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CENTRIFUGAL MODELLING : A REMEDY OF SCALING ERROR EFFECT IN GEOTECHNICAL MODELLING ?

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ABSTRACT

Serious scaling effect has been overlooked since the concept of modelling technique was introduced. Even though dimensional analysis is the best tool when relating the model-prototype however, the scaling of stresses needs yet to be justified. This paper demonstrates the presence of scaling effect by comparing 3 model studies based on a centrifugal and conventional small model test using sand as an embedment media. This enables potential errors in direct extrapolation of the latter to field scale to be evaluated.
(Keywords: Centrifuge , Scaling Effect, Prototype, Model, Conventional, Stress)

Notations

The following symbols are used in this paper

* Notation contain ***m and p subscript*** refers to model and prototype value respectively.

d	:	Plate Diameter
D	:	Pile Diameter
D_f	:	Settlement at Failure
e	:	Pulling Height
e/L	:	Pulling Height ratio
g	:	Earth Gravity
h	:	Height of Anchor Plate
H	:	Embedment Height
L	:	Pile Length
L/D	:	Dimensionless Embedment Height
M'_{ps}	:	Prototype Moment Factor
N	:	Scaling Factor
Q	:	Load Bearing
S_{fm}	:	Moment Shape Factor
g	:	Soil Unit Weight
s_1	:	Major Principle Stress
s_3	:	Minor Principle Stress

INTRODUCTION

Equality of stresses between model and prototype built of the same material is crucial to maintain the similarity in model of particulate assembles such as soil structure. Conflicts between various requirements for complete similarities are common, especially in geotechnical models with no exception to other engineering disciplines. A great advantage in observing a miniature prototype is that all facets of the problem can be controlled, boundary conditions are quantitatively known, and materials parameters are easily selected by the experimenter. Apart from the above parameters, identical circumstances can be repeated. Although it seems simple in nature, it may be problematic when treating soil mechanics problems as the major component of loading and stresses is the self weight of the soil itself. Under these circumstances, complexities of model/prototype scaling are obvious.

Model stresses at a right location, directly compatible to the prototype situation, are greatly appreciated. However, these ideal cases are not easily achievable. To provide quantitative assessment, three model studies are demonstrated. The Lateral Resistance of Vertical Anchor Plate (Leung (1981), Plate Loading Test (King et.al (1984)) and Lateral Resistance of Short Pile Foundation in Sand (Nazir (1994)). Results from prototype condition are based from the self actuated gravity via the centrifugal machine. The reliability of the centrifugal modelling application in replicating field stress condition is reported elsewhere by Fuglsang and Ovesen (1988).

CENTRIFUGAL MODELLING

Edouard Philips in 1869, proposed the earliest idea of centrifugal modelling as reported by Craig (1989). It came under fruition when an earliest study in replicating the effect of body forces in a small model of an earth structure were performed by Bucky et. al (1935) and Pokrovsky and Fedorov (1936), independently. Numerous reports and demonstrations such as Bassett & Horner (1979), Craig (1983, 85, 89), Dickin & Leung (1983, 85), Fuglsang and Ovesen (1988), Dickin & Nazir (1993, 1994)) just to name a few, have been forwarded. Their works are aimed, predominantly, at providing an elimination of the scaling effect incorporated with the application of centrifugal modelling technique. Avgherinos and Schofield (1969) reported an elementary centrifugal modelling technique in applying to a small model. The two basic principles are (i) an increase of self weight with the increase in acceleration and (ii) the reduction of time for model test as the scale is reduced. They explained these two basic principles by using two basic problems in soil mechanics i.e slope stability and consolidation. Craig (1983) summarised the scaling relationship for centrifuge modelling as shown in Table 1.0.

Table 1.0 : Fundamental scaling relationship for centrifuge modelling after Craig (1983)

QUANTITY	SCALE : MODEL AT Ng
Length	1 : 1/N
Accelaration (Gravitational, Inertial)	1 : N
Area	1 : 1/N2
Volume	1 : 1/N3
Density	1 : 1
Mass	1 : $1/N^3$
Force	1 : $1/N^2$
Stress	1 : 1
Strain	1 : 1
Displacement	1 : 1/N
Frequency of Loading	1 : N
TIME	
Creep, Viscous Phenomena	1 : 1
Initial Effects	1 : 1/N
Fluid Flow, Diffusion Phenomena	1 : $1/N^2$

In general, when a model is scale down to 1/N of prototype size, it must then be subjected to a force of N times earth's gravity in order to simulate the prototype behaviour. Schofield (1988) reported that an increase in acceleration in the centrifuge have no effect or whatever on material properties. In principle a properly defined material property should not be affected by acceleration. However stresses are much affected in soil.

SCALING ERROR'S EFFECT

Leung (1981) performed a test to examine the scaling effect upon the horizontal pulling resistance of vertical anchor. Conventional tests were carried out on a 0.025m high model anchor. Apart from that, tests were also conducted on a various height of anchor plates ranging from 0.025 to 0.15m. Prototype ranging from 0.5m to 2.0m high single and continuous anchors were modelled by a 25mm and 50mm high anchor plates which were spun at an accceleration up to 40g. Observations were made in terms of ***Force Coefficient,*** M_{gq} and ***Relative Failure Displacement,*** D_f/h ***(%)***. In all cases, Leung observed that M_{gq} decreases with the increase of anchor size as shown in Figures 1(a) and 1(b). It is significant that for an anchor of less than 150mm high, the force coefficient dramatically reduced, showing that significant scale errors exist. Apparently, relative failure displacement for single and continuous anchors as seen in Figures 2(a) and 2(b) respectively, increase with embedment ratio. However, not only the failure displacement increase with embedment ratio but it also increases with plate size itself as shown in the later figures. This shows that in requiring a limited anchor displacement, small-scale data used as a design base is questionable due to the scaling problem. King et al. (1984) performed a plate loading test in a study of the effect of plate diameter. Using prototypes ranging from 0.15m to 1m diameter plates, a centrifugal model ranging between 12.5mm and 50mm diameter plate were spun at 40g. Results were plotted in terms of dimensionless quantity, i.e ***Bearing Capacity,*** $Q/_{g}d$, and ***Relative Failure Displacement,*** D_f/d. Figure 3(a) shows a considerable reduction in prototype bearing capacity as plate size increases. The change is significant, particularly in a range up to 0.5m. Conversely the relative displacement increases with an increment of plate diameter as shown in Figure 3(b) in broad agreement with Leung's finding as shown in Figures 2(a) and 2(b). Thus, it demonstrates that the scaling error does exist for conventional small model test. Demonstration of a scale effect which exists when a pile is tested at different stress levels was performed by Nazir (1994). A small model pile of 20mm in diameter with length ranging from 40mm to 120mm were employed. Comparisons made with a medium size pile with diameter of 100mm having a similar embedded length, L/D with a small pile. Different stress levels were employed via the application of centrifugal machine. Both pile sizes were simulated to a 1m diameter prototype. Moment factor, M'_{ps} was employed in comparison between prototype moment factor with pulling height ratio, tested on a model at three different stress levels for L/D ranging between 2 and 4. Results acquired show that at a lower stress level, a higher prototype moment factor was obtained. Evidents based on pile size tested at different stress levels as shown in Figure 5 show that moment factor decreases considerably with an increase in pile diameter up to 1m. It shows that the value of moment factor for pile, with a size of 240mm diameter, is having an average of 40% higher than that for it 1m diameter prototype.

DISCUSSION AND CONCLUSION

It has been shown that scale error is very significant in associating with stress dependent structure. In the model studies considered, the conventional model test seriously overpredicts the prototype value. This error is largely attributed to the influence arises from the stress dependent behaviour of the sand typified by the triaxial test data as shown in Figure 6(a) and 6(b) obtained by Liem (1988). It shows that both maximum stress rate and dilation characteristics are reduces with and increased in confining stress level.

Work such as Dickin and Leung (1983) and Nazir (1994) shows that, the application of shape factor could remedy the problem of scaling affect. While Dickin and Leung suggested that the shape factor does not effect the model size, Nazir introduced a moment shape factor which has less significant effect on the models geometry by the stresses as shown in Figure 7. Franke and Muth (1985) found that the scale effects are due to the influence of the elasticity and crushing strength of the sand grain.

It can be concluded that prediction for a full scale prototype behaviour based from the conventional small scale model tests cannot be relied upon. Results based from the prediction of a small scale model tested at low stress level tend to be seriously overpredicted when applied to field event. In the state-of-the art of geotechnical modelling, the centrifugal modelling technique provided a reliable and economic alternative means of simulating prototype behaviour as models can be tested at identical stress levels to those in the field.

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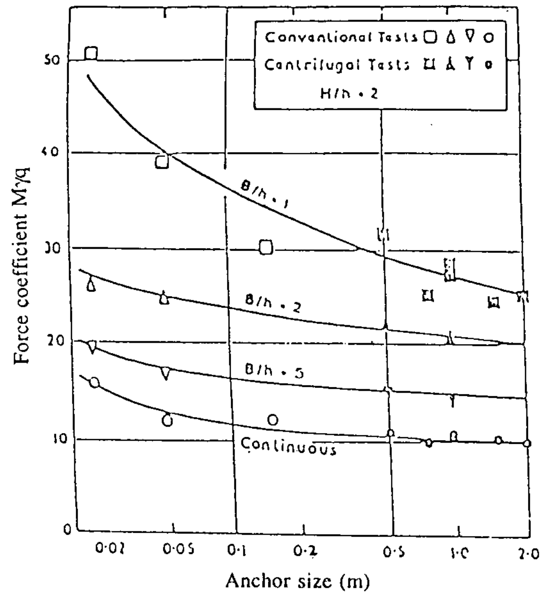

Figure 1(a) : Variations of Force Coefficient with various anchor sizes for single and continuous anchor plates (Leung (1981)).

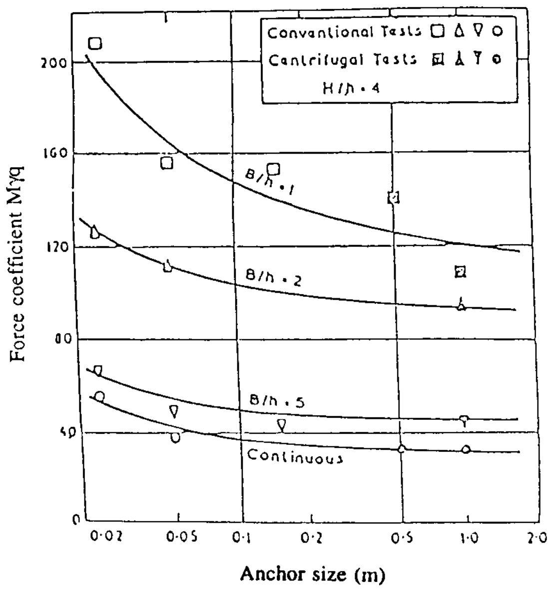

Figure 1(b) : Variations of Force Coefficient with various anchor sizes for single and continuous anchor plates (Leung (1981)).

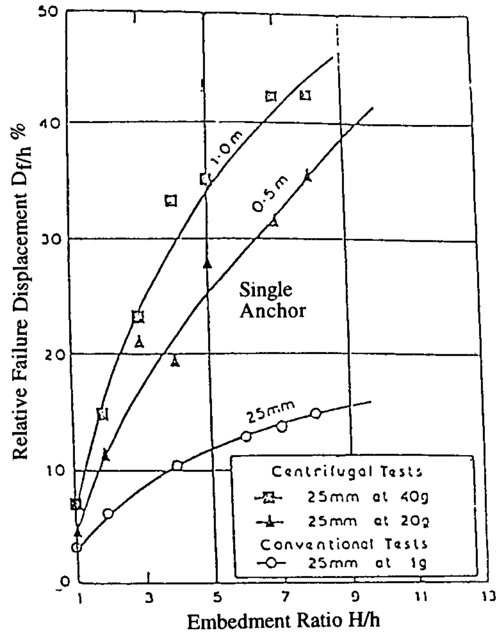

Figure 2(a) : Variations of Relative Failure Displacement with Embedment Ratio H/h various sizes of anchor plate (Leung (1981)).

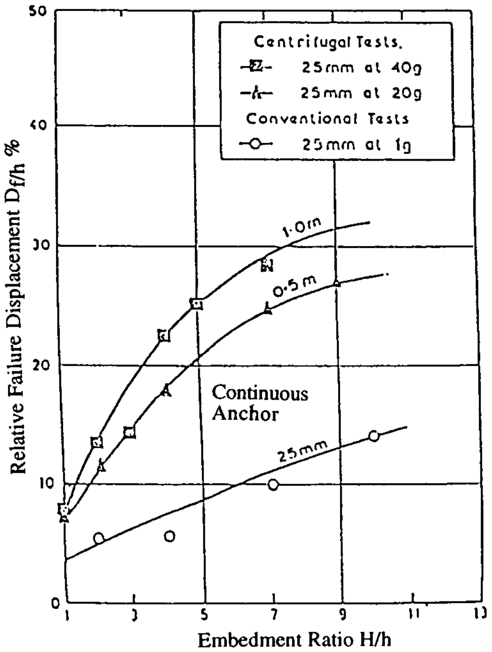

Figure 2(b) : Variations of Relative Failure Displacement with Embedment Ratio H/h various sizes of anchor plate (Leung (1981)).

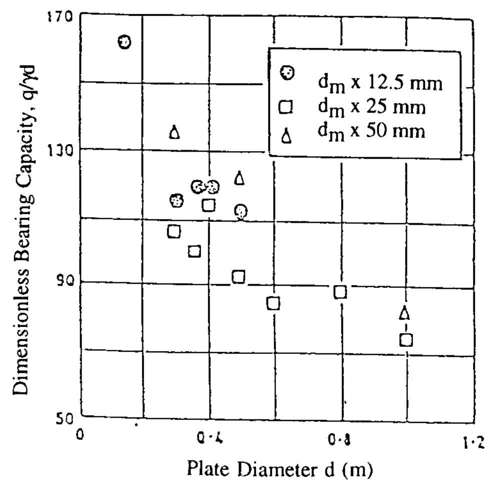

Figure 3(a) : Variation of Dimensionless Bearing Capacity with plates diameter in Plate Loading Tests (King et.al (1984)).

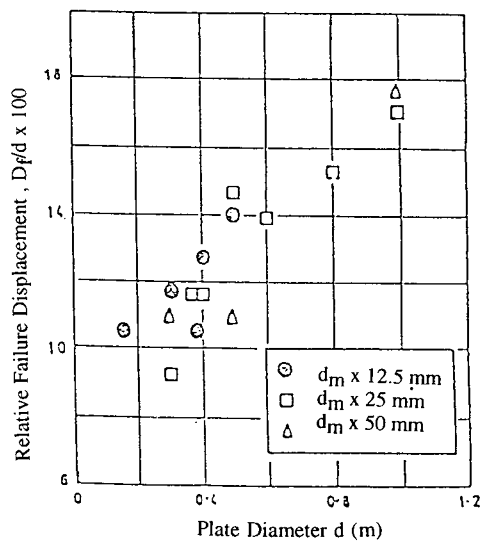

Figure 3(b) : Variation of Relative Failure Displacement with plate diameter in Plate Loading Tests (King et.al (1984)).

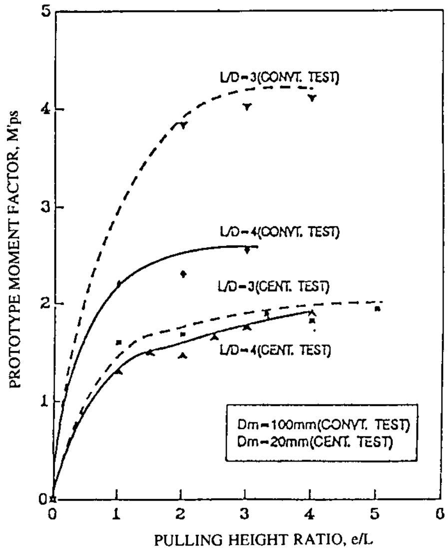

Figure 4(a) : Comparison between conventional test and centrifugal test for 1m diameter prototype pile in dense sand.

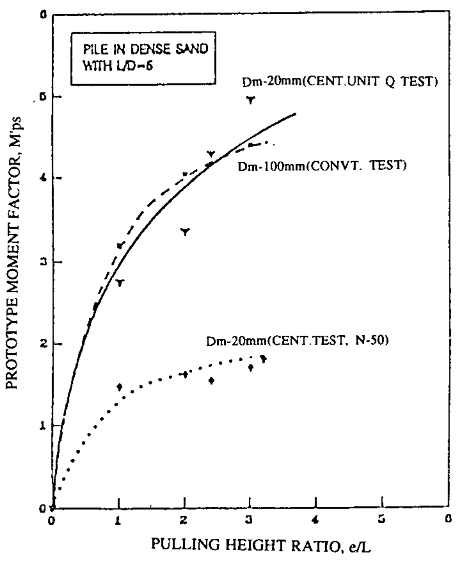

Figure 4(b) : Comparison between conventional test and centrifugal test for 1m diameter prototype pile in dense sand.

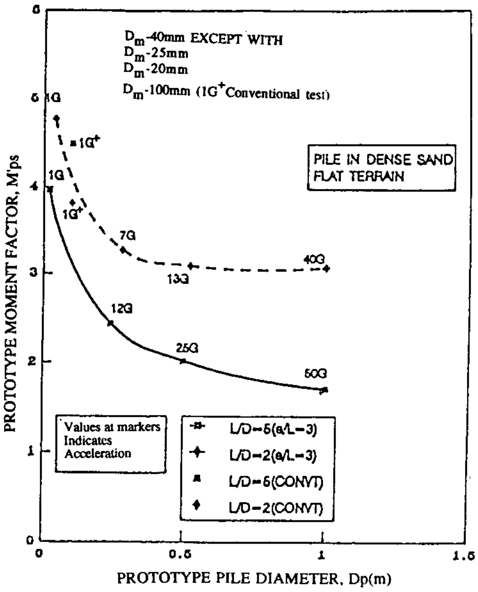

Figure 5 : Variation of prototype moment factor with prototype pile diameter test at different stress level

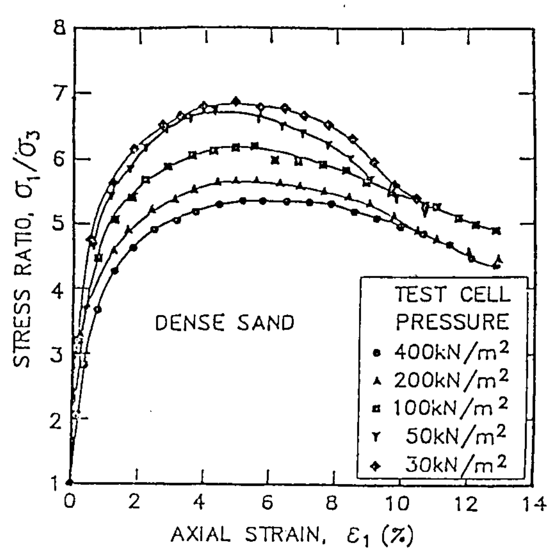

Figure 6(a) : Variations of strength and dilatant characteristics with stress level for a typical sand (Liem (1988))

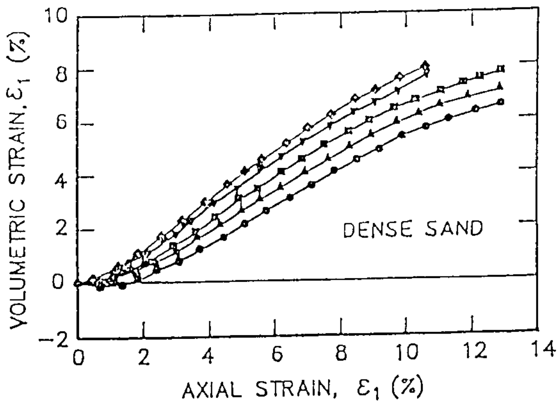

Figure 6(b) : Variations of strength and dilatant characteristics with stress level for a typical sand (Liem (1988))

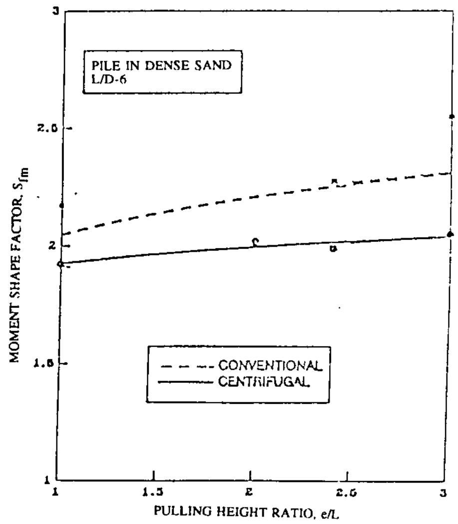

Figure 7 : Comparison of moment shape factor between centrifugal and unit gravity test for pile in dense sand