General Report: Technical Session 2 – Foundations & Retaining Walls

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1. INTRODUCTION

The intention of this session is to cover the engineering risk associated with foundations and retaining walls. The papers submitted, however, represent a very narrow view of the overall subject and it is perhaps questionable whether they relate to the issues of greatest risk. Is it not self evident that piled structures carry less risk than those founded on shallow footings or that the commonest "failure" of engineering structures is that of retaining walls? Yet this session has 70 percent of the content devoted to piles and nothing to retaining walls.

These questions and statements are spurious and are merely intended to provoke discussion. As suggested in the guidelines to authors, all aspects of geomechanics relate to "risk" of some sort and hence the theme of the conference must be interpreted broadly. The purpose of this report is to highlight the principal points of interest of each paper in the hope that this will stimulate interested parties to read on for more information.

2. GENERAL

The papers assigned to this session fall into the following broad categories:

- Piles:
  - Axial capacity : 4 papers
  - Lateral capacity : 4 papers
  - Practical aspects : 1 paper

- Raft Foundations : 3 papers
- Small footings : 1 paper

Almost all of these are concerned with research projects; only one paper being authored by a designer outside of the research establishments. However, most of the papers are relevant to either design or construction practice despite the content varying widely from mathematical analyses to practical techniques and case histories.

In the following sections, the reporter comments on each paper of this session, always from the perspective of a design engineer.

3. REVIEW OF SESSION PAPERS ON DEEP FOUNDATIONS

3.1 Class A Predictions of Pile Behaviour

Poulos presents here an interesting comparison of predicted pile performance against actual measured performance. He elected to use "... one of the simplest and least sophisticated approaches ..." for the capacity prediction; that of correlating skin friction and end bearing resistance to CPT cone resistance. For the prediction of load-settlement behaviour a boundary element analysis was employed but the input parameters were still based on correlations with CPT data and "... the author's limited experience ...". The methods themselves are worthy of note, particularly the rationale for the selection of the empirical factors. However, the main points of general interest are well summarised in the papers conclusions, namely:

- Despite relatively favourable circumstances, Class A predictions were "fair only".
- The methods used for prediction are of less significance than the assessment of the parameters.

More specific points of interest may be highlighted as follows:

(a) The pile load distributions (Figures 4 & 5 of the paper) give some clue as to where the predictions may be most in error. However, the reporter believes that this may be one of those occasions where a dimensional plot would be of more value than the normalised plots given, particularly where the measured load differs markedly from the predicted. For example the load distribution for the cased pier would be as shown in Figure 1. If it weren't for the complication of diameter change, the unit skin friction would be proportional to the slopes of these lines. It can be seen that prediction of unit skin friction is reasonable except in the near surface sand above the water table. This also applies to the "slurry pier" to some lesser extent but, for the driven piles, the average unit skin friction has been predicted very closely in soil mechanics terms.

We learn from this, that we should predict higher long term unit skin frictions for the bored piles in non-saturated sand.

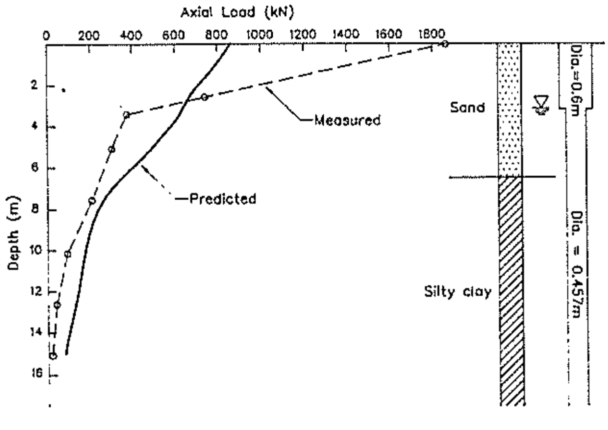

Figure 1: Predicted and measured load distributions for cased pier

(b) The influence of time effects was quite different to that expected by the author. He had expected more benefit from the driven piles and none at all for the bored piles. Table 1 presents the data in terms of proportion of long term load. It will be seen that the time effects are very similar for all piles. This would imply that it is not pore pressure controlling the time effects.

TABLE 1
SUMMARY OF TIME EFFECTS

Pile	Proportion of long tern capacity		
	2 weeks	4 weeks	43 weeks
H-Pile	0.78	0.84	1.0
Pipe	0.61	0.70	1.0
Slurry Pier	0.63	0.82	1.0
Cased Pier	0.61	0.85	1.0
Average	0.66	0.80	1.0

In the light of point (a) above, it would be interesting to know if it were the unsaturated sand which provided the primary influence on the time effects.

(c) Despite the wide range of predicted capacities from the other participants, it would appear that the standard design factor of safety of 3 would rarely result in actual factors of safety being less than 1.8 and would more likely be unnecessarily conservative (and expensive) with actual factors of safety in the 5 to 10 range. Table 2 summarises the actual factors of safety which would result in a real world design situation based on the predictions of the other participants.

TABLE 2
SUMMARY OF ACTUAL FACTORS OF SAFETY

Pile	Most conservative design		Least conservative	
	Predicted allowable load with F=3	Actual factor of safety	Predicted allowable load with F=3	Actual factor of safety
H-Pile	203	5.0	557	1.8
Pipe	187	5.5	550	1.9
Slurry pier	192	9.6	753	2.4
Cased pier	193	9.6	443	4.2

It would appear that the designers of pile foundations could afford to be more adventurous in general.

3.2 The analysis of ancillary loaded piles in layers or non-homogeneous soils

Small and Lee have introduced the "finite layer" method as a means of computing vertical displacements of piles. Despite some confusion with notation, it appears to be a useful addition to the growing list of available numerical methods. This is particularly so because it is intended for use in layered soils or soils with increasing stiffness with depth; circumstances which tend to represent the real would better than the homogeneous elastic half-space.

It is interesting to test some of the results in relation to a typical practical design situation. Take, for example, conditions similar to those described in the previous paper (Poulos, 1992) and assume:

- Axial load = 500 kN
- Sand stiffness = 2 x clay stiffness = 60 MPa
- Pile is concrete with stiffness = 1000 x clay stiffness = 30 GPa
- Depth of sand = 6 m
- length of pile = 15 m

Using Figure 4 of the paper, a settlement of less than 2 mm is predicted and this is compatible with the observed load-displacement curves (see Figures 2 and 3 of Poulos, 1992). However, bearing in mind that it would normally be considered a little adventurous to terminate a pile in clay of shear strength of (say) 60 kPa, the questions must be asked:

- Is settlement an issue with pile foundations?
- Are numerical methods of any real value?

In the reporter's experience, any structure which may be that sensitive to settlement is likely to have piles founded in much stiffer materials than assumed for the example and, though working loads may be considerably greater, measured settlements have rarely been more than about 5 mm at working loads.

3.3 Identification of failure mechanisms in soft rock using stereo-photogrammetry

The title of this paper by Choi & Johnston succinctly describes the content. The problem of bearing capacity in weak rock has taxed both researchers and designers for some time. Current design methods either derive from soil mechanics theory or are based on empirical relationships between capacity and uniaxial compressive strength. The work described in the paper appears to offer a means of starting again from first principles, namely the identification of failure mechanisms in a brittle, crushable material.

The paper concentrates on methodology. We should look forward to seeing the results of a developed research programme.

3.4 Analytical predictions for side resistance of piles in rock

The work for this paper by Kodikara, Johnston and Haberfield clearly complements that of the previous paper (Choi & Johnston, 1992). The paper presents a rational "model" for adhesion in weak rock which, rather than relating simply to uniaxial compressive strength, uses other normalised parameters such as the ratio of modulus to strength (E/q_u) and the ratio of strength to confining stress (q_u/σ_{no}). The simplified design charts for Melbourne mudstone based on this model appear to give good results compared with previous work (Williams et al., 1980) except with low strength materials (q_u < 1 MPa). At these low strengths, the model predicts "adhesion factors" (α) less than 0.5 and yet Williams et al. (1980). present data with α in the range 0.5 to 1.0 for both Melbourne mudstone and "other rocks".

At this point it is worth noting that this rock mechanics "adhesion factor", which relates side shear resistance to uniaxial compression strength, is not the same adhesion factor of soil mechanics which relates side shear resistance to shear strength (e.g. Tomlinson, 1977). There is a factor of two here, despite use of the same symbol (α). This is the cue, perhaps, for a point for discussion. When dealing with transition materials such as strong soils/weak rocks, the separate theories, constitutive models, notation and terminology must all be compatible.

In this respect, the Melbourne mudstone model appears more realistic than the data of Williams et al. (1980) because it predicts lower adhesion factors, more compatible with values of stiff clay. Figure 2 reproduces Figure 6 of Kodikara et al.(1992) with some values proposed by Tomlinson (1977) for bored piles in stiff clays superimposed. Discussion on why there should be discontinuity in the trends would be of interest.

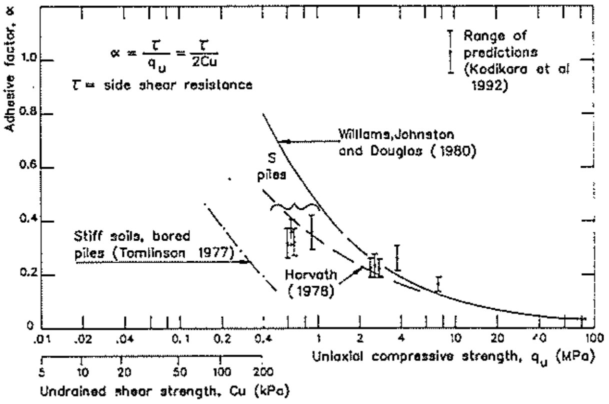

Figure 2: Examples of adhesion factors at soil/rock transition

It is not clear from the paper what makes the model specific to the Melbourne Mudstone. Can the simple design charts be used for other weak rocks?

3.5 Piled bridge abutments on soft clay - experimental data and simple design methods

Stewart, Jewell and Randolf present a clear and useful review of current methods of assessing lateral loads on bridge abutment piles due to embankment loadings. They point out that these tend to be inconsistent and go on to describe a new approach based on centrifuge tests. Results of the new method are promising but the authors readily concede that development must continue.

It is hoped that further research will consider the effects on raked piles, the positions of the piles in relation to the embankment and the effects of downdrag. The latter may contribute far more to bending moments in raked piles than the lateral movement of soil.

3.6 Behaviour of fixed and free head piles in a laterally sliding soil

Hull, Lee and Poulos look at essentially the same problem as the previous paper (Stewart et al., 1992) using a numerical soil-structure interaction method. Their findings are well summarised in the paper's conclusions. The method provides useful in-sight into the behaviour of piles of various stiffness and degree of head fixity in response to laterally sliding soil of various slide depths. The examples use realistic pile sizes so that results could be useful for real problems. However, as the authors point out, the very large predicted displacements (in terms of tens of metres) cast doubt on the validity of using a small displacement formulation.

It appears that the main point of the research work is to determine design procedures for piles used as landslide stabilising measures. The reporter has had this problem on many occasions and welcomes this contribution. However, having come up with a cost effective design with reasonable pile sizes spaced at realistic intervals, the problem invariably degenerates to something more fundamental. The question is asked : What happens downslope of the piles? If this portion of the slip mass continues to slide away, the line of piles then becomes a retaining wall and must now be designed for the internal active forces from the upslope soil mass. These may well be greater than forces calculated for the intact slide because the fixity conditions have changed.

3.7 Lateral soil movement loading on bridge foundation piles

The third paper on the same subject by Hull and McDonald describes a case history of an actual failure and its back analysis. The analysis involved making an assessment of soil movements and then using a computer program (PALLAS) with a long established soil model (Poulos 1973) to analyse the response of the pile. The main point of interest was that the 350 mm square section piles driven through a 10 m layer of soft clay tend to move with the soil; significant relative displacement only occurring in the very soft soil near ground surface.

3.8 Sensitivity analysis of laterally loaded piles

Budkowska and Szymczak present a theoretical paper concerned with determining the effects on computed values (e.g. displacements and bending movements) in a lateral pile analysis due to small changes in the design variables. The authors conclude that "... approximation of the changes of the displacements of the pile by means of their first variations is good even for 20 percent change of the design variable".

A reader not familiar with the method adopted ("adjoint method") and some of the notation, may find this paper difficult to follow.

3.9 Risk associated with construction of large diameter bored piles in cavernous marble

In contrast to the preceding paper, this paper by Li is a practical discourse on construction techniques. The risks discussed are those associated with construction rather than permanent risk relating to the finished product. The paper is essential reading for all parties involved in a project of a similar nature.

4. REVIEW OF SESSION PAPERS ON SHALLOW FOUNDATIONS

4.1 An analysis of rectangular rafts of finite flexibility subjected to concentrated loads

Zhang and Small introduce again the finite layer method (see Small and Lee, 1992 - section 3.2 above), this time for analysis of rafts. The method still requires a computer but the formulation is supposed to be comparatively simple in relation to other numerical models such as finite element or finite difference soil-structure interaction codes. This is particularly desirable for analysis of rafts as 3-dimensional effects are significant.

The author's point out that spring models are still widely used for the analysis of rafts. This is certainly true in New Zealand. Yet it has been shown quite convincingly (Hemsley, 1987) that there are serious differences between results of analyses for spring or continuum models. Figures 3 and 4 are reproduced from Hemsley (1987); the former showing that predicted bending moments for the spring model can be as much as 5 times that for the continuum model and the latter showing that the sense of the bending moments can be exactly opposite for the two models. In other words, not only would a design based on a spring model be unnecessarily expensive, but the main reinforcement may be in the wrong place.

But even the elastic continuum model can be significantly in error. It predicts in some circumstances, infinite contact pressures. Clearly, real soil would yield with consequent redistribution of stresses, bending movements and displacements. It is certainly time more attention is given to rigorous analysis of rafts. The paper by Zhang and Small goes some way in the right direction but the method still relies on "elastic" soil. What are needed, of course, are more case histories and instrumentation/monitoring data.

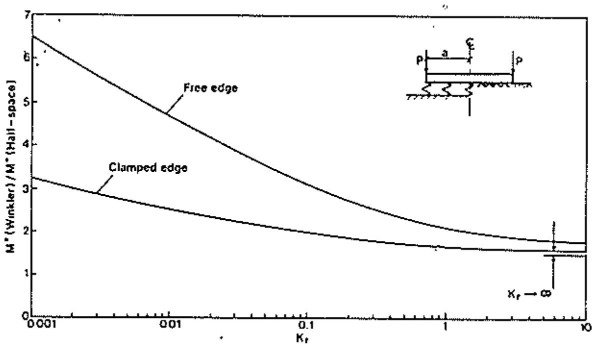

Figure 3: Ratio of maximum bending moments for edge loaded circular raft on spring or half-space foundation (After Hemsley, 1987)

4.2 Prediction and measurement of settlement of a heavily loaded raft

Olds obliges by presenting here a well documented and concise case history of raft design and performance monitoring. The main points of interest are:

(a) The soil modulus profile for design was determined using the unload/reload cycles of pressuremeter tests.

(b) The design was based on the more conservative modulus (i.e. "secant" modulus) of the reload curve but the monitoring data indicated that the stiffer value of the "average" modulus of the unload/reload loop would be more appropriate.

(c) Settlement predictions were reasonable and consistent on the conservative side, as would be expected in a design situation with a critical structure. Settlements may continue to increase with time.

(d) Settlement analyses used a finite element multi-layered, elastic model (program FOCALS). The detailed analysis of the raft was "decoupled" from the analysis of settlement, and is not reported here.

4.3 The cellular raft and horizontal ground strains

This paper by Pellissier and Williams is about mitigation of risk. The paper is devoted to explaining the advantages of using a cellular raft for accommodating horizontal ground strain, particularly in relation to subsidence in longwall mining areas. The arguments are convincing for small structures (i.e. low rise dwellings) and may even be applicable for mitigation of earthquake risk.

The main point of technical interest relates to the tests on the soil/raft slip interface. It would seem that a simple sandwich of cut-back bitumen between sheets of plastic sheeting under the flat bottomed raft may well provide cheap and effective base isolation as well as an effective damp proof course.

The concept of designing flat slabs to accommodate horizontal strain is not new. Bell (1977) describes how systems have been used in Britain since the "fifties". There, however, they favour thin flexible rafts to accommodate curvature also. The authors claim that the stiffer cellular rafts are advantageous in areas of expansive soils. Certainly they would be advantageous in areas prone to differential settlement or, possibly, liquefaction.

This particular cellular raft, termed the Boucell raft, has been patented by the CSIR (South Africa). It is not clear what feature of the raft is patented. It is hoped that it is only a matter of detail and that there would be no restrictions on engineers designing from first principles!

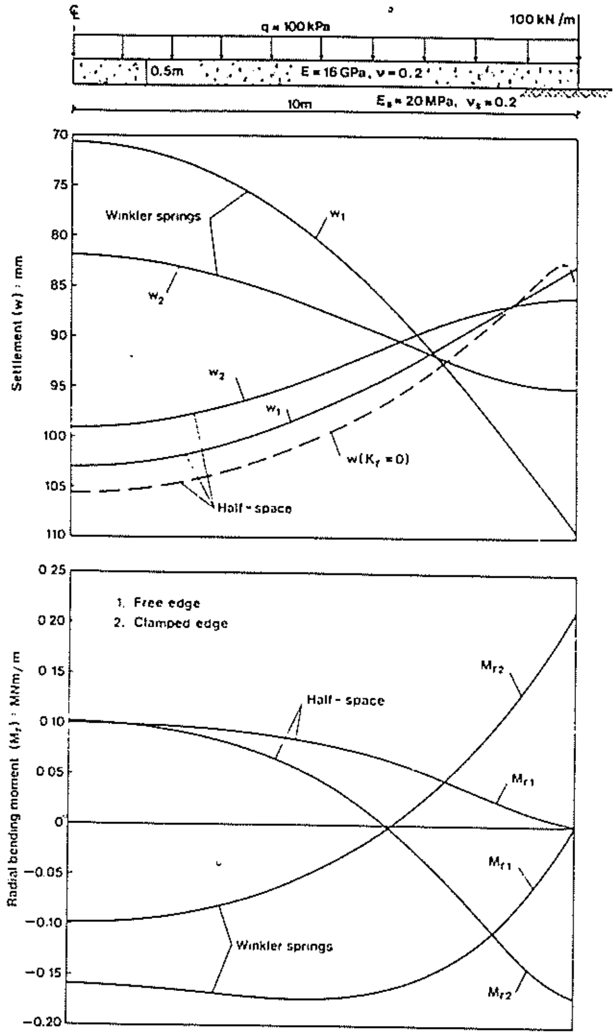

Figure 4: Example results for circular raft with combined edge and uniform distributed loading on spring or half-space foundations (After Hemsley, 1987).

4.4 Study of a case of unsuitable structural system on heterogeneous soil

This paper by Reyad presents a fairly straight forward case history of settlement of dwellings and remedial measures. As the author points out, the selection of simple strip footings to found buildings in an area of very variable ground conditions would appear inappropriate. Certainly the combination of fill, collapsible sand and expansive clay in a situation prone to extreme changes in wetting and drying (watering and arid zone evaporation) should have sounded some alarms. Perhaps the cellular raft of the previous paper (Pellissier & Williams, 1992) would have been the answer here.

It would be interesting to hear if the remedial measures described have been successful.

5.0 CONCLUSIONS

There can only be one conclusion to a session report : If there appears to be anything of interest, read the papers! However, in recognition of the conference theme, the report concludes with some statements which the reporter considers may hold some truth but should be challenged in open discussion:

- There is little risk of catastrophic failure of foundations. Designs are very conservative and unnecessarily expensive.
- The greatest risk in foundation engineering is that due to differential settlement of shallow foundations. Settlements of deep foundations are generally not significant.
- The greatest risk associated with deep basements arises at time of construction. Generally designs of permanent walls are over conservative, despite (or because of) a pre-occupation with the "K_0" fallacy.
- The commonest failures of engineering structures are associated with retaining walls and ground retention systems, yet research is only modest in this field.

6. REFERENCES

6.1 General

Bell, S.E. (1977) Successful design for mining subsidence. Proc.Conf. on Large Ground Movements and Structures, Cardiff, Pentech Press.

Hemsley, J.A. (1987) Elastic solutions for axisymmetrically loaded circular raft with free or damped edges founded on Winkler springs or a half-space. Proc.Instn.Civ.Eng. Part 2, 83, Mar., 61-90.

Tomlinson, M.J. (1977) Pile design and Construction Practice, Viewpoint Publications, London.

6.2 Session papers

The following papers, reviewed in this report, are included in the Proceedings of the 6th ANZ Geomechanics Conference, 1992.

Budkowska, B.B. and Szymczak, C. (1992). Sensitivity analysis of laterally loaded piles.

Choi, S.K. and Johnston, I.W. (1992). Identification of failure mechanisms in soft rock by stereo-photogrammetry.

Hull, T.S., Lee, C.Y. and Poulos, H.G. (1992). Behaviour of fixed and free head piles in a laterally sliding soil.

Hull, T.S. and McDonald, P. (1992). Lateral soil movement loading on bridge foundation piles.

Kodikara, J.K., Johnston, I.W. and Haberfield, C.M. (1992). Analytical predictions for side resistance of piles in rock.

Li, K.S. (1992). Risk associated with construction of large diameter bored piles in cavernous marble.

Olds, R.J. (1992). Prediction and measurement of settlement of a heavily loaded raft.

Pellissier, J.P. and Williams, A.A.B. (1992). The cellular raft and horizontal ground strains.

Poulos, H.G. (1992). Class A predictions of pile behaviour.

Reyad, M.M. (1992). Study of a case of unsuitable structural system on heterogeneous soil.

Small, J.C. and Lee, C.Y. (1992). The analysis of axially loaded piles in layered or non-homogeneous soils.

Stewart, D.P., Jewell, R.J. and Randolph, M.F. (1992). Piled bridge abutments on soft clay - Experimental data and simple design methods.

Zhang, B.Q. and Small, J.C. (1992). The analysis of rectangular rafts of finite flexibility subjected to concentrated loads.