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Contributions to Foundation Engineering in Geotechnique

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Contributions to *Géotechnique* 1948–2008: Foundation engineering

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Many of the important developments in the field of foundation engineering have been addressed in *Géotechnique* papers over the past 60 years. This paper briefly reviews some of these developments and related articles, particularly with respect to shallow and deep foundations. In the early days of *Géotechnique*, the power to perform sophisticated numerical analyses did not exist. Papers tended to focus on the solution of problems using simple models in which soil was modelled either as linear elastic or as perfectly plastic. Engineers sought simple closed-form analytical solutions for boundary-value problems. With the development of more powerful analytical, computational and experimental capabilities, and of more sophisticated pile installation technology (especially offshore), more recent papers have explored much more sophisticated approaches to a range of foundation problems, striving to achieve more realistic representation of working conditions. *Géotechnique* papers have attempted to solve the problems faced by the foundation engineering industry, with a strong emphasis on the underlying science; as a result, these papers have played a key role in the advancement of both the science and its applications in our discipline.

KEYWORDS: footings/foundations; historical review

Au cours des 60 dernières années, des communications de *Géotechnique* se sont penchées sur un grand nombre de développements importants dans le secteur de la technique des fondations. La présente communication se penche brièvement sur certains de ces développements et articles connexes, en particulier sur le plan des fondations superficielles et profondes. Au début de l'existence de *Géotechnique*, on ne disposait pas de la capacité d'effectuer des analyses numériques sophistiquées : les communications avaient tendance à se concentrer sur la solution de problèmes au moyen de modèles simples dans lesquels le sol était modélisé comme étant élastique linéaire ou parfaitement plastique. Les ingénieurs recherchaient de simples solutions analytiques de forme close pour des problèmes aux valeurs limites. Puis, avec le développement de moyens analytiques, de calcul et expérimentaux plus sophistiqués, et l'avènement d'une technologie plus sophistiquée pour l'installation de piles (notamment en mer), des communications plus récentes se sont penchées sur des méthodes beaucoup plus sophistiquées pour résoudre toute une série de problèmes de fondations, en s'efforçant de réaliser une représentation plus réaliste des conditions de travail. Des communications dans *Géotechnique* ont tenté de résoudre les problèmes affrontés par le secteur des techniques des fondations, en mettant l'accent sur la science sous-jacente ; en conséquence, ces communications ont joué un rôle essentiel dans les progrès réalisés tant sur le plan de la science que sur ses applications, dans notre discipline.

INTRODUCTION

Given that the worldwide body that represents much of the *Géotechnique* readership was, for many years, called the International Society for Soil Mechanics and Foundation Engineering, one might expect a substantial fraction of *Géotechnique* to be devoted to foundations. Somewhat surprisingly, this is not the case, with fewer papers than expected being devoted primarily to foundations. An interesting observation is that the most notable work on foundations does not appear in a few landmark papers, but as groups of papers dealing with distinct themes. Each theme was sustained over a number of years by groups of authors, and attracted a series of papers that collectively advanced the subject. These sustained contributions are an important demonstration of *Géotechnique*'s vitality. In this paper, we discuss these contributions collectively within themes rather than concentrating on individual papers.

The topic of foundations naturally divides into the study of shallow foundations and deep foundations (almost exclusively piles). Another division is into issues of capacity and deformation. Some papers present theories, while others report practical records, either at laboratory or at full scale. We have organised the discussion of papers based primarily on whether they deal with shallow or deep foundations.

In the early days of *Géotechnique*, the power to perform sophisticated numerical analyses did not exist, so problems were analysed using mainly simple models, in which soil was modelled either as linear elastic or as perfectly plastic. Simple closed-form analytical solutions for boundary-value problems were employed. Over the past 60 years, geotechnical engineers have gained a much better understanding of how soil responds to loading, and have developed numerical analyses that attempt much more realistic solutions to boundary-value problems. Significant progress has also been made in the technology used both to install and test deep foundations, and to address the specific requirements of offshore foundations—a challenge that hardly existed at the inception of *Géotechnique*.

We preface our review by some comments on offshore foundations. We view these as nothing other than shallow or deep foundations with specific design issues, related mainly to the magnitude of the loading, its cyclic nature, and the large horizontal component from environmental forces. The first explicit reference to offshore foundations in *Géotechnique* is the key paper by Bjerrum (1973), who introduced many of the major offshore foundation themes relevant to the emerging North Sea oil developments. The particular challenges that engineers faced in the North Sea drove the foundation engineering community to design much larger foundations than previously used. Open-ended pipe piles

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Discussion on this paper closes on 1 December 2008, for further details see p. ii.

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with much larger diameter and length than onshore piles required more powerful hammers with which to drive them. Gravity-based structures focused the attention of the profession on bearing capacity, with high cyclic horizontal loads and moments. In parallel, jack-up platforms used around the world introduced the challenge of estimating the penetration resistance of 'spudcan' foundations that were 10–20 m in diameter and penetrated up to two diameters in soft soil before achieving sufficient resistance for the stability of the mobile platform to be assured. Papers appearing in *Géotechnique* have captured these themes.

SHALLOW FOUNDATIONS

Bearing capacity

One of the first themes to emerge early in *Géotechnique* was that of the bearing capacity theory of foundations. The basis of the bearing capacity factor approach had of course already been set out by Terzaghi; it drew significantly on work on the indentation of metals, with appropriate modification for the frictional nature of soil, but much work remained to be done. An important early contribution, much cited later, was by Meyerhof (1951), who attempted a theoretical treatment of the bearing capacity of shallow foundations, accounting for the effects of foundation embedment depth. For many years the approach he pioneered, using shape and depth factors, became the standard approach for bearing capacity calculation. He also presented the results of field load tests for foundations in sand and clay. These results had a lasting impact because they provided data on bearing capacity that anchored theoretical calculations, providing engineers with a measure of confidence in their calculations, although by more exacting modern standards the amount of data presented in support of the theories was relatively slim.

At around the same time, an equally influential paper by Skempton (1951) on foundations in clay was published in a conference rather than *Géotechnique*!

Complementing the work of Meyerhof and Skempton was the early, and now famous, case study by Peck & Bryant (1953) of the bearing capacity failure of the Transcona grain elevator. In the same issue of *Géotechnique*, there is an interesting eyewitness account of the failure. The elevator was built on a raft foundation in Winnipeg, Canada, in 1911, on rather uniform, 10–15 m thick deposits of almost pure clay, overlying thinner layers of mixtures of clay and gravel and then limestone. The failure occurred in 1913 upon filling of the elevator. Calculations using the Skempton (1951) form of the bearing capacity equation for clay produced good agreement with the load at collapse, which was estimated from the known amount of grain stored at the time of failure, the dead weight of the structure, and the amount of pressure relief due to excavation of the soil for construction of the raft. Peck & Bryant recognised some of the difficulties in establishing a representative value of shear strength for the clay, including the possible effect of progressive failure and of the presence of closely spaced slickensides. In many ways, this paper still serves as a model of thoughtful back-analysis of a case history, although of course a more sophisticated analysis would now be possible.

A difficulty that Peck & Bryant did not mention is that, where strength increases with depth, averaging of shear strength values over certain depth ranges can produce misleading results. The elegant analysis by Davis & Booker (1973), who studied the bearing capacity of shallow foundations on soil with strength increasing with depth, allows a much more rigorous treatment of bearing capacity problems on clay. The Davis & Booker paper is a fine example of the contribution that numerical analysis began to make to the subject from the mid 1960s onwards.

Returning, though, to Meyerhof's contributions, although he contributed other papers to the early issues of *Géotechnique*, his highly influential paper on inclined and eccentric loading of foundations was published at the Third International Conference on Soil Mechanics and Foundation Engineering (Meyerhof, 1953). It was this paper that really set the pattern for bearing capacity calculations, with its use of inclination and eccentricity factors. Eccentric loading (or equivalently moment loading) was taken into account by considering an 'effective width' $B' = B - 2e$ (where e is the load eccentricity) and a corresponding 'effective area'. This simplification proves to be well founded, but the basis for a number of the other multiplicative factors that have been used in bearing capacity theory is rather less secure. This approach achieved its zenith in the work of Brinch Hansen (1970) and Vesić (1975), whose methods are both still much employed in practice. It is interesting that neither publication was in a mainstream journal, let alone *Géotechnique*.

Work in recent years has refined our understanding of some of the factors used in conventional bearing capacity analysis. For instance, Salgado *et al*. (2004) used modern numerical techniques to obtain more accurate shape and depth factors equations (see also Edwards *et al*., 2005; Lyamin *et al*., 2007). Other issues have been explored experimentally: for example, centrifuge tests by Kimura *et al.* (1985) showed that N_γ depends on the size of the footing.

An alternative approach to the calculation of the capacity of foundations has been developed, principally in the past 15 years. Rather than using a plethora of inclination, eccentricity and shape factors, the yield surface is considered directly as a function of the combinations of the vertical load V, lateral load H and moment M on the foundation leading to yield. *Géotechnique* has played a central role in publishing the papers that describe the development of the approach, but it should be noted that in fact it owes its origins to the work of Roscoe & Schofield (1957), and later Butterfield & Ticof (1979). It is interesting to speculate whether these ideas might have gained earlier acceptance had Roscoe & Schofield chosen to publish in *Géotechnique* rather than the *British Welding Journal*.

The most important driver for investigating the (V, H, M) yield surfaces has been their importance for offshore foundations. Various authors throughout the 1990s revisited the effective area concept for accounting for overturning moment and inclination factors for the effect of combined vertical and horizontal loads. Bransby & Randolph (1998) published the results of numerical analyses of the limit bearing capacity of undrained skirted foundations. They demonstrated that the yield locus for skirted foundations was not symmetric in H–V space owing to the deformation mechanisms that constrained failure. In fact, the issue of what exactly is the shape of the (V, H, M) yield surface has been the focus both of experimental work (e.g. Butterfield & Gottardi, 1994; Martin & Houlsby, 2000) and theoretical work (e.g. Bransby & Randolph, 1998; Taiebat & Carter, 2000; Gourvenec & Randolph, 2003; Randolph & Puzrin, 2003).

While the use of a (V, H, M) yield surface can be applied directly to bearing capacity calculations, it also serves as the starting point for the development of complete 'force resultant' or 'macro-element' plasticity models used to describe the entire response of a shallow foundation. This concept was first described by Nova & Montrasio (1991) in an important paper in *Géotechnique*, although the concept was anticipated by that of Schotman (1989). Since then, much work has been done on the development of force resultant models (e.g. Houlsby & Cassidy, 2002). These find particular applications to offshore applications, as they allow a complete and consistent numerical analysis of both foundation and structure. This is important, for instance, for dynamically sensitive structures, such as jack-up units or offshore wind turbine installations. One of the most important features of these models is that they offer a combined treatment of capacity and settlement, in much the same way that critical-state soil mechanics unified concepts of deformation and shear strength.

Jack-up foundations (or spudcans) have received particular attention. They are penetrated under a preload that is of the order of the maximum design axial load. The preload is then removed to provide the adequate safety factor on bearing capacity. This fascinating topic has motivated extensive research, particularly on the subject of penetration through a multilayered soil profile, and the strength (in V, H, M space) and stiffness of the preloaded foundation. The rotational stiffness of a spudcan foundation has an important effect on the structural integrity of the jack-up during extreme loading. Martin & Houlsby (2000, 2001) developed a macro-element model of the type described above to simulate the response of spudcan foundations to generalised, incremental (V, H, M) loading. This type of sophisticated foundation model is a considerable advance over the linear springs used hitherto, enabling calculation of a much more realistic load distribution in the jack-up structure.

Settlement

The importance of small-strain non-linearity is now well recognised, but this was not appreciated for much of the life of *Géotechnique*, and it was widely believed that deformation problems could be assessed with sufficient accuracy using linear isotropic elasticity theory. Linearity, of course, has the enormous advantage that superposition can be employed, so elastic solutions still play a vital role in assessing deformations, but their shortcomings are now better understood.

Geotechnical problems offered a whole range of new boundary-value problems to explore using elasticity theory, and *Géotechnique* has played a central and sustained role in the publication of these analyses, most of which relate to foundations. Among these are a number of papers from the group at Sydney University (especially E. H. Davis, H. G. Poulos and P. T. Brown), such as Davis & Poulos (1968). Much of this work led to the important reference work by Poulos & Davis (1974).

A key contribution was that by Gibson (1967); this contribution was so important that it receives the rare accolade that reference to a 'Gibson soil' is enough to define a soil with the shear stiffness increasing linearly with depth. This led to a whole new family of problems and solutions. Useful contributions to this were made by Awojobi, in a series of papers in the early 1970s (e.g. Awojobi, 1974). More recently, Gazetas and co-workers have made a number of contributions in elasticity. For example, Gazetas *et al.* (1985) proposed an equation that can be used in the calculation of settlement of a footing with any of a variety of shapes embedded in a homogeneous elastic soil.

The engineer using elastic analyses must: (a) match the engineering problem to an available, suitable solution to a similar boundary-value problem; and (b) properly define the soil properties. Assuming a solution is found that is applicable to the problem at hand, the problem reduces to one of establishing a soil profile and selecting suitable soil properties to use in calculations. This is not always so simple. For example, many solutions are available for a homogeneous elastic soil, when in fact the 'elastic' parameters of the soil, even for a relatively uniform deposit, will vary, with elastic modulus typically increasing with depth. An important decision is to choose suitable values for the elastic parameters, which requires identification of some depth of influence (depth over which most of the soil deformations will take place) and a suitable averaging algorithm. Of course, certain solutions more realistically capture specific problems: for instance, a 'Gibson soil' fits more closely the pattern of increasing stiffness with depth that is observed for many soft clay deposits.

In reality, footing settlement is not elastic except for exceptional cases in which displacements are extremely small. The linear elastic, perfectly plastic paradigm shaped much of the engineering thinking of the twentieth century, but soils are now known to yield very early in the loading process, so plasticity plays a role long before a complete plastic mechanism has formed. For long-term settlements in clay, for example, the role of consolidation (a plastic process) was recognised early, and Skempton & Bjerrum (1957) proposed an analysis to take three-dimensional consolidation into account when calculating these settlements. But plasticity asserts itself also for immediate settlements, depending on how far the combined loading action is from the (V, H, M) failure envelope. As long as plastic zones developing in the soil below and around the foundation remain confined by soil that is still in the elastic range, plastic deformations will be of the same order as elastic deformation, the role of plasticity is diminished, and the use of equivalent elastic parameters may be appropriate. As plastic zones begin to coalesce, the use of equivalent elastic parameters becomes increasingly inappropriate, and parameter values must, for sufficiently large settlements, be determined either from experiments or from more rigorous analyses that do take into account the plasticity of the soil in a sufficiently rigorous manner. An alternative path is to develop simplified analyses that take into account both the elastic and plastic responses of the soil, such as the interesting analysis proposed by Osman & Bolton (2005), in which they propose procedures to map from a representative stress–strain curve directly to the load–deformation response of a footing.

PILE FOUNDATIONS

Although many new techniques for pile installation have appeared over the last two decades, at the time of publication of the first issues of *Géotechnique*, piles were of one of two types: displacement piles (piles installed by displacing or pushing aside the soil occupying the space intended for the pile) and non-displacement piles (piles installed by first removing the soil from the space intended for the pile, then constructing the pile). Displacement piles were usually driven, and non-displacement piles were usually bored. Designing either displacement or non-displacement piles for axial loads using the working stress design approach consists in estimating the pile base resistance and the shaft resistance, adding these to obtain an ultimate load, and dividing the ultimate load by a suitable factor of safety.[§] This was the design practice 60 years ago. Then (and still in many cases at present), settlements were dealt with indirectly by using a factor of safety that experience showed to be sufficient to limit the settlement to a tolerable value. In the last two to three decades, analyses have appeared that allow explicit evaluation of settlement. The methods for design of laterally loaded piles, out of necessity, have focused more on deflection from the outset. Several papers appearing in *Géotechni-*

[§] Variations of this procedure are used when load and resistance or partial factor design is employed.

que on pile foundations have started or contributed significantly to these trends. Pile installation technology has not been a meaningful part of the journal, but design innovations (piled raft design methods being a recent example) have. Most *Géotechnique* papers have approached pile analysis using the soil-property-based approach, in which the shaft and base resistances of axially loaded piles and lateral resistances in laterally loaded piles are estimated from soil properties (shear strength or stiffness) instead of from direct correlations with in situ test measurements.

Axially loaded piles

In the design of axially loaded piles, geotechnical engineers seek to prevent settlements that may endanger the superstructure or render it unserviceable. Originally, this was done by calculating a relatively loosely defined ultimate load (gradually, the load corresponding to a settlement of 10% of the pile diameter became the generally accepted definition for ultimate load) and dividing that load by a factor of safety that would keep settlements to tolerable levels. This required the capability to compute the shaft and base resistance of a pile that would correspond to this ultimate load. As an example, this was the focus of the work of Skempton (1959), who sought a correlation between the limit unit shaft resistance q_{sL} of bored piles installed in London Clay and the shear strength s_{u} of the clay. Skempton (1959) showed that the ratio $\alpha = q_{\mathrm{sL}}/s_{\mathrm{u}}$ is linked to aspects of construction techniques such as boring and concrete placement, and that it can be quite low (according to the paper, in the 0·3 to 0·6 range, with a typical value of 0·45) for piles installed in overconsolidated clay. This was one of the first studies attempting to link pile resistance to construction details. Although Skempton (1959) did not specifically identify one important construction-related factor (development of residual strength even before axial loading because of augering), he made important observations that allowed not only better estimation of shaft resistance in stiff clay but also an understanding of why the magnitude of this resistance was substantially less than the ‘undisturbed’, undrained shear strength of the clay as estimated from laboratory tests. Glossop (1968) noted in his Rankine lecture that there was a widespread belief (as late as 1950) that skyscrapers could not be built in London because the city rested on clay. The confidence in the use of large-diameter bored piles as foundations for tall buildings changed that perception, and Skempton’s work contributed to that process.

The development of shaft resistance is of course more complex than contemplated by Skempton (1959), regardless of the pile type. This complexity is well illustrated by the work of Potts & Martins (1982), who analysed a section of a pile sufficiently removed from the pile top and base such that a one-dimensional finite element analysis, with the soil around the pile modelled as a disc of finite elements, suitably models the problem. The constraint was imposed that all nodes lying along a vertical line were tied together with respect to all degrees of freedom (directions). Application of this constraint guaranteed that shearing took place only in the vertical direction, and that there was no bending of the sides of any element. The pile itself was not modelled; instead, vertical displacements were applied to an internal cylindrical boundary to model pile loading. Potts & Martins (1982) made some important observations, including that the evolution of the stress state near the pile is not simple, potentially leading to substantial changes in the coefficient of lateral stress at the pile/soil interface as well as considerable shear strain localisation near the pile as a result of loading. The authors also stressed that the quality of the simulation of the response of soil near the pile, and thus of the shaft resistance, is very much dependent on the soil model, and on how completely this model describes the features of soil stress–strain response.

An important feature that any analysis must have is the ability to take into account the fact that materials that are not linear elastic tend to show strain localisation, as demonstrated also by Jardine *et al.* (1986) not only for piles but also for other types of foundation. As discussed by Randolph dolph(2003)and\object="okra43"-
) and White & Lehane (2004), the shaft resistance of driven piles and piles jacked into the ground using multiple jacking strokes is subject to degradation (this has become known as friction fatigue) owing to the changes in the state of the soil (including fabric, density and stress state) as the soil is subjected to multiple loading cycles during pile installation. Understanding and modelling this process is essential to development of full theoretical analyses for shaft resistance of these piles. A practical implication of this is that the presumed advantage of jacked piles over driven piles (because driven piles are subjected to many more loading cycles) is very much dependent on how many jacking strokes are used, and on what the shaft resistance against loading cycles asymptote is.

There have also been contributions in *Géotechnique* to the important problem of settlement analysis. The essence of the problem is to calculate the settlement corresponding to a given applied load at the pile head, which requires the intermediate step of calculating the load-transfer curve corresponding to that load. This is where the difficulty resides: how does one determine how much of the shaft and base resistance are mobilised for a given load (or given settlement, since the two go together)? As the applied load increases, we can expect the unit shaft resistance to increase gradually to a limit value. This limit will be reached first near the pile head, but will then be observed at cross-sections near the pile base as the load increases. If the load keeps increasing, end bearing resistance will be mobilised, and it too will increase towards its limit value, causing the pile to plunge if this limit is achieved. The papers that have proposed solutions for this problem (three examples from *Géotechnique*: Poulos & Mattes, 1969; Banerjee & Davies, 1978; Mylonakis, 2001) have assumed linear elastic soils, being more directly applicable to low load levels. Additional assumptions have been made to simplify the analyses: for example, Poulos & Mattes (1969) calculated the effects of shaft resistance by integration of Mindlin’s equation, and Mylonakis (2001) assumed simplified stress and displacement fields in the soil. It is important to recognise that these methods are all continuum-based, but that they can be linked to the more accessible (but less rigorous) approach of replacing the soil by Winkler springs.

Laterally loaded piles

For laterally loaded piles, greater focus is placed on predicting lateral deflection and internal forces (shear forces and bending moments) than ultimate loads. Ultimate loads for very short piles may be reached because of the formation of shallow mechanisms in the soil, but, for piles with typical lengths, a pile would break or yield even before a mechanism formed in the soil, and the deflections would be too large before that happened.

Papers in *Géotechnique* have focused on modelling the soil as a continuum in the analysis of laterally loaded piles (e.g. Banerjee & Davies 1978; Randolph, 1981). There has been a resurgence of continuum-based analysis in recent years because better, more rigorous analyses, better soil models and greater computer power have become available; 20 to 30 years ago this was not true, and the p–y method, despite its numerous shortcomings, became the tool that practising engineers used in most laterally loaded pile analyses. This method replaces the soil with disjointed springs that have a non-linear force–deflection relation, a so-called *p–y* curve, *p* being the lateral load per unit length of pile and *y* being the lateral deflection. It is impossible to obtain theoretically rigorous *p–y* curves, but efforts have been made to make the process of obtaining them as rational as possible. One of the goals in this regard is to anchor them properly at large deflections, that is, to have a proper limit value for *p*, as that value naturally affects the values of *p* for smaller values of deflection. Randolph & Houlsby (1984) investigated the limit resistance of laterally loaded piles in clay using limit analysis, and showed that the resistance is less at small than at large depths (which, incidentally, can be critical in laterally loaded pile analyses), for which the ratio of the unit resistance to the undrained shear strength is of the order of 10.

Pile groups and piled rafts

The recognition that the load response of a pile in a group is influenced by neighbouring piles predates *Géotechnique*. Methods to take that interaction into account in a meaningful way in the prediction of the load response were only developed later, enabled by the computer, and papers in *Géotechnique* provided important contributions. Poulos (1968) studied the problem of pile groups by using Mindlin's equation, as done before by Poulos & Davis (1968) and later by Butterfield & Banerjee (1971) to account for the effect of loading throughout the length of a given pile on every other pile in the group. Poulos (1968) made the assumptions of no soil–pile slip, no bearing resistance against the pile cap, linear elasticity and incompressible piles (restricting the results to piles in comparatively weak soils). Poulos (1968) also introduced the useful concept of the interaction factor (the ratio of the additional settlement of a pile due to loading on an adjacent pile to the settlement of the pile under its own load), later also used by Randolph & Wroth (1979), and showed plots of the interaction factor against pile spacing and length. Randolph & Wroth (1979) also investigated pile group response, basing their pile group analysis on their previous work on the load–settlement response of single piles (Randolph & Wroth, 1978). Mylonakis & Gazetas (1998) showed that pile compressibility has an effect on the values of the interaction factors.

As in the Poulos (1968) solution, most solutions for pile groups neglected the raft action of the pile cap. Caps in which the resistance of the cap itself was taken into account became known later as piled rafts, a design concept that has received increasing attention in the last two decades or so, even if the concept first appeared in the literature in the 1950s and in practice much earlier. Perhaps a reason for the greater interest in this type of solution in recent years is that proper design of this type of foundation system is analysis-intensive, which means that, with the availability of better analyses and adequate computer power, the design of piled raft systems has become economically feasible in an increased number of projects. However, before engineers converge on piled rafts as the design solution for a particular project, simplified analyses are needed to assess whether performance-related gains more than compensate for the greater design cost. Poulos (2001) examined the entire design sequence, discussed analyses of various levels of sophistication that may be used to address the piled raft problem, and pointed to a number of key references covering them. Poulos showed, using his own analyses, that: (a) there is an optimal number of piles; (b) increasing raft thickness reduces differential settlements (but increases bending moments); (c) strategic placement of piles is required for optimal differential settlement reduction; and (d) modelling of column loads using an equivalent uniform loading is acceptable for estimation of total settlement, but not for prediction of differential settlements or bending moments. As Poulos (2001), Horikoshi & Randolph (1998) and Reul & Randolph (2003) also discussed the design process for piled rafts, using case histories (including centrifuge data) as illustrations.

Offshore piling

Although the pile capacities (and therefore pile sizes) needed for offshore structures are generally much larger than for land structures, it is surprising to find that the pile capacity estimation methods used today by the offshore industry have not been published in *Géotechnique*. However, the equally important question of the drivability of these piles is a theme that was addressed by Litkouhi & Poskitt (1980). Although the one-dimensional wave equation modelling of piledriving had been developed 20 years earlier, the dynamic resistance of typical stiff North Sea clays had not received much attention. Litkouhi & Poskitt demonstrated by simple laboratory tests that the viscous damping of these soils was highly non-linear. Most users of wave equation analysis software today use linear viscous damping (dynamic resistance proportional to pile velocity), and are blissfully unaware of the actual behaviour of the soil!

The theme of pile resistance to driving and the post-driving capacity of the plug in an open-ended pipe pile was a subject of research in the late 1980s, and Randolph *et al.* (1991) provided important insights into sand plug behaviour during and after driving. An understanding of the mechanisms of load transfer between the plug and the pipe during loading was developed further by De Nicola & Randolph (1997), but the implications of that work have yet to permeate industry practice.

Rankine Lectures

Finally, we note that two Rankine Lectures have been devoted to piling, both from Australia and both concentrating on the appropriate analysis techniques. Poulos (1989) examined the range of problems and solutions involving axially loaded piles, highlighting the need for a proper match between the level of rigour of an analysis and the problem to be solved, as well as the critical importance of knowing the operative values of soil properties. Randolph (2003) examined the science underlying piling engineering. He showed how it is possible with current knowledge to use effective stress analysis to understand and predict pile resistance, and called attention to important effects not widely recognised, such as shaft resistance degradation (friction fatigue) at a set depth as a pile is driven (or jacked in cycles) further and further beyond that depth. Randolph also examined the state of pile driving analysis, and of the analysis and design of piled rafts.

CONCLUSIONS

For 60 years, *Géotechnique* has published papers addressing the problem of how to best analyse, design and construct foundations. The papers in the journal show a clear evolution from simple, even rudimentary analyses to the relatively sophisticated ones that incorporate today's understanding of how soil responds to different types of loading, of modern numerical techniques for capturing soil response, and the sometimes complex displacement, strain and stress fields appearing in the boundary-value problems of foundation engineering, and the effects of foundation construction. Many of the papers were drivers of innovation, expanding knowledge and establishing new trends in foundation design; virtually all were driven by the desire to solve the very real problems of foundations engineering.

The eighth Rankine Lecturer, R. Glossop, called attention to the fact that, throughout the nineteenth century, there was no systematic approach for foundation problems, and that there was indeed a reluctance to accept a scientific approach to foundation design. Although there continues to be a boundary between science and its application, that boundary is gradually becoming more permeable, thanks to the increasing quality and applicability of the science. *Géotechnique*, with its emphasis on proper science, and its recognition of new and improved design and technology, will continue to play a role in shaping the foundation engineering of the future.

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