Effect of foundation embedment on consolidation response

Effet de l'enfouissement des fondations sur la réponse en consolidation

S.M. Gourvenec & M.F. Randolph

Centre for Offshore Foundation Systems, University of Western Australia

ABSTRACT

Embedment will generally reduce the magnitude and rate of consolidation settlement of shallow foundations due to the resistance of the soil above foundation level, the reduction in foundation load due to side friction and the longer drainage paths. Conversely, embedment provided by foundation skirts may increase the magnitude and rate of consolidation settlement due to additional one-dimensional compression within the soil plug. This paper presents an investigation into the consolidation response of surface and variously embedded foundations in an isotropic elastic half-space. The results show that embedment, the type of embedment and interface roughness can have a marked effect on consolidation response.

RÉSUMÉ

L'enfouissement va généralement réduire l'amplitude ainsi que la vitesse du tassement en consolidation des fondations de surface, du fait de la résistance du sol au-dessus du niveau de la fondation, de la diminution de la charge due au frottement latéral et de l'allongement des chemins de drainage. A l'inverse, l'enfouissement provenant des jupes structurales de fondations peut augmenter l'amplitude ainsi que la vitesse du tassement en consolidation du fait de la compression unidirectionnelle additionnelle dans le bouchon de sol. Ce papier présente une investigation de la réponse en consolidation des fondations de surfaces ainsi que de diverses fondations enfouies dans un demi-espace élastique isotrope. Les résultats montrent que l'enfouissement, le type d'enfouissement ainsi que la rugosité de l'interface peuvent avoir un effet significatif sur la réponse en consolidation.

Keywords : foundations, consolidation, excess pore pressure, finite elements

1 INTRODUCTION

Various analytical solutions have been proposed for three-dimensional consolidation beneath surface loads or pad and raft foundations, typically with a smooth interface, on an elastic half-space (e.g. McNamee & Gibson 1960, Schiffman et al. 1969, Gibson et al. 1970, Booker 1974, Chiarella & Booker 1975, Booker & Small 1986). In practice, foundations are generally embedded though little attention has focused on the effect of embedment on the magnitude or rate of foundation settlement.

An embedded foundation would not be expected to settle as much as a surface foundation of equivalent bearing area due to the resistance provided by the material above foundation level (Davis & Poulos 1968, Butterfield & Banerjee 1971, Poulos & Davis 1974). Embedment will also affect the rate of consolidation as longer drainage paths will lead to longer consolidation times. If embedment is provided by foundation skirts, as is commonly the case for offshore applications, the mechanism of consolidation is complicated by one-dimensional compression within the soil plug. Additional one-dimensional compression will potentially increase the magnitude and rate of consolidation settlement compared to conventional embedded foundations.

This paper presents results from finite element analyses of smooth and rough, rigid, impermeable, circular, surface and embedded foundations. A single embedment ratio (i.e. embedment depth to foundation diameter) d/D = 0.5 is considered with embedment provided by (i) burial of a plate, (ii) a solid structural element and (iii) skirts around the periphery of a surface plate (Figure 1). The analyses investigate the effect of embedment, the type of embedment and interface roughness on consolidation response, compared with a surface foundation. The analyses assume idealised elastic soil conditions with constant and isotropic soil properties to enable benchmarking against established analytical solutions.

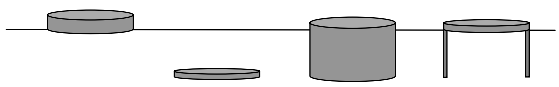

Figure 1. Schematic of surface and embedded foundations

2 METHODOLOGY

2.1 *Finite element models*

Circular foundations were represented in axial symmetry, modelling a buried plate (plate thickness t_p = 0.02D), a solid structural foundation and a skirted foundation (skirt thickness t_s = 0.002D). The soil was represented by a homogeneous elastic half-space with Biot-type consolidation governing the stress-pore fluid coupling and constant and isotropic elastic parameters and permeability were assumed in all analyses. Results are presented in terms of dimensionless quantities such that they are independent of the actual foundation geometry, soil stiffness or permeability adopted in the finite element model. Three-dimensional consolidation response is affected by the magnitude of Poisson's ratio, although over a practical range of drained Poisson's ratio, $0.1 \leq \nu' \leq 0.3$, the effect is limited (Schiffman et al. 1969, Booker & Small 1986). A mid-range value of drained Poisson's ratio, ν' = 0.2, was selected for the analyses in this study. Interaction between the foundations and soil was represented by either a fully rough or frictionless interface in shear.

The foundations were represented as rigid bodies and the soil as a deformable solid with first-order, fully-integrated, axisymmetric, stress-pore fluid, continuum elements. Zero-displacement boundary conditions were prescribed in the radial direction around the circumference and vertically across the

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-638

base of the mesh, located sufficiently remotely so as not to affect the foundation or consolidation response. During consolidation, a zero pore pressure boundary condition was prescribed along the surface of the mesh representing the soil while the foundation was considered impermeable. Drainage was not permitted across the circumferential boundary of the mesh.

All finite element analyses were carried out with the commercially available software ABAQUS (HKS 2008).

2.2 *Analysis procedure*

The foundation was in place at the start of each analysis, i.e. installation was not modelled. Each analysis was carried out in two stages. In the first stage excess pore pressures were set up within the soil by applying a nominal compressive load to the foundation plate (ensuring small displacements), over a short time period with no drainage permitted. In the second stage a drainage boundary was specified along the soil surface and consolidation was permitted until excess pore pressures had dissipated.

The time step over which the excess pore pressure regime was set up and the minimum time step permitted during consolidation can be expressed as (Vermeer & Verruijt 1981):

$$\Delta t_{min} = h^2 \frac{\gamma_w}{6Ek} \tag{1}$$

where h is the characteristic element size (i.e. the distance between the Gauss points) near the draining surface, γ_w is the unit weight of the pore fluid, E is the Young's modulus of the soil skeleton and k is the coefficient of soil permeability.

3 RESULTS

3.1 *Validation*

The finite element model of a smooth surface foundation was benchmarked against available analytical solutions for initial contact pressure (Muki 1961) and time-settlement response (Booker & Small 1986). Figure 2 shows that the finite element prediction of the distribution of contact pressure beneath the surface foundation agrees well with the theoretical stress distribution under a rigid die, given by (Muki 1961):

$$\frac{\Delta u_i}{\Delta q} = \frac{1}{2\left(1 - \frac{x^2}{(D/2)^2}\right)} \tag{2}$$

Comparison of the finite element prediction of the time history of consolidation settlement with the established analytical solution for a smooth, rigid, impermeable surface foundation (Booker & Small 1986) also shows good agreement (see later, Figure 5).

3.2 *Consolidation response*

Figure 2 shows contact pressures beneath the base plate, and at foundation level of the skirted foundations, immediately after application of the foundation load, expressed as the ratio of the initial change in excess pore pressure to the change in applied foundation pressure ($\Delta u_i/\Delta q$).

The initial contact pressures beneath the surface foundation are independent of interface roughness and exhibit the established concave distribution, with an initial contact pressure at the midline of the foundations of half the applied external pressure, increasing towards a stress concentration at the edge of the foundation. Concave pressure distributions are also observed at foundation level for each of the embedded foundations. Embedment generally leads to a reduction in contact pressure, with the exception of the smooth skirted foundation, as the foundation load is transmitted to skirt tip level under one-dimensional conditions. The skirted foundations exhibit a relatively uniform contact pressure distribution under the base plate as load is prevented from shedding laterally due to confinement by the skirts. The rough solid and skirted foundations carry less load at foundation level than their smooth counterparts due to the portion of foundation load carried by friction along the skirts.

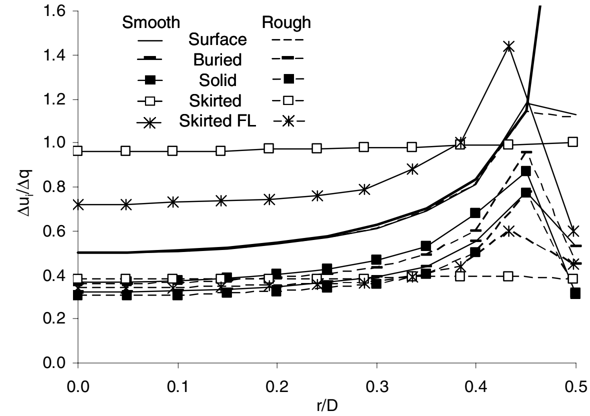

Figure 2. Initial contact pressures at foundation-soil interface

Figure 3 shows contours of excess pore pressure immediately after load application, expressed as a ratio of the applied external pressure at intervals of $0.1\Delta u_i/\Delta q$.

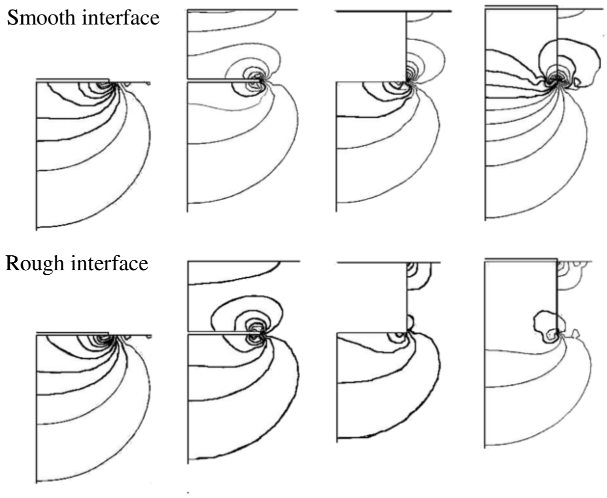

Figure 3. Initial excess pore pressure fields

The excess pore pressure fields around the surface foundations are independent of interface roughness and indicate a stress change of 10% of the applied surface pressure at a depth z/D ~ 1, consistent with analytical solutions (Poulos & Davis 1974). The initial stress changes are less extensive beneath the embedded foundations than the surface foundation, as would be expected. The extent of the initial stress change beneath the buried plates is independent of interface roughness while the initial stress change is less extensive beneath the rough solid and rough skirted foundations than beneath their smooth counterparts, due to the portion of foundation load carried by friction along the skirts. The initial stress change beneath the smooth skirted foundation is the most extensive of the embedded foundations due to the foundation load being transmitted to skirt tip level under one-dimensional conditions, without any portion of the foundation load carried by friction along the skirt.

Figure 4 shows time histories of excess pore pressure dissipation beneath the base plate, and at foundation level of the skirted foundations, along the midline of the foundations in terms of the dimensionless time factor $T = c_v t/D^2$. Pore pressure time histories for the skirted foundations are shown at foundation level to eliminate the effect of the extended drainage path. Excess pore pressures are expressed as (a) the ratio of the applied stress ($\Delta u/\Delta q$) indicating relative magnitude, and (b) normalised by the initial change in excess pore pressure ($\Delta u/\Delta u_i$) indicating the degree of consolidation. The initial data points in Figure 4a correspond to the contact pressure at the midline of the foundations as shown in Figure 2.

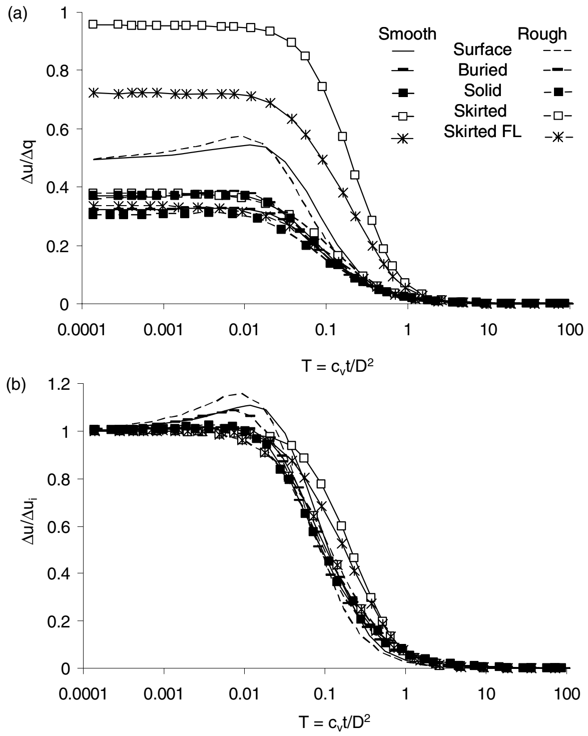

Figure 4. Excess pore pressure time histories

The solid and skirted foundations exhibit a sustained reduction in pore pressure with time while the surface foundations and buried plates exhibit an increase in excess pore pressure in the early stages of consolidation over and above the initial increment. The temporary increase in excess pore pressure is characteristic of the Mandel-Cryer effect (Mandel 1950, Cryer 1963). The effect is more pronounced for the surface foundations than for the buried plates and in both cases the effect is more pronounced for the rough foundation interface. The smooth skirted foundation exhibits the slowest dissipation of excess pore pressure beneath the base plate, due to extra compression in the soil plug.

Figure 5 shows consolidation settlement time histories, measured along the midline of the foundations. Consolidation is expressed in terms of (a) the relative magnitude of settlement by the dimensionless quantity $w_cG/D\Delta q$, and (b) the degree of consolidation w_c/w_{cf}. Note the much longer times for overall consolidation (Figure 5) compared with the dissipation of excess pore pressure measured at the same point (Figure 4). The difference increases with time as overall consolidation is dominated by dissipation of excess pore pressures in the far field rather than in the vicinity of the foundation.

The embedded foundations exhibit less settlement than the surface foundations, with the exception of the smooth skirted foundation. In general, embedment leads to smaller settlements due to the additional resistance provided by the material above foundation level, while the smooth skirted foundation experiences larger settlements due to the additional one-dimensional compression within the soil plug.

Settlement of the buried plates is independent of interface roughness and is similar to that of the smooth solid foundation. The rough solid foundation experiences less settlement than its smooth counterpart, and the buried plates, due to the portion of the foundation load carried by side friction. Initially the rough skirted foundation experiences similar settlements to the rough solid foundation, but diverges with time due to the compression within the soil plug.

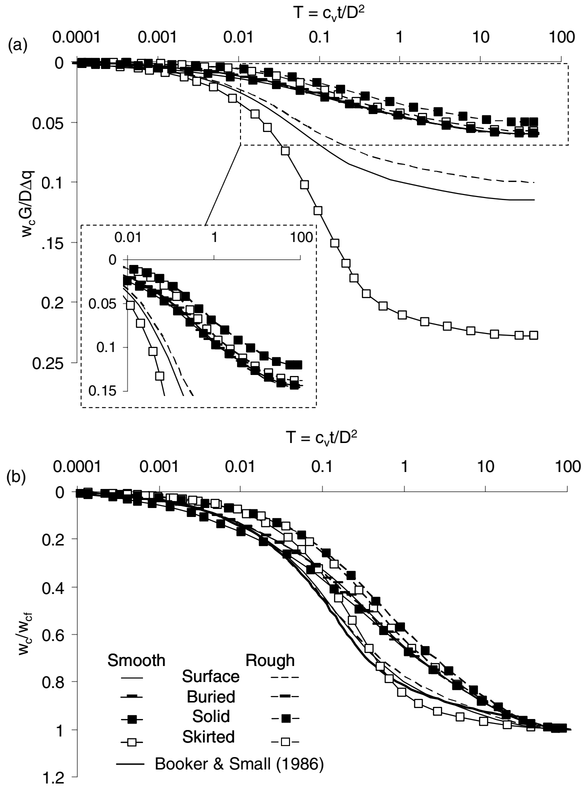

Figure 5. Settlement time histories

The reduction in consolidation settlement due to embedment can be expressed in terms of the ratio of settlement at T_{100} of the embedded foundation to that of a surface foundation of equivalent bearing area. For the embedment ratio and soil conditions considered in this study, reduction factors for the consolidation component of settlement range between 0.5 and 0.6, with the exception of the smooth skirted foundation that exhibits a settlement factor of two. Note that because the initial settlement for all foundation shapes is much closer to that for the surface foundation (in the range 0.7 to 0.95), the ratios of total settlement are also closer to unity. For example, for the embedded plate the ratios of total settlement by the end of consolidation are 0.69 (smooth) to 0.72 (rough), which are consistent with results from Butterfield and Banerjee (1971).

The normalised displacement time histories indicate the increased time for consolidation due to embedment. The slowest consolidation occurs beneath the rough solid foundation with a five-fold increase in T_{50} compared to the surface foundation.

Rate of consolidation is illustrated explicitly in Figure 6. The embedded foundations generally exhibit a slower rate of consolidation than the surface foundations, as would be expected. Of the embedded foundations, the consolidation rate beneath the smooth-sided foundations is greatest, followed by the buried plates and the rough-sided foundations respectively. The rate of consolidation beneath the smooth skirted foundation initially lags behind that of the surface foundations, but with time the rate of change of consolidation increases in comparison with the surface foundations leading to a higher rate of consolidation, due to the additional one-dimensional compression within the soil plug. The rate of consolidation beneath the rough skirted foundation is similar to that beneath the rough solid foundation, indicating side friction is more significant to the overall consolidation response than consolidation in the soil plug.

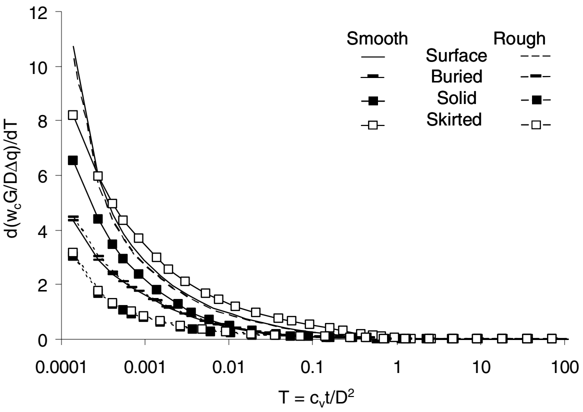

Figure 6. Rate of consolidation time histories

4 CONCLUSIONS

A finite element study has investigated the effect on the consolidation response of foundation embedment considering the type of embedment and foundation-soil interface roughness. The results have shown that embedment generally reduces the magnitude and rate of consolidation settlement due to the resistance of material above foundation level and the increased drainage path length; the magnitude and rate of consolidation settlement reduces still further for rough-sided foundations due to the portion of foundation load carried by side friction. The reverse trend is observed for smooth skirted foundations due to one-dimensional compression within the soil plug.

The investigation presented in this paper considered idealised homogeneous, elastic conditions and constant and isotropic permeability to enable benchmarking with established analytical solutions and to identify the underlying characteristics of consolidation response for different types of embedded foundations and interface roughness. In reality, stiffness will increase with depth, reducing settlements further, even for smooth-sided foundations and yielding around the skirt tips of skirted foundations will lead to stress transfer and reduced settlements. Further investigation of the effects of heterogeneous stiffness, plasticity and yielding, as well as permeability dependence on void ratio, anisotropic permeability, and a range of embedment ratios, would provide a useful next step to a better understanding of the consolidation response of embedded foundations.

ACKNOWLEDGMENTS

The work described here forms part of the activities of the Special Research Centre for Offshore Foundation Systems, established under the Australian Research Council's Research Centre Program and now supported through grants FF0561473 and DP0665958 and Centre of Excellence funding from the State of Western Australia. .

REFERENCES

Booker, J.R. and Small, J.C. 1986. The behaviour of an impermeable flexible raft on a deep layer of consolidating soil. International Journal for Numerical and Analytical Methods in Geomechanics Vol. 10, 311 – 327.

Boussinesq, J.V. 1885. Application des potentials à l'étude de l'équilbre et du mouvements des solides élastiques. Paris: Gauthier-Villars.

Butterfield, R. and Banerjee, P.K. 1971. A rigid disc embedded in an elastic half space. Geotechnical Engineering, 2(1): 35-52.

Chiarella, C. and Booker, J.R. 1975. The time-settlement behaviour of a rigid die resting on a deep clay layer. International Journal of Numerical and Analytical Methods in Geomechanics, 8, 343-357.

Cryer, C.W. 1963. A comparison of the three dimensional consolidation theories of Biot and Terzaghi. Quarterly Journal of Mechanics and Applied Mathematics, 16, 401-412.

Davis, E.H. and Poulos, H.G. 1968. The use of elastic theory for settlement prediction under three-dimensional conditions. Géotechnique, 18, 67-91.

Gibson, R.R, Schiffman, R.L and Pu, S.L. 1970. Plane strain and axially symmetric consolidation of a clay layer on a smooth impervious base. Quarterly Journal of Mechanics and Applied Mathematics, 23, 4, 505-519.

Gourvenec, S.M. and Randolph, M.F. 2008. Consolidation beneath skirted circular foundations. Submitted to Int. J Geomechanics.

HKS (2008). ABAQUS Users' Manual, Version 6.5, Hibbit, Karlsson and Sorensen, Inc.

Mandel, J. 1950. Etude mathiematique de la consolidation des sols. Actes du Colloque International De Mechanique, Poitier, France, 4, 9-19.

McNamee, J. and Gibson, R.E. 1960. Plane strain and axially symmetric problems of the consolidation of a semi-infinite clay stratum. Quarterly Journal of Mechanics and Applied Mathematics, 13, 210-227.

Muki, R. 1961. Axisymmetric problems of the theory of elasticity for a semi-infinite solid and thick plate. Progress in Solid Mechanics, 1, North Holland Publishing Co. Amsterdam.

Poulos, H.G. and Davis, E.H. 1974. Elastic solutions for soil and rock mechanics. New York: Wiley.

Schiffmann, R.L., Chen, A.T.F and Jordan, J. 1969. An analysis of consolidation theories. Journal of Soil Mechanics and Foundations Division. Proc. ASCE. 285-313.

Vermeer, P.A.., and Verruijt, A. 1981. An accuracy condition for consolidation by finite elements. International Journal for Numerical and Analytical Methods in Geomechanics, 1, 1-14