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# General Report – Session 2

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Commemorate the Legacy of Ralph B. Peck
April 29 - May 4, 2013 CHICAGO
Seventh International Conference on
Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker

# GENERAL REPORT – SESSION 2

## 2. Case Histories of Unexpected Behaviour of Foundations

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## INTRODUCTION

The complete title of Session two on case histories of unexpected behavior of foundations made reference to unusual soils, diverse environments, a wide range of foundation test methods and structures ranging from historic monuments to tall buildings and towers. In attempting to provide a narrative to the myriad papers submitted which match the session themes we must consider whether unanticipated foundation behavior can ever be described as unexpected. In every project Geotechnical Engineers are charged with predicting the response of structures composed of or built on naturally heterogeneous material. The process (which is not linear) consists of many stages including site investigation, design, and construction and monitoring. If undertaken properly, uncertainties should reduce as the process advances and there should be sufficient feedback and flexibility to allow knowledge gained to influence other stages of the process. Each project therefore is a case history in which knowledge gained can help to develop the empirical knowledge of the designer. Case histories are therefore an integral part of the education and development of all Geotechnical Engineers. Our report groups the papers submitted into four sections which can be roughly aligned to stages in the design process, namely; investigation, design, installation and performance. Many papers naturally contain contributions which address multiple headings and our classification, though subjective was to assign papers in the area where we felt the major contribution lay. Of the 32 papers submitted for this session, 5 deal primarily with investigation, 10 are focused on design, 5 consider the effects of installation and unsurprisingly, given the conference theme the vast majority (12 papers) considers foundation performance.

We begin our review with papers whose primary concern is the investigation of site conditions both at the usual time, i.e. prior to construction and also after construction where problems arise in a forensic investigation of the causes for failure. One of the areas of rapid advance in Geotechnical Engineering continues to be in the area of in-situ testing using mechanical probes (e.g. Cone Penetration Tests, full flow penetrometers and Dilatometers etc) and through non-destructive methods including a range of geophysical procedures. Papers describing intensive site investigation using modern interpretive techniques are contained in the proceedings. Other papers present more traditional techniques. It is important to remember though that even routine site investigations which measure index properties of soils, can if specified, performed and interpreted properly be a very valuable source of information.

We then consider design. In an area where significant focus is given to how design should be undertaken, i.e. the move from working stress design to load and resistance factor design or full probabilistic assessments, it is sometimes overlooked that many of our capacity models, particularly those for estimating pile behavior are largely empirical and relatively unreliable. The papers in our session deal with a number of important soil-structure interaction problems, including; single pile design, piled rafts, the performance of offshore foundations subjected to significant non-vertical and dynamic loading and the effect of backfill properties on the response of embedded structures.

Understanding the installation response of geotechnical structures such as piles, walls and tunnels is key to optimising the design and reducing risks including safety and financial uncertainties. Installing displacement piles continues to cause problems in terms of structural damage, environmental issues (including detrimental effects to mammals during offshore pile installation) and unforeseen ground conditions can cause premature refusal. Papers to this conference address topics which address these challenges including improved methods of predicting displacement response during driving and the effects of ageing on pile capacity.

In the performance section we have a number of papers dealing with load testing of foundations. A number of innovative testing procedures such as the O-Cell are being used more widely to provide insights into pile response during static load tests.

Although the basic principles of geotechnical engineering are universal, a number of papers present case histories of building damage caused by local or regional problem soils. These papers are a useful reminder of the importance of local experience and the scientific compilation of case histories to help avoid mistakes in future designs.

A relatively new source of case histories relates to papers considering offshore geotechnics. The recent interest in developing offshore renewable energy resources in many parts of the world has resulted in increased interest in the design of offshore structures. Whilst a vast body of knowledge has been developed form the offshore oil and gas sectors in the last 40 years, the renewable energy industry provides a new set of challenges. In the oil and gas sector offshore installations tend to be one-off relatively large structures with high dead loads. Offshore renewable energy converters tend to be installed in arrays, have relatively low dead loads and high environmental loads and are dynamically sensitive to forcing frequencies from environmental loads.

## INVESTIGATION

Firouzianbandpey et al. (Paper No. 2.34) present seismic piezocone data from two sites in Denmark, the east harbour in Aalborg, where the soil is predominantly sand, and the harbour at Fredrikshaven, a clay site. The seismic piezocone is a very useful investigation tool which collects data on shear wave velocities (i.e. small strain stiffness data) in addition to the usual large strain data on cone end resistance, sleeve friction and pore pressures. The authors compared the measured stiffness modulii with values predicted using published correlations. Whilst they found that the correlations provided reasonable estimates of the in-situ stiffness (See Figure 1), they did note that local geological features and test details meant that it was important to develop site specific correlations. Factors which affected the test results included geological features including low sleeve friction values and the presence of agglomerates, and testing details, e.g. the energy absorption in near surface road layers and noise from nearby traffic. Whilst significant research effort has allowed the development of frameworks for our understanding of the relationship between small strain stiffness and large strain strength of soils, for example the use of normalised strength data (Eqn. 1) and the effects of ageing, See Robertson (1997), Fahey et al. (2003) and Schnaid et al. (2004). Data scatter in these relationships tends to be large and site specific correlations are invaluable for reducing uncertainty.

[1]

$$q_{c1} = \left(\frac{q_c}{p_a}\right)\sqrt{\frac{p_a}{\sigma'_v}}$$

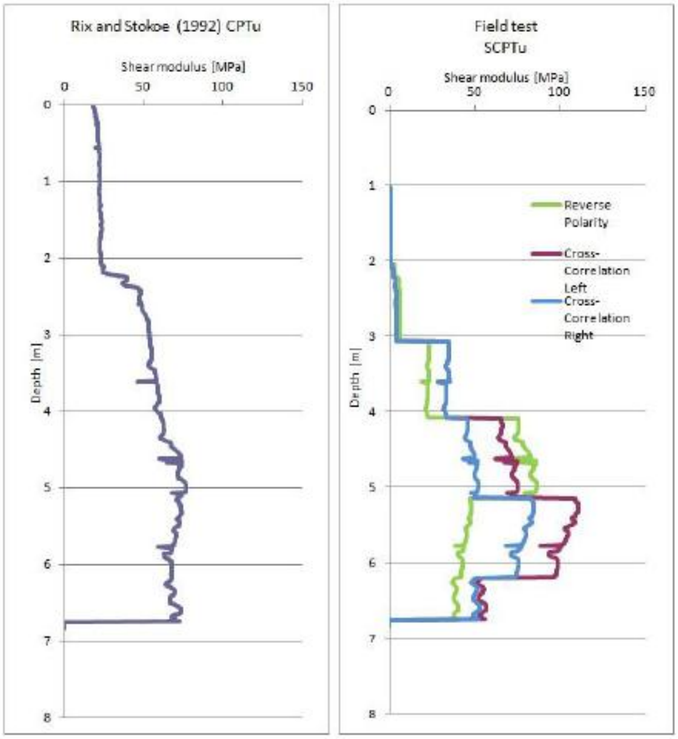
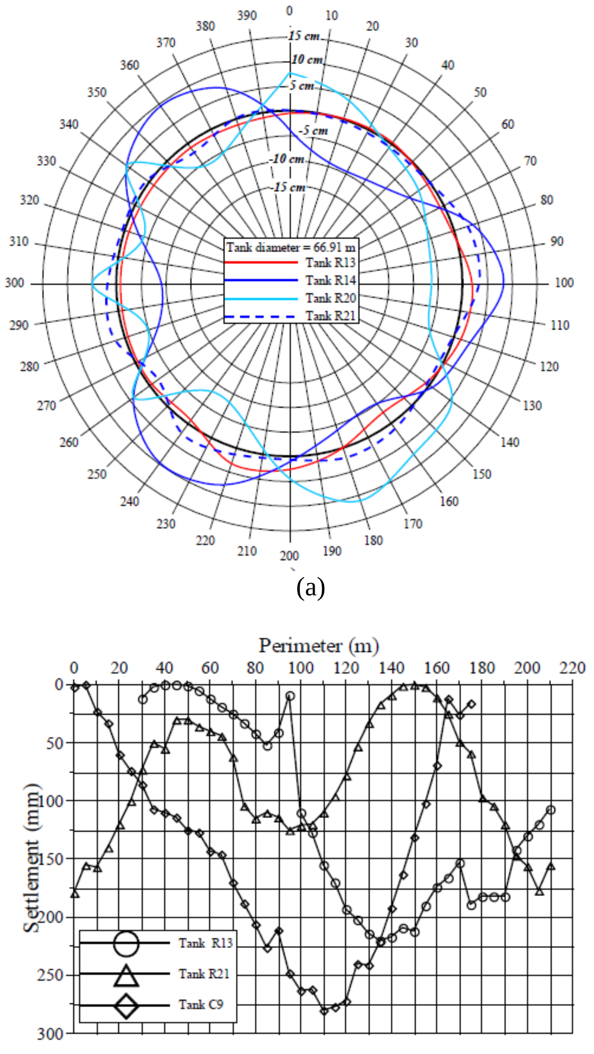


**Figure 1 Estimated and measured shear modulus in sand at Aalborg Harbour**

Kumor and Mlynarek (Paper 2.04) discuss a case history in which an inadequate site investigation for a bridge construction project resulted in poor understanding of the geotechnical and hydrogeological conditions and exposed the project investors to considerable additional costs. Diyaljee (Paper No 2.30) highlight the problems of constructing replacement infrastructure on the vicinity of an obsolete bridge and demonstrate how the challenges of soft soil and existing foundations were overcome at the investigation, design and construction stages.

Hermeda et al. (Paper No. 2.05) present a comprehensive case study of the site investigation (including geotechnical drilling and geophysical investigation), determination of the building natural frequency and subsequent seismic hazard assessment performed for the Habib Sakatani's Palace in Cairo. The analysis highlighted the potential for resonance with the natural frequency of the ground and palace being very similar.

Ramdane et al. (Paper No. 2.26) present a case study describing long-term differential settlement of oil storage tanks in Bejia, Algeria. The tanks which were founded on 3 m thick granular fill exhibited large differential settlement 25 years after construction (See Figure 2).



(a)

(b)

**Figure 2. (a) Distortion of tanks (b) Differential settlements observed along perimeter of 3 tanks**

A major investigation programme including deflection measurement, in-situ tests (including CPT and pressuremeter) and laboratory tests revealed the presence of deep, soft compressible soils. 2D and 3D finite element analyses using the Cam Clay model were found to give good agreement with measured settlement and a series of miropiles were installed as a remedial measure.

## DESIGN

Three papers in the session deal with continued development of design methods for piles. Flyn, McCabe and Egan (Paper 2.49) present the results of an instrumented pile load test on a 340-mm nominal diameter driven cast-in-situ pile (DCIS). The pile was driven to a depth of 5.75 m in an alluvial sand deposit that was investigated with five CPTs. The test pile was installed at the location of one of the CPTs. The test pile was loaded in compression until a pile head movement of 50 mm (about 15% of the nominal pile diameter) was measured, which corresponded to an axial load of about 2.5 MN applied at the pile head. Vibrating wire strain gauges installed at depths of 0.3 m, 2.5 m, 4.0 m and 5.5 m were used to measure axial compressive loads along the depth. The reported results indicated that that full skin friction was mobilized at pile movements on the order of 7-8 mm, which is in line of previously published data that indicate that small displacements are required to fully mobilize skin friction. The pile then behaved essentially as an end bearing pile. Back calculated local shaft friction along the pile depth; See Figure 3 and $N_q$-value (base resistance) are presented and compared to other values reported in the literature. Capacities estimated from empirical correlations with CPT results (LCPC and ICP-05 methods) indicated that the empirical methods underestimated the measured pile capacity. In addition to the usefulness of the results presented in the paper, it is concluded that DCIS piles behave essentially in the same manner as full-displacement precast concrete piles.

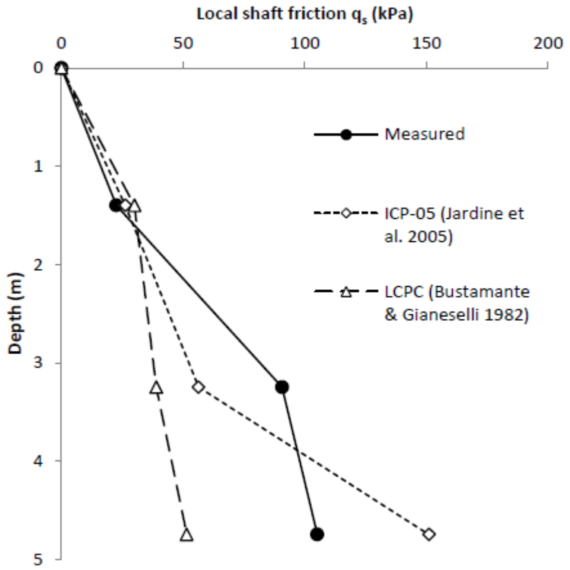


**Figure 3 Comparison of measured and predicted local shaft friction on DCIS pile in sand after Flynn et al.**

Abishid and Hajai (Paper 2.24) present a semi-empirical and finite element study of the axial load carrying behavior of drilled shafts. The study presents a discussion surrounding the percentage of load carried in side shear and through base resistance. However, the complexities (including geometry, installation effects, soil models etc) of this problem are over-simplified by the authors, limiting the application of the approach presented.

Momenzadeh et al. (Paper No. 2.58) provide a detailed description of the use of miropiles to retrofit a bridge in the San Francisco area. The paper considers the choice of the foundation system, the installation is confined headroom and the testing required for a foundation subjected to dynamic loading, where load reversals can occur.

Three papers address the complex problem of piled raft design. Momeni and Yazdani (Paper 2.40) describe a case study of the design of a raft foundation in a 30 m thick compressible calcareous soils sandy soils. The authors' approach was to analyze a corner block of 27.1m by 51.4 m block of the building block which has a footprint of almost 200 m in length, with each of the blocks being divided by seismic joints. Plate load tests and Terzaghi's formula was used to obtain a Modulus of sub-grade reaction. Using a finite element model, the authors through a trial and error obtained an appropriate Modulus of sub-grade reaction for the winklers springs based on the computed settlements in a pure raft foundation model and subsequently applied this to the combined pile raft modeling, see Figure 4. The pile stiffness was obtained from a load test on a micropile 14 m length and 0.15 m in diameter which was also compared to a FE modeling. The development of loads in the piles during the early stages of construction was considered. Using this approach the authors were able to design the raft for settlement reduction and pile capacity putting in more piles where the pile load was exceeded. Some caution on the effect of foundation shape, scale-effects etc. should be noted before application of this approach in practice.

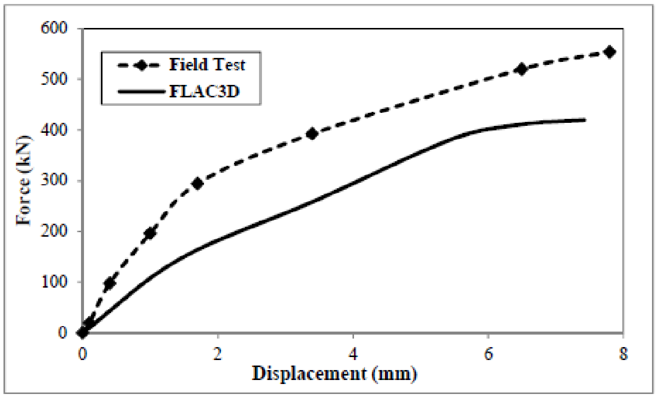


**Figure 4 Comparison of field test on raft foundation and numerical analysis (Momeni and Yazdani)**

Park et al. (Paper 2.15) present a centrifuge study of model piles and pile groups to compare the foundation response in a range of soil conditions. Tests were performed for both loose and dense sand formations Applying appropriate model scaling factors they computed the carrying capacity of the prototype piled raft and pile groups. They confirmed that the load capacity of a piled raft was greater than that of the pile groups. The level of additional carrying capacity obtained in the experiments was 13% for dense sand and 22% for loose sand.

Saeedi et al. (Paper no 2.44) consider finite element modeling of piled rafts in soft clay soil which are subjected to seismic loading using ABAQUS. The finite element results were compared to laboratory centrifuge test results and a parametric study is reported. The authors found that an increase in pile length caused a decrease in settlement for the raft under vertical and seismic loads. However, the maximum moments in the pile increased with increasing pile length. In a study of pile spacing, s the authors note that increased spacing causes less interaction and therefore reduces settlement. The trade-off is that the pie bending moments increase.

Two papers from authors at Aalborg University consider the very interesting issue of the design of offshore foundations for the renewable energy industry. Ibsen et al. (Paper 2.21) present a summary of a model testing programme undertaken into the performance of suction bucket foundations. The test results were compared to existing theories regarding the response of shallow foundations under combined loading (moment, horizontal, and vertical). The test programme considered drained tests on model scale offshore bucket foundations in saturated dense sand. The suction bucket capacity was determined to be largely dependent on the embedment ratios and load path. The three-dimensional yield criterion proposed by Villalobos et al. (2005) was modified in order to achieve best fit curves with the measured data from the physical model tests. In contrast to previous studies using the failure envelope approach, which have suggested that yield surface is constant in shape, these tests indicated that the bearing capacity of the bucket foundation is severely influenced by the skirt length and the load path when they are subjected to combined loading. This is contrary to the observations noted by Byrne (2000) where constant values of yield surface fitting parameters were noted. The results in this paper stem from the physical mechanism that longer skirt length implies further mobilization of horizontal and moment capacities due to the side friction and the lateral resistance along the skirt.

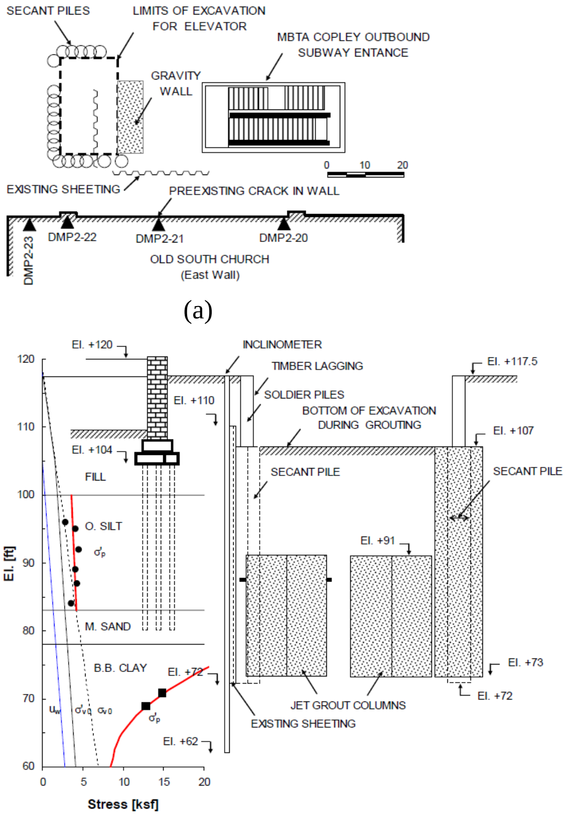
In paper 2.23 Bayat et al. investigate the dynamic response of offshore piles using a range of dynamic vibration analysis tools. The authors should be commended for exploring the application of unconventional dynamic methods to the offshore wind energy sector and in time the results will most likely lead to changes in industry practice. However, it is noted from this work that the application of these techniques is still very much at an early stage and it is likely a considerable way from being used in practice. One limitation of the analysis proposed is the default assumption that the propagating waves occur uni-directionally along the central axis of the steel tubular piles. The authors imply that the analysis will provide a better understanding of the dynamic response of offshore structures; however for in-service conditions the primary motions will include a significant out of plane component. Therefore although to avert damage to offshore foundations, it becomes necessary to identify and quantify the soil-structure interaction and the related damping effects on the system, in this paper the results are not applicable to realistic soil-structure movements. However, despite this limitation, it is recognised that this paper is a valuable starting point for investigating this problem by means of boundary integral equations. Somigliana's identity, Betti's reciprocal theorem and Green's function are employed to derive the dynamic stiffness of pile, assuming that the soil is a linear viscoelastic medium. The dynamic stiffness is compared for solid and hollow cylinders by considering different values of material properties including the material damping. Modes of resonance and anti-resonance are identified and presented. It is observed that the absolute value of normalized dynamic stiffness is independent of Young's modulus and Poisson's ratio, whereas it is dependent on the soil's damping. These results are very useful and it is hoped that this work will be developed further.

Anderson and Morechi (Paper 2.18) investigate soil-structure interaction effects for nuclear power stations founded on bedrock. One structure had a large footprint and shallow embedment the second had a small footprint with large embedment. The effect of using a site specific shear wave velocity profile and a generic profile for hard rock in the SSI analysis was found to be negligible. The authors suggest that for the sites considered, that the assumption of using fixed-base or hard rock conditions was validated and that rocking and soil induced translation effects could be ignored.

## INSTALLATION

Pinto et al. (Paper 2.53) used a 3D finite element analyses to consider the complex soil-structure interaction problem associated with the construction of an elevator shaft for a subway in Boston adjacent to historic buildings (See Figure 5). The analyses which used advanced non-linear soil-models and accounted for existing structural defects proved that significant deformations experienced during the works were caused by quality assurance issues during installation of the jet-grouted piles.

Chong (Paper 2.59) presents a very useful set of analyses regarding soil displacements in the immediate vicinity of displacement piles. The effects of displacement piling are well documented with many cases of movements caused to adjacent structures and detrimental effects on recently installed piles. The author's experience with dealing with ground displacements of raft piling in deep marine clays in Singapore led to the development of a method for calculating the ground movements to assess the cumulative effects of pile driving.



(a)

(b)

**Figure 5 Plan (a) and Elevation (b) of Copley station works (after Pinto et al.).**

The method is derived from soil mechanics parameters, principle of potential energy, strain energy and work done by the stresses in the soil undergoing a cylindrical cavity expansion process and the stresses in the soil undergoing large

strains direct shearing process due to the pile shaft friction. Published case histories of ground displacements have been back-analysed. The calculated movements compared well with these past field tests and laboratory experimental data. In the moderate to far field distances from the pile, the heave to lateral displacements can be expressed as a function of the ratio of lateral forces to soil weight. For near field distances, the calculations show that the heave reaches a maximum, and then turns sharply into a downdrag near to the pile shaft. The method is, however, unstable at distances close to the pile shaft due to numerical errors. The proposed methodology has a sound basis in the controlling mechanisms and is based in a firm understanding of the soil behavior to the applied stress paths. Furthermore, the proposed methodology is also validated by a series of independent measurements from previous studies and also new experimental field data. The resulting methodology can therefore be considered a practical tool for use by industry practicing engineers.
Lutenegger (Paper 2.03) provides an interesting historical account of the development and initial applications of wrought iron screw piles in the mid 19th century. This type of pile was invented by Irish engineer Alexander Mitchell and saw its first application as foundation for the Maplin Sands lighthouse near the mouth of the Thames estuary in England. Subsequent applications included foundations for both pleasure and commercial piers in England and around the world. One of the most important applications in the United States was for the pier at Lewes, DE, built in 1871. Screw piles fell into disuse toward the end of the 19th century as piling technology progressed, and the steam powered pile hammer was introduced. However, screw piles saw a resurgence in the 1980s as installation equipment with large hydraulic torques was developed. Screw piles are commonly used in transmission line applications both as foundations and as anchors for guy wire support.

Reuter (Paper 2.32) considers four different CPT based design relationships which were used (LCPC, Eslami and Fellenius, KTRI and Togliani) in determining the ultimate geotechnical resistances of piles driven to support a bridge structure. These relationships provided ultimate geotechnical resistances for piles embedded to 40.2 m varying from a low of 2539 kN to a high of 9688 kN with the average of 7397 kN for all but the lowest result which was provided by the LCPC method of design. One of the notable aspects of the evaluation was the insitu testing of the production piles which showed a remarkable increase in shaft resistance in a very short time due to pile set-up when subjected to high strain dynamic testing using the Pile Driving Analyzer and the Minnesota Department of Transportation Nominal/Ultimate Resistance Pile Driving Formula. The first indication of pile set-up was observed during the time delay during the first and second splicing of the three pile section of each of the four test piles, with one test pile installed at each of the four pier locations (See Figure 6 which compares the pile resistance to the CPT based predictions).

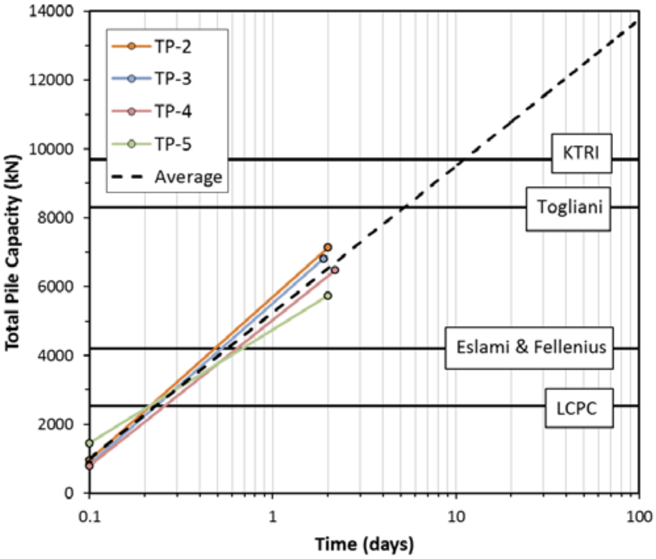


**Figure 6 Comparison of measured pile resistance and CPT based predictions (after Reuter)**

Analysis of the results of the PDA tests and pile driving formula provided almost similar ultimate geotechnical resistances determined at the end of initial driving (EOID). However, these values increased considerably on restrike 1.9 to 2.2 days after EOID for the PDA test but 50 % or less than those predicted resulting from pile driving formula. However, these higher ultimate geotechnical resistances from the pile driving formula were not considered to be reliable as a result of non uniformity of applied energy and hammer stroke. The PDA predicted resistances were not as high as anticipated due to the set being less than that generally required to engage the full ultimate geotechnical resistances of the piles. This was attributed to the average set attained being smaller than 2.5 mm/blow generally required to mobilize the full ultimate geotechnical resistance.

The significant increases in the ultimate geotechnical resistances due to pile set-up on restrike after only 2 days were therefore considered to provide lower bound ultimate geotechnical resistances, which were expected to be much larger if waiting periods before restrike were increased. Overall this study illustrates the necessity of understanding both the subsurface conditions which were provided by the cone penetrometer tests along with local site experience. However, there were large variations in the predictive ultimate geotechnical resistances using the cone penetrometer relationships depending on the method of analysis used, with the LCPC method providing a value closest to the EOID. The paper aptly illustrates the significant influence of pile set-up on ultimate geotechnical resistance.

Man and Halpern (Paper 2.42) present a case history related to driven pile installation difficulties for bridge abutments in Los Angeles County, CA. The subsurface investigation that provided data for pile design consisted of two hollow stem auger boreholes extended to a depth of 25 feet. The boreholes were terminated at 25 feet because coarse gravel and cobbles impeded further drilling. No standard penetration test sampling was reported. The geotechnical report warned about driving piles would be difficult because of the presence of cobbles and boulders. Interestingly, the abutment foundations were designed as 14-inch diameter, 35-foot long, closed-end, driven pipe piles. It became evident early on that such piles could not be driven to the design depth, even after using pre-drilling. The design was eventually modified and consisted of drilling a 20-inch diameter hole to 35 feet, dropping the pipe in the hole, and pressure grouting the annulus between the pipe and the wall of the hole. Pile load carrying confirmation was provided by performing additional axial and lateral load analyses.

Zimmerman et al. (Paper 2.56) describe an interesting case history of a new garage construction on the south shore of lake Michigan using H steel piles foundations which is adjacent to an existing 80 year old reinforced concrete underground water reservoir. The soil conditions were understood based on previous projects on and around the site. Below the top 9 feet of fill was some 21 feet of fine sand which was the bearing layer for the existing water reservoir. Load test and dynamic testing on one of four test piles which was driven some 62 to 72 m into the clay hard pan layer confirmed the load capacity of the pile for the proposed garage structure. The water reservoir structure which was monitored with strain gauges and settlement measurement throughout the pile driving showed heaving instead of expected settlement and leaks occurred in pre-existing cracks. Subsequent changes were made to the pile driving sequence to correct and minimize the damage. The authors draw a number of lessons one which was that they should have relied on and interpreted data coming from the instruments which was contrary to their expectations. The other was discontinuity in the effects created by the unreinforced construction joint. The authors suggested that the density of the fine sand properties could have changed by being densified over time by the dynamic loads of water in the reservoir and also earthquakes in the past. The paper clearly highlighted a need for quantifying the state of the cohesionless soils.

Perko et al. (Paper 2.50) discuss the benefits of using rotary driven piles to support a 14 storey building in an urban environment. The authors demonstrated the successful use of a simple relationship between torque and installation resistance. Torque readings taken over time confirmed that set-up occurred. The piles were fitted with a geothermal conduitllop to allow their use as energy piles.

## PERFORMANCE

The papers in this sub-section are divided into 3 categories covering case histories describing the performance of deep foundations, shallow foundations and problems caused by local geological conditions.

### Pile Foundations

Diyaljee (Paper 2.01) describes an investigation of the load-carrying capacity of 57-year old cast-in-place concrete piles to determine their suitability for re-use. The investigation included reviewing original construction drawings dating back to 1952, as well as exposing the piles for concrete coring and compression load testing. The piles were relatively short (less them 7-m long) and originally driven to virtual refusal into a hard clay till. Driving criterion consisted of 8 blows/25 mm for a final driving distance of 75 mm using a No. 1 Vulcan Hammer. The piles were originally designed for a maximum compressive load of 45 tons. The maximum compressive loads under the new structure would be in the range of 55 to 60 tons. Cores obtained from the piles disclosed good quality concrete with compressive strengths ranging from 46 to 62 MPa, which exceeded the originally specified strength of 17 MPa. A series of confirmatory static compression load tests were performed on selected piles with maximum test loads reaching values of 210 tons. The pile settlements under the maximum test loads were as much as 1.1 inches with expected settlements of less than 0.5 inches under the new proposed maximum structural loads of 55 to 60 tons. This case history illustrates a viable approach to assessing existing foundations, which is a topic of interest to superstructure revitalization due to the cost savings associated with foundation re-use.

Sinreich and Simpson (Paper No. 2.16) present results of load tests on drilled shafts (bored piles) to ascertain the benefits of base grouting to improve shaft response to load. Case histories from five sites in the United States are presented where six pairs of adjacent grouted and ungrouted shafts were statically load tested. All tests were performed using the Osterberg cell (O-cell) test method (See Figure 7).

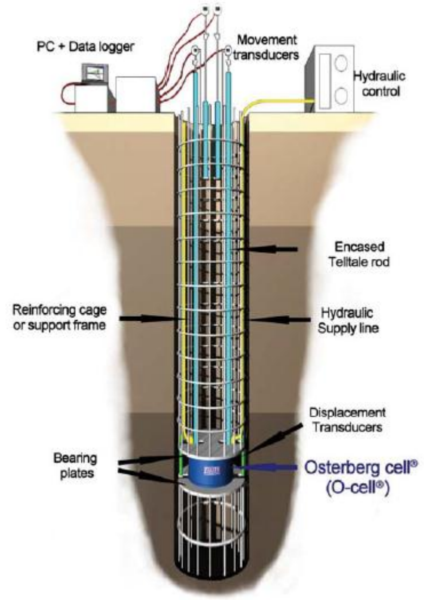


**Figure 7 Schematic representation of o-cell test (paper No. 2.16)**

Drilled shafts ranged in diameter from 0.6 m to 3.0 m and were installed to depths ranging from about 9 m to 37 m. The diameter and depth of the grouted and ungrouted test shafts were the same at four sites, but at one site the ungrouted shaft had a diameter of 1.5 m while the grouted shaft had a diameter of 3.7 m. Unfortunately the paper does not present detailed information regarding the subsurface conditions at the five test sites, but it describes the subsurface conditions as consisting primarily of sands at two sites, sands and silty clay at one site, loose silt and soft clay underlain by medium to very stiff clay with trace gravel at one site, and shale at one site. The comparisons between load test results for grouted and ungrouted shafts were inconclusive. In four cases, base grouting improved the initial bearing stiffness of the shaft, but it had little effect on the ultimate capacity when compared to the ultimate capacity of the tested ungrouted shaft. In one case the ultimate capacity of the grouted shaft was significantly higher than the ultimate capacity of the ungrouted shaft, and in one case the ultimate capacity of the grouted shaft was less than the ultimate capacity of the ungrouted shaft. The authors could not establish any obvious correlation between the effects of base grouting and soil materials, construction technique or grouting procedure. They suggested that further research is needed to clarify the mechanics of post-construction base grouting and its impact on shaft capacity. This can be accomplished through systematic load testing of drilled shafts; both grouted and ungrouted, in order to assess technique, methods and quality control in various materials.

As a result of the variability and complexity in the surficial and bedrock geology determined from the geotechnical site investigation of the area proposed for the construction of the New Victoria Hospital in Glasgow, Scotland Boyd and Ozroy (Paper No. 2,08) describe the design of rock socket piles as the presence of coal seams meant that reliance on end bearing might result in large settlements. Standard design correlations link that the shaft resistance to RQD and unconfined compressive strength (UCS) of the surrounding rock led to highly variable predictions for pile resistance from a low of 129 psi (0.89 MPa) to a high of 292 psi (2.01MPa). This disparity in results prompted axial compressive pile load tests to be done to evaluate the actual shaft resistance since higher values would be beneficial to the overall project costs. Two tests were undertaken one to measure the shaft resistance only by inserting a soft toe (compressible medium) at the toe the pile and the other without the soft toe (See Figure 8). In comparing the results of these two tests it was determined that the pile without the soft toe showed a stiffer load deformation relationship by attaining a higher peak load and smaller deformation than the pile with the soft toe. As the rock socket was relatively short (with a socket length to pile diameter of 4) this finding contradicted somewhat the observation by Tomlinson based on test results from Osterberg and Gill's work which showed that for pile to develop both shaft and toe bearing resistances the ratio of the socket length to pile diameter should be less than four (4).

**Figure 8 Soft pile toe used to eliminate base resistance in load tests on rock socket piles (See Paper 2.08)**

For QA/QC purposes two additional piles were tested in axial compression up to 1.5 times their working load. The end result of the QA/QC pile load tests showed that both of the piles satisfied the structural performance criteria set out in the specifications requirements and no change in design philosophy was required. In addition to the axial compressive load tests two lateral load tests were conducted to evaluate whether the overall construction time could be reduced if the erection of the structural frame could take place without waiting on the casting of the ground slabs. These tests, done on different sized piles, showed that the deformations were satisfactory and hence resulted in significant savings in terms of construction time and project budget.

Three papers deal with pile groups and piled rafts. Minh Hai and Fellenius (Paper No. 2.12) present a very comprehensive case study of the performance of a piled raft foundation at the CAI MEP container port in Vietnam. Geotechnical conditions in the region can be challenging and the site in question comprised of reclaimed land overlying 30 to 40m of soft compressible clay over dense sand. Whilst a standard solution to provide axial resistance in this geology is the use of pre-stressed concrete piles end bearing in the dense sand deposit, the project scale made this solution uneconomical. An alternative system of driven pre-cast concrete piles mobilising shaft friction in conjunction with a surcharge and wick drain system to accelerate settlements was adopted. The construction sequence and ground response is shown in Figure 9.

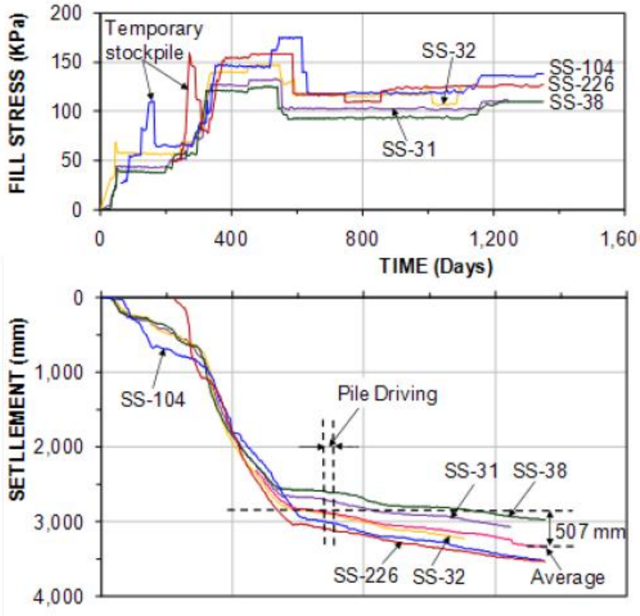


**Figure 9 Ground reaction to application of surcharge and pile driving at the CAI MEP container facility, Vietnam (paper No. 2.12)**

An unforeseen problem arose in that the wick drains did not function properly at depths in excess of 20 m below ground level. As a result significant settlement continued after removal of the surcharge load and downdrag on the piles caused them to settle in unison with the soil. A remediation strategy was implemented which involved extending the piles beneath the clay layer which reduced the ground settlements.

Ho and Pena-Iguaram (Paper No. 2.47) describe the use of rock-socket micropiles for underpinning adjacent to deep excavation in New York. The working conditions with low headroom provided a constraint to the designers. A static load test was carried out on an instrumented pile to confirm the factor of safety was adequate.

George et al. (Paper No. 2.43) describe a interesting case study of the geotechnical foundation failure of a pile supported raft in the deltaic plains of the Niger river. An interesting review of the failure mechanisms is described and post-analysis is conducted to identify the most likely cause of the collapse.

A well was to be drilled in search of oil and gas in allocation within these plains. As often done, a reinforced concrete slab was constructed for the drilling platform to support the drilling rig and the ancillary tools. The drilling operation commenced with the installation of a conductor casing 750mm diameter and 105m long. The drilling proceeded without any adverse event until a depth of 1000m was attained. At this depth the drilling bit got stuck in the hole and all attempts to retrieve the bit and the drilling string failed. The frantic lifting attempts inadvertently made the cellar slab to provide the reaction system for the applied uplift loads. A severe damage was caused to the cellar slab. Further attempts eventually caused the collapse of the drilling platform. This paper presented the records and events that led to the collapse of the drilling platform, the findings of the post-failure investigation and the proffered solution for the reconstruction of the platform.

## Shallow Foundations

Akili (Paper No. 2.11) describes the design and performance of shallow foundations supported on rock in Qatar. In the absence of a design framework to describe the response of a the variable diagenetic limestone encountered in the region, the author suggest that plate load tests provide a reliable means of foundation design.

Milovic and Djogo (Paper 2.65) present the laboratory and field test together with a numerical analysis to investigate the reasons for large settlements encountered under three 12 storey buildings constructed near Belgrade. The authors found that the Loess deposits on which the buildings are founded were very sensitive to disturbance particularly due to wetting and suggest that deep foundations would be more appropriate in these soil conditions.

## Regional Geology

Salcedo and Orozco (Paper 2.10) illustrate the effects of poor site investigation in the piedmont area of Bogotá for which flawed, and insufficient, information about the foundation soils resulted in a pile foundation solution which was too short. As a result large differential settlement occurred and expensive remdial measures including underpinning with micropiles was required.

Jain and Kumar (Paper No. 2.31) propose a new solution to problems which have resulted from construction on expansive black cotton soils in India. Severe problems have occurred due to swelling and shrinkage of the soil caused by seasonal moisture variation. The failure cases include roads, boundary walls, railway embankments, houses etc. Lack of knowledge about the nature of soil and poor engineering practice are the main reasons for such failures and loss. An integrated approach (using either remove and replace or the use of lime piles) to repair of a sunken floor is suggested in the paper. The approach is fast, less cumbersome, cheaper and caused minimum disturbance for the residents of the house.

Farid and Hamid (Paper 2.06) describe a somewhat limited feasibility study of the use of the soil replacement method to address problems caused by expansive soil formations in Egypt.

## DISCUSSION

A range of case histories on aspects related to the investigation, design, installation and performance of shallow and deep foundations have been presented. Case histories are a vital element of the development of individual geotechnical engineers and indeed of the profession. A number of important issues arise for discussion:

1. In many case histories presented to this conference and elsewhere, poor details of the geotechnical conditions at the site in question are provided.
2. What site investigation methods should we use in the future and should part of the budget be spent on instrumentation to provide confirmation of soil models and of design assumptions.
3. A number of papers to this session report time related effects on foundation capacity. Some of these effects are related to consolidation effects which can be easily incorporated into analysis. Others include ageing which are still poorly understood. Should performance testing be addressing this issue?
4. Many design codes are based on relatively unreliable, semi-empirical methodologies. Do we understand sufficiently the limitations of these approaches and test their validity in practice?

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