equal to $\sigma_v \frac{D^2}{8\, tg\, \phi_a}$ which is distributed over a height h_b. It seems reasonable to expect that the height h_b will be a function of the diameter of the cylinder. It is proposed that the height h_b is taken as D/2 as indicated by measurements.

The displacement required to mobilize the skin friction is small, a few millimeters, compared with the point resistance. A displacement of 10% to 20% is necessary to mobilize the point resistance of a cylinder buried in the soil. A considerably smaller displacement is required if the cylinder has been driven or pushed down.

Load tests on short piles suggest that the bearing capacity and the skin friction resistance of a driven cylinder in clay depend mainly on the undrained shear strength of the clay. There are no results available from load tests on open short cylinders where the soil inside the cylinder is loaded.

If a soil plug develops in the cylinders the ultimate point resistance will correspond to 9 c_u, where c_u is the undrained shear strength of the clay down to a depth that corresponds approximately to the diameter of the cylinder. The length of the plug will be relatively large in clay. The length can be reduced if the cylinder is filled with a granular material.

Settlements

The total settlement δ_t will be equal to(δ_a + δ_b + δ_c)where δ_a is the settlement caused by the stress increase q_a just below the loaded plate, δ_b and δ_c are the settlements caused by the stress increase q_b just above and below the bottom of the cylinder, respectively, as illustrated in Fig. 2. However, the settlements δ_a and δ_b will be small since the stress difference (σ_v - σ_v) is small in the cylinder.

The settlement δ_a can be estimated from the relationship

$$\delta_a = 1/2\; q_a\; h_a/M \quad (4)$$

where q_a is the contact pressure below the loaded plate and M is the compression modulus of the soil. It has thus been assumed that the load q_a is uniformly distributed and that it decreases linearly below the plate. The transfer length h_a (Fig. 2) can be estimated from the relationship

$$h_a = \frac{D}{2\; K\; tg\; \phi_a} \quad (5)$$

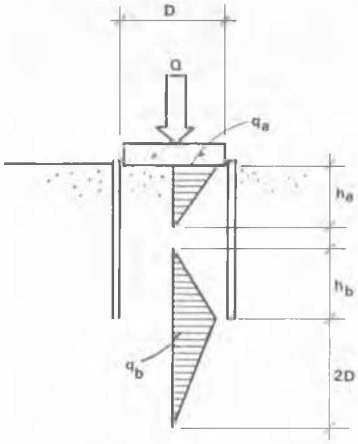

Fig.2 Stress increase in the soil inside and below the loaded cylinder

At e.g. $\phi = 30^\circ$ and $K = 0.8$ then $h_a = 1.08$. According to equation (5) the transfer length will be independent of the applied load when the cylinder is filled with cohesionless soil.

The settlement δ_b is dependent on the stress increase q_b at the bottom of the cylinder and can be estimated in the same way from the relationship

$$\delta_b = \frac{q_b D}{2\ M} \qquad (6)$$

while the settlement below the cylinder can be calculated from the equation

$$\delta_c = \frac{0.8\ q_b\ D(1 - \nu^2)}{E} \qquad (7)$$

This equation is based on elastic theory where E is the modulus of elasticity and ν is Poisson's ratio. It has thus been assumed that the soil behaves as an ideal elastic material. Equation (7) can be rewritten as

$$\delta_c = \frac{0.8\ q_b\ D\ (1 - \nu)^2}{M\ (1 - 2\ \nu)} \qquad (8)$$

At $\nu = 0.3$

$$\delta_c = \frac{0.98\ q_b\ D}{M}$$

The settlements below the cylinder will thus be about two times the settlement of the soil within the cylinder. However, the settlement δ_c will increase with increasing value on Poisson's ratio.

The load q_b at the bottom of the cylinder depends on the skin friction resistance along the cylinder. The skin friction resistance is normally small and account for about 10% to 20% of the total bearing capacity.

The compression modulus can normally be determined from oedometer, plate load or cone penetration tests. The most accurate is the plate load test. Oedometer tests on cohesionless soils are normally carried out on disturbed samples where the structure of the soil has been destroyed. The compression modulus can also be determined from static cone penetration tests and corresponds normally to 4 q_c to 6 q_c where q_c is the cone resistance within a depth that corresponds to one to two diameter of the loaded area. A lower limit is 2 q_c. Plate load tests or penetrometer tests can generally not be used if there are stones of boulders in the soil. Then the compression modulus had to be estimated.

Model tests

The behaviour of tubular elements as foundation has been investigated in a steel tank with 1 m diameter and 1.2 m height which was filled with sand. Steel cylinders with 0.2 m diameter were placed in or pushed down into the sand. The cylinder were loaded either statically with hydraulic jacks or dynamically using a free falling weight. The displacement of the cylinders, the load distribution along the cylinder and the applied load were measured. The results were plotted on a x-y-recorder type Hewlett-Packard. A minicomputor (Alpha LSI) was used to store the data.

A uniform medium coarse sand ("Silver Sand 55") was used in the investigation. This sand has previously been tested at the Royal Institute of Technology (KTH). The grain size distribution is shown in Fig. 3. The angle of internal friction determined by drained triaxial tests on dry sand was 35° and 38° when the relative density was 55% and 92%, respectively. No change of the grain size distribution or of the shape of the particles due to crushing was observed during the tests.

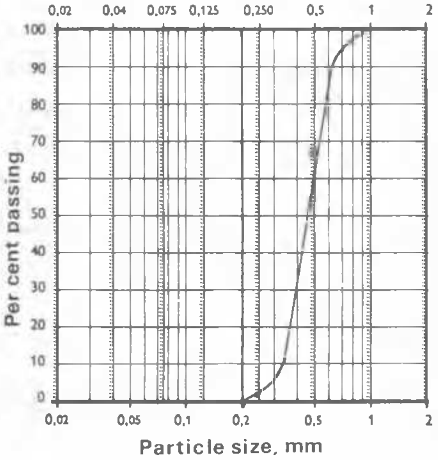

Fig. 3 Grain size distribution

The behaviour of the loaded cylinders were investigated in loose and dense sand. The loose sand was placed in the steel tank using a flexible hose which was provided with a spreader plate. The hose was held 100 mm above the surface of the sand in the tank. The unit weight was 1.51 t/m^3. A spreader plate was not used for the dense sand. The hose was held 800 mm above the sand surface in the tank. The sand was compacted in 100 mm layers to a unit weight of 1.64 t/m^3 using a hand tamper. The compaction was checked by weighing the tank with sand. The relative density was 40% and 80%, respectively.

The influence of the length and the diameter of the cylinders as well as the level of the soil within the cylinders on the ultimate bearing capacity, the load distribution along the cylinders, the settlements within and below the cylinders and on the penetration resistance were investigated. The effect of repeditive loading on the ultimate bearing capacity and on the settlement was also determined.

Test results

Stress distribution The axial and circumferential stress distributions in the cylinder were measured with strain gauges attached to the wall of the cylinder. The cylinders were filled with a dense uniform medium fine sand. The depth of embedment was 500 mm. The sand inside the cylinders was loaded.

The axial stress distribution in the cylinder is shown in Fig. 4. The axial stress was the largest just below the center where it corresponded to 71% to 78% of the applied axial load. The load transferred through the soil in the cylinders was thus relatively small. Part of the load was also transferred through skin friction to the soil around the cylinders.

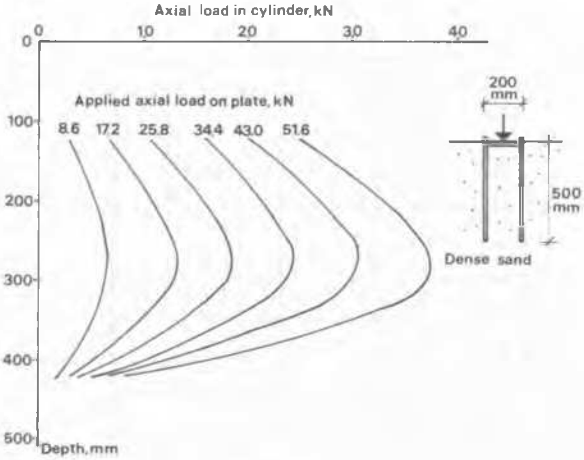

Fig.4 Axial stress distribution in cylinder

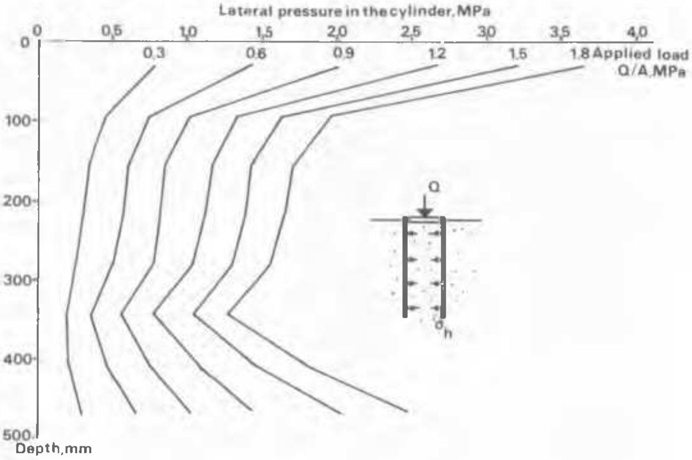

Fig.5 Lateral pressure in soil in the cylinder

The corresponding radial stress distribution calculated from the measured circumferential stress is shown in Fig. 5. It can be seen that the lateral pressure in the soil was smaller at the bottom than at the top of the cylinder, where lateral pressure was approximately twice the average contact pressure below the loaded plate. This high lateral pressure was mainly caused by a high local contact pressure along the perimeter of the plate. The maximum contact pressure must have been at least four to six times the average contact pressure. (The lateral pressure was probably half to one-third the vertical pressure.) The lateral pressure was smaller in the lower part than in the upper part of the cylinder. It increased from about 50% of that at the top of the cylinder at low load levels to about 70% close to failure.

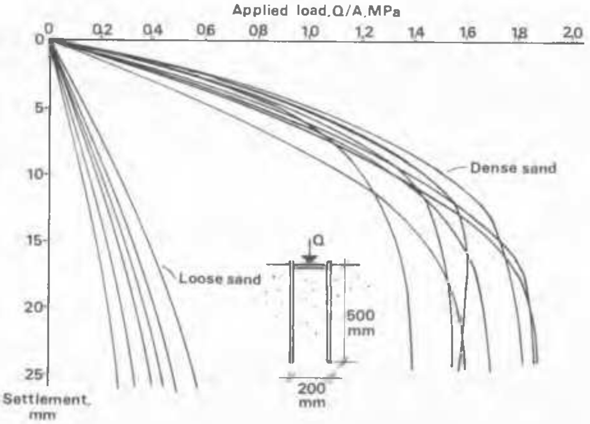

Fig.6 Ultimate bearing capacity of the cylinders at an embedment length of 500 mm

Ultimate bearing capacity The bearing capacity of the cylinders in loose and dense sand is shown in Fig. 6 when the length of the cylinders was 500 mm (2 1/2 times the diameter of the cylinder). The cylinders were placed in the sand during the filling of the test tank.

It can be seen from Fig. 6 that the displacement of the cylinder increased approximately linearly with increasing applied load when the sand was loose. When the displacement corresponded to 10% of the diameter the load was 0.2 to 0.5 MPa. (The average load was 0.34 MPa.) The spread of the test results was relatively large indicating that the load-displacement relationships are very sensitive to small variations of the relative density of the sand.

In dense sand the displacement initially increased approximately linearly with the applied load. The maximum resistance was reached when the displacement was 5% to 10% of the diameter of the cylinder. The failure load was 1.4 to 1.8 MPa which corresponds to the bearing capacity of the soil.

The effect on the bearing capacity when the depth of embedment was 0, 100, 200, 300, 400 and 500 mm is shown in Fig. 7. The displacement of the load plate increased approximate linearly with the applied load when the sand was loose (D_r = 40%). When the depth of embedment increased from 0 to 500 mm the load which corresponded to a displacement of 10% of the diameter increased 8 to 9 times.

For dense sand (D_r = 80%) the bearing capacity reached a maximum when the displacement was 5 to 10% of the diameter of the cylinder. The bearing capacity increased 3 to 4 times when the depth of embedment increased from 0 to 500 mm.

The location of the load plate inside the cylinder was also varied. Load was applied either at the bottom of the cylinder or 200 mm above the bottom. Typical load-deformation relationships are shown in Fig. 8 for loose sand. When the load was applied 200 mm above the bottom the behaviour was the same as when the cylinder was completely filled with sand. The settlement of the cylinder was about 1 mm less than the displacement of the loaded plate.

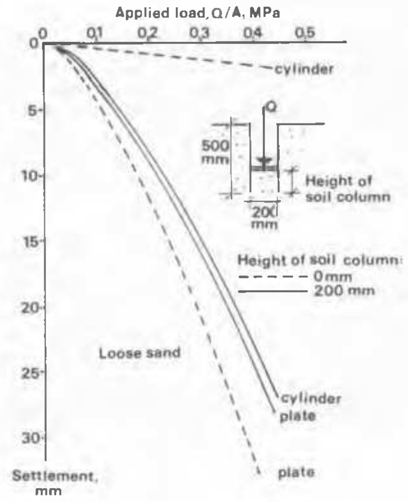

Fig.8 **Effect of the location of the load plate on the ultimate bearing capacity**

When load was applied at the bottom of the cylinder the displacement of the cylinder was about 5% of the displacement of the plate. The ultimate bearing capacity was about 80% of that when the cylinder was completely filled with sand and the load was applied at the ground surface. The skin friction resistance of the cylinder corresponded approximately to 20% of the total bearing capacity.

The tests indicate that a fill with granular material in a cylinder which corresponds to the diameter is sufficient to pull the cylinder down through the soil. The measured radial pressures indicate that about 100 mm, half the diameter of the cylinder, will be sufficient.

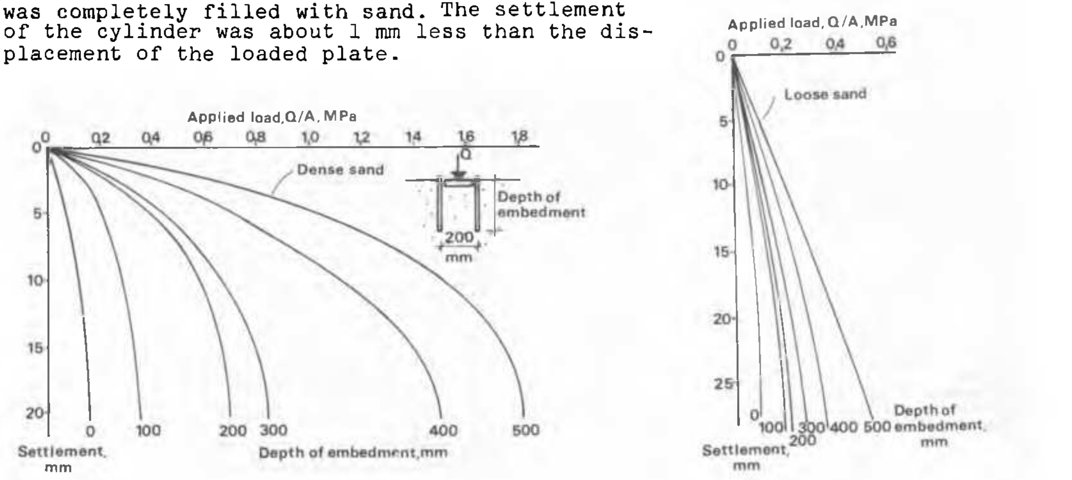

Fig.7 Effect of the depth of embedment on the ultimate bearing capacity

Settlements The settlements inside and below the cylinder were measured with 40 mm diameter plates placed at different depths. Each plate was provided with a rod in a plastic tube to reduce the friction along the rod. The rods passed through holes drilled in the loaded plate. The settlements were measured at the center of the cylinder and at 250, 500 and 750 mm depths.

Results from the tests in dense and loose sand are shown in Figs 9 and 10. It can be seen that the loaded plate, the cylinder and the soil in the cylinder moved as a unit. The compression of the sand in the cylinder and the resulting settlements were small compared with the total settlement of the loaded plate and of the cylinder. At a depth of one diameter the displacement corresponded to 20% to 30% of the total settlement.

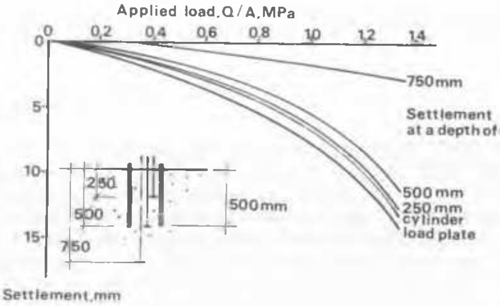

Fig.9 Settlements at different depths (Dense sand)

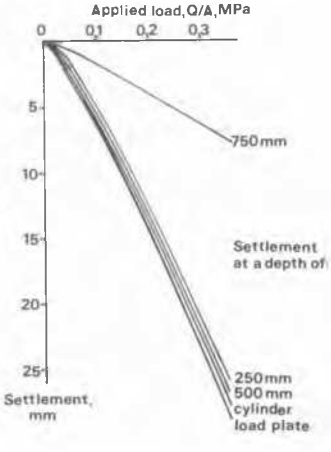

Fig.10 Settlements at different depths (Loose sand)

The settlements of the load plate and of the cylinder were about the same.When the relative density of the sand was low the difference was 0.5 to 2 mm (Fig. 10). For dense sand the difference was 1 to 2 mm (Fig. 9). It developed when the applied load was low and did not increase when the load was increased.

CONCLUSIONS

The test results indicate that the ultimate bearing capacity and the settlements of the new proposed foundation method with tubular elements will correspond to those of a spread footing founded at the same depth. The compression of the granular material in the cylinders was small and could be neglected compared with the settlement below the cylinder. The load plate and the cylinder moved as a unit even when the height of the sand column inside the cylinders was only one diameter.

A definite failure load was observed in dense sand while the displacement increased with the applied load when the sand was loose. High lateral pressure develop in the soil in the cylinders which were much larger than the average pressure below the loaded plate.

ACKNOWLEDGEMENTS

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