PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON PILING AND DEEP FOUNDATIONS
LONDON / 15-18 MAY 1989

Piling and Deep Foundations

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Ove Arup & Partners, London

OFFPRINT

A.A.BALKEMA / ROTTERDAM / BROOKFIELD / 1989

On the effects of sand grading on driven pile performance

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Precast prestressed concrete piles designed to be end-bearing in a sand stratum at Drax Power Station met with extremely variable resistance during driving. Some piles came to virtual refusal almost immediately on entering the sand whereas others were driven to considerable penetration with very low resistance. Redriving and load tests on piles experiencing low resistance on initial drive showed that take up in strength occurred over a relatively short period of time. Investigations involving the use of pneumatic piezometers revealed the development of significant excess pore pressures during driving. Samples from boreholes showed that piles met the least resistance when the sand had a high silt content. Comparison with the original site investigation data demonstrated the difficulties in predicting detailed pile behaviour. The varied behaviour could not be related to the original borehole logs or to SPT or static cone penetrometer results. The factors controlling pile driving behaviour were essentially geological and could only be explained with reference to local soil grading.

INTRODUCTION

The construction of the second phase of Drax Power Station in North Yorkshire required the driving of approximately 20,000 pre-stressed concrete piles. Details of design, production and contractural aspects have been discussed by Woolley & Gains (1984).

This paper describes the driving characteristics and post-driving increase in bearing capacity of some piles and presents evidence that this behaviour could be attributed to the development and subsequent dissipation of excess pore-water pressures in silty sand. Local lithologies were found to influence markedly the driving resistance and ultimate performance of piles.

GEOLOGY AND GROUND CONDITIONS

The village of Drax is situated in the Vale of York approximately 25km south of York and 40km east of Leeds, the terrain being generally low-lying and flat. The River Ouse which runs nearby provides water for the power station and coal is transported directly to the site by rail link from the newly developed Selby coal-field approximately 15km northwest of Drax. Geologically, Drax is situated at the centre of the 40km wide outcrop of Triassic rocks which dip gently towards the east. A location plan is given as Figure 1.

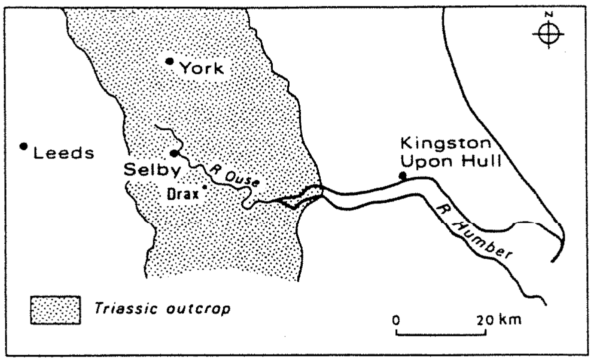

Figure 1. Location map

A simplified borehole log indicating typical conditions encountered across the site is presented in Figure 2. Bedrock comprises a weak, poorly cemented, fine sandstone with typical unconfined compressive strength of between 2 and 5 MPa. The eroded surface of the sandstone dips gently away to the north-east of the site.

The overlying Quaternary sediments were deposited as part of the '25-Foot Drift'

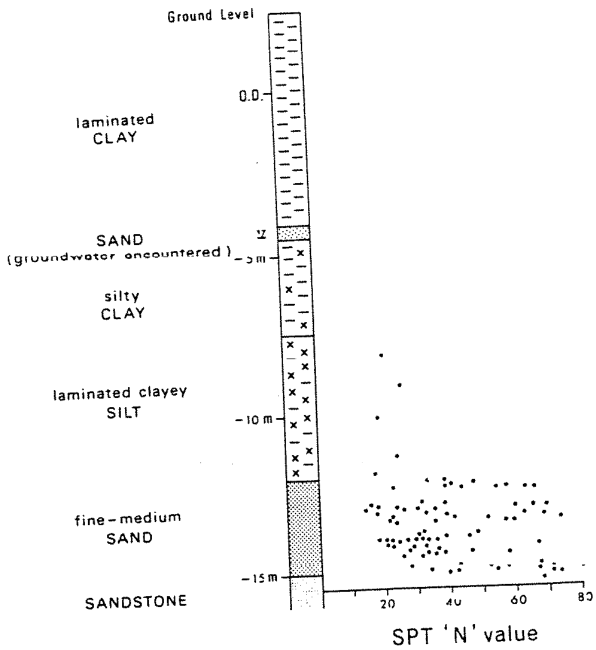

Figure 2 Simplified borehole log

of Devensian age which underlies much of the Vale of York (Penny, 1974). The detailed stratigraphy of the area was described in an unpublished report to the Central Electricity Generating Board by Dr. Gaunt of the Institute of Geological Science (now British Geological Survey).

The transported "Lower Sand", immediately overlying the sandstone is a dense, fine-grained sand with a variable silt and clay content and may well represent an outwash fan deposited from braided streams feeding from the snout of a glacier. Silt and clay lenses within the sand probably represent the infillings of local depressions on the outwash plain.

Standard Penetration Test 'N' values for the sand are given in Figure 2, typical values being greater than 30.

The overlying silts and clays are in a firm to stiff condition and are probably pro-glacial in origin having been deposited in 'Lake Humber' which was blocked off by ice to the north at Eskrick and across the Humber gap to the southeast (Gaunt et al., 1971). The Lower Sand grades into the overlying finer deposits. The clays at the top of the sequence are varved, individual sheets in samples resembling the pages of a book on partings of silt, fine sand and commonly coal dust. Sub-artesian groundwater is first encountered in a thin sand layer met consistently across the site at about -4.5mOD.

FOUNDATIONS AND PILE DESIGN

Site investigations, carried out in 1964 and 1968 for the first half of Drax Power Station (completed in 1974), into the characteristics of the strata described above indicated the need for deep foundations, and, in particular, end bearing piles founded in the Lower Sand.

Experience on the first half of Drax Power Station proved the technical adequacy and cost-effectiveness of partially prebored, driven pre-tensioned piles manufactured on-site. This system, was therefore, adopted for the Drax Completion Project.

The vast majority of the piles were designed to support their structural loads together with any negative shaft friction by end bearing in the sand. (The allowance for negative shaft friction reflected both constructional surcharge and pile-generated consolidation of the silts and clays). The piles carrying the turbine blocks, with their dynamic loads, were designed to be end bearing in bedrock with construction procedure amended to include full length pre-boring under bentonite.

Piles of trapezoidal cross-sectional areas of 0.17 m^2 and 0.13 m^2 designed to carry upto 1300 and 1100 kN respectively were cast on piling beds about 200 m long with individual pile lengths separated by end plates. Prestressing was carried out for the complete length of each bed. Lengths of piles for casting were selected for each area on the basis of both boreholes and pile tests carried out before the main piling front advanced into the relevant part of the site. These lengths were chosen to allow driving to an SPT 'N' value of 60 within the sand, in accordance with bearing capacity calculations.

Apart from the turbine blocks, the piles were pitched in pre-augered holes taken to a depth of about 8 metres. To reduce vibrations (see Mallard and Bastow, 1980), the first piles were driven with a 6 tonne drop hammer. The vast majority of piles, however, were driven by Hera 3500 kg diesel hammers to a predetermined set calculated from the Delmag formula, as discussed by Woolley & Gains (1984).

PILE DRIVING AND TESTING CHARACTERISTICS

Details of the driving record for the first test pile installed are shown in Figure 3 together with the log and SPT 'N' values from a nearby borehole. The number of hammer blows to drive the pile 25 mm are plotted and the ultimate load during driving as calculated from the Delmag formula indicated.

The low driving resistance through the silts and clays (less than 2 blows per 25 mm penetration) was typical of all subsequent piles. On reaching the Lower Sand the resistance increased, with the pile coming to virtual refusal close to the sand/bedrock interface. Unlike a second test pile, which reached a comparable toe level, for Test Pile 1 the increased driving resistance within the Lower Sand did not correlate with measured SPT values. The ultimate bearing load at the end of driving TP1, calculated from the Delmag formula, was 3.3 MN. Using the SPT values at the same depth, ultimate loads of 1.59 MN and 1.27 MN are calculated using the equations given by Berezantsev et al. (1961) and Meyerhof (1976) respectively for no side friction. Both piles performed well under tests to 250 % working load (2.75 Mn), the settlement characteristics being well within the requirements for the contact.

On the basis of the two test piles and five boreholes which showed apparently uniform conditions, lengths for casting

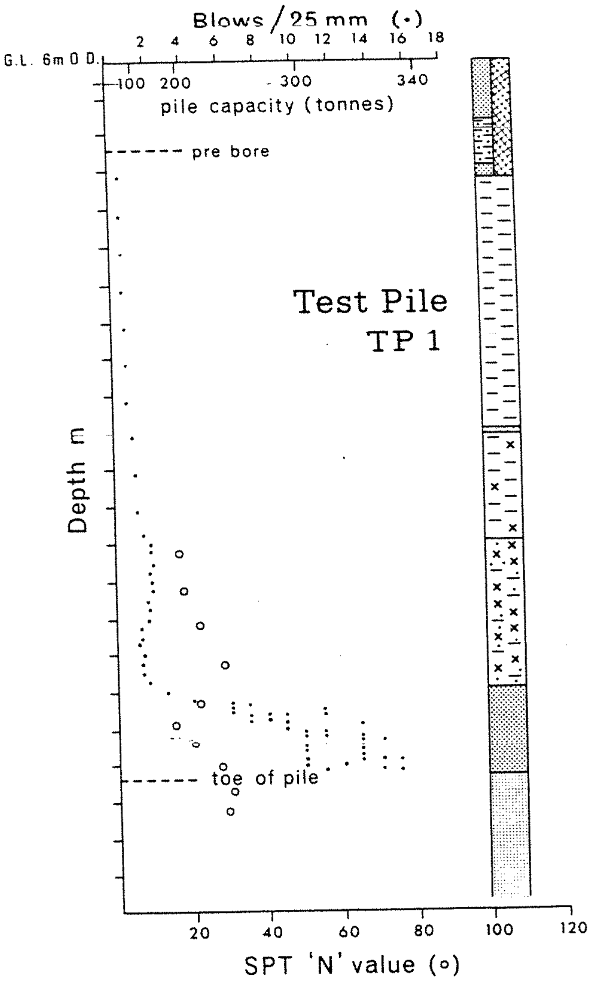

Figure 3 Details of test pile TP1

the first working piles were selected.

The driving performance of working piles in this same area was found to be variable. Whereas the majority of piles reached similar toe depths to the two test piles, some piles came to early refusal on entering the Lower Sand whilst others were driven to pile carpet level, apparently penetrating some considerable distance into the sand without achieving the required set. On occasions piles only one or two metres apart differed in toe level by more than two metres.

The heads of piles driven to carpet level without reaching the required set were excavated and redriven, usually a day or so after initial driving. Almost invariably it was found that piles had gained resistance in the intervening period. Often piles that had been advancing 25 mm for only two hammer blows when the pile head reached carpet level refused any attempts at redriving after excavation around the pile head. Several pile heads were smashed in vain attempts to redrive piles.

Under proof load testing (150 % working load) it was found, in general, that piles penetrating furthest into the Lower Sand performed best. Piles coming to early refusal on reaching the Lower Sand, although perfectly acceptable, gave the highest residual displacement (see Figure 4). Piles driven more than one metre into the sand, whatever the resistance during driving, seldom showed residual displacements greater than 50 % of the acceptance criteria.

The practical difficulties arising from this behaviour concerned both the problem of cutting through a swathe of piles in order to excavate the heads of piles that had not reached the required set on first

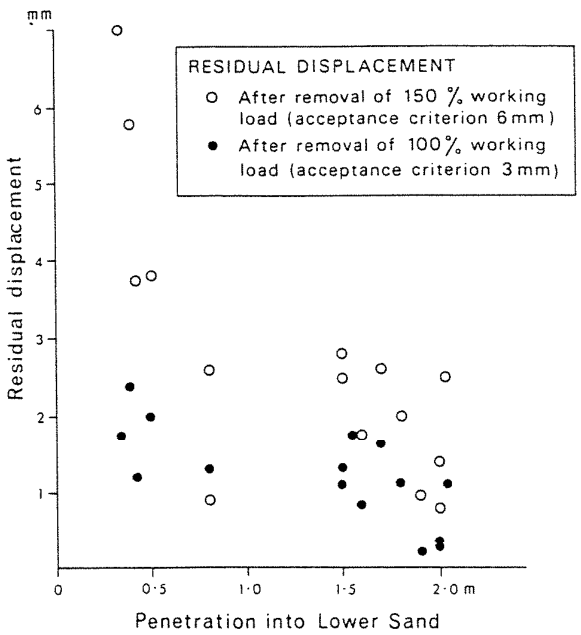

Figure 4 Residual settlements for piles penetrating different distances into the Lower Sand

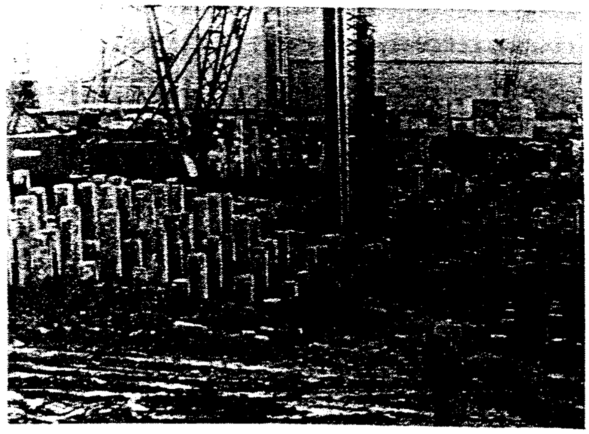

Figure 5 View of pile heads indicating variable toe depths

drive and the frustration of finding that such piles generally could not be redriven anyway. This led to the practical expedient of casting piles longer than was strictly thought necessary so as to avoid an excessive number of redrives by allowing deeper penetration on initial drive. Although considerable waste concrete had to be trimmed from many piles, this was the most efficient method of working. A view of the site showing the variable penetration of piles is given in Figure 5.

It was found that areas of deep penetration could not be predicted from SPT results. Contours of the SPT '60' value bore little relation to the toe levels reached by the piles. Figure 6 shows the toe levels reached by a line of piles for the boiler house foundation together with the ground conditions encountered in boreholes and soundings. It can be seen that none of the reported borehole lithologies (silt/sand), the SPT results or the static cone penetrometer soundings could have been used to predict the toe depths of these piles.

DISCUSSION

Poor correlation between pile capacity as calculated from driving formulae and capacity as revealed by static loading has been reported and discussed by many authors (see, for example, Ramey &

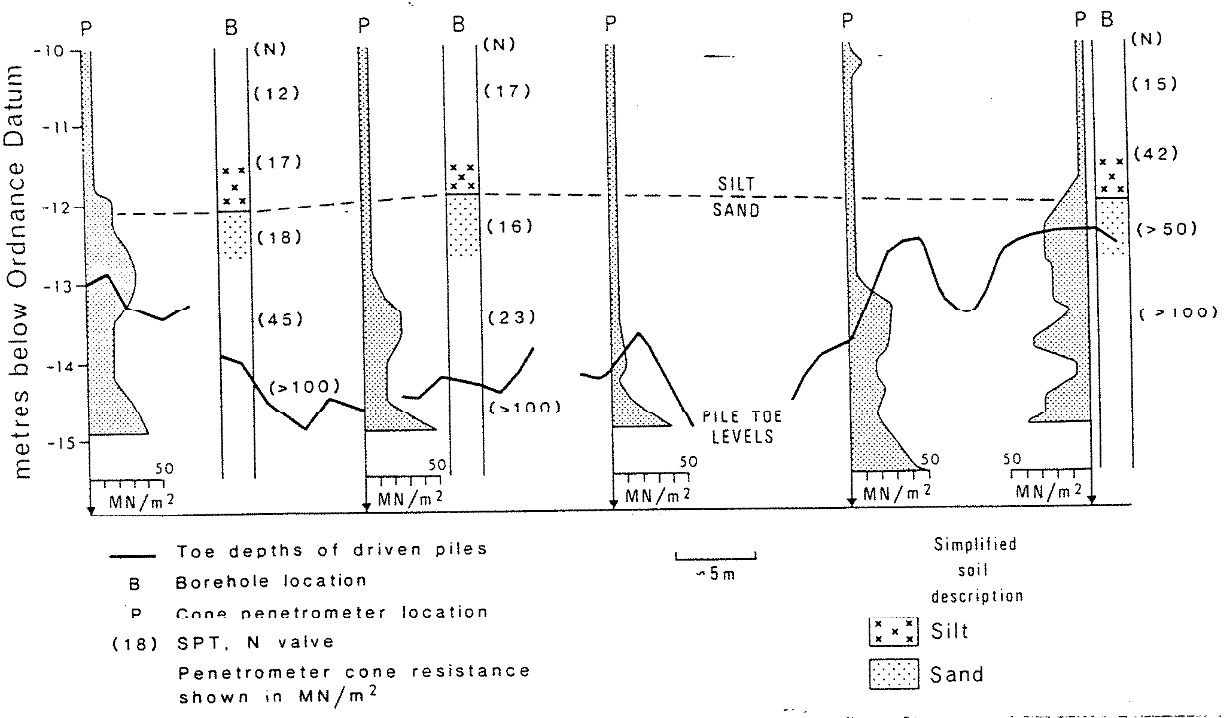

Figure 6 Toe depths for one line of piles together with relevant ground investigation data

Johnson, 1979; Whitaker, 1970). Some authors have attributed such poor correlation to inaccuracies in estimating the energy of the pile-driving system (Tavernas & Audy, 1972; Thompson & Thompson, 1985).

Undoubtedly one cause of the poor predictive abilities of driving formulae stems from the time-dependant behaviour of saturated soils. The behaviour of soil under dynamic conditions during pile-driving can be very different to that under static loading as a result of the development of excess pore-water or suction pressures which subsequently dissipate. Several authors have measured very high pore-pressures during pile driving (for example, Appendino et al., 1979; Siu & Kwan, 1982).

'Take-up' in resistance following the dissipation of excess pore pressures has been well documented for piles driven through clay (Lo & Stermac, 1965; Bjerrum & Johannessen, 1960). However, in higher permeability soils, such as most sands and gravels, water is thought to escape during driving and changes in capacity subsequent to driving are not generally expected.

In intermediate materials, such as silty sands and fine sands, there have been several reports of a reduction in bearing capacity after driving (for example, Yang, 1956; Moller & Bergdahl, 1981; Terzaghi & Peck, 1967). Such behaviour is generally attributed to the generation of negative pore-water pressure on dilation of the soil leading to a temporary increase in capacity which is lost after driving ceases. Moller & Bergdahl (1981) report that between 4 and 10 % of all piling contracts carried out in Sweden experience such 'false sets'.

As far as the authors are aware, take-up for piles end-bearing in sandy soils as observed at Drax and discussed in detail below, has not previously been attributed to post-driving dissipation of pore pressures. Lacy (1981) presents a case history of piles driven through clays to sand and noted that some piles penetrated considerably further (20 m) than others without achieving the expected set. After careful study he attributed this behaviour to the generation and subsequent dissipation of pore pressure within the overlying clays but it seems reasonable to conclude that high excess pressures measured within the sand would also have affected driving performance and contributed to subsequent take-up.

INVESTIGATION

Although all the working piles driven at Drax and subsequently load tested were found to meet the requirements of the specification, in order to understand the variable driving behaviour and in an attempt to allow better prediction of required pile lengths, a detailed investigation was carried out. This included controlled driving and load testing of piles, instrumentation and soil sampling.

Piles reaching refusal on first entering the Lower Sand were redriven after a period of time. They showed no reduction in capacity as might be observed if these piles were exhibiting 'false sets', as discussed in the previous section.

To address the possibility that take-up of the deeper penetrating piles was due to dissipation of excess pore pressure in the overlying clays and silts (which would still not explain the easy driving through the sand), a pile was driven to a level just above the Lower Sand and left for several hours before redriving. There was no significant increase in driving resistance on redrive.

The results of these simple tests suggested that the variable driving performance might be attributable to local variations in the Lower Sand stratum with excess water pressure being generated in pockets within the 'sand' allowing easy driving. After driving, the pressures would dissipate resulting in an increase in resistance, as proposed for clays by Lo

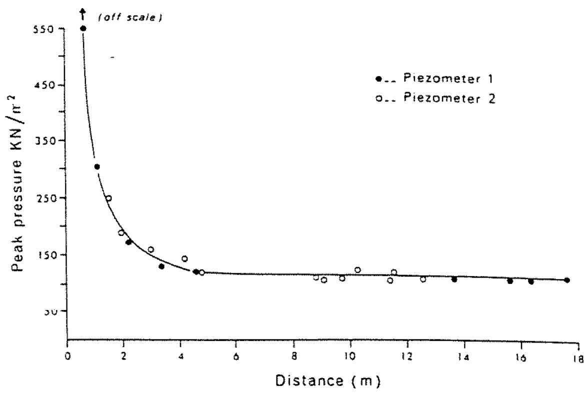

Figure 7 Peak pore pressures measured in Lower Sand during pile driving

& Stermac (1965), producing an opposite time-dependant effect to that sometimes reported for fine and silty sands.

To establish whether significant water pressures were being generated and sustained in the Lower Sand, two pneumatic piezometers were installed approximately 1 m into the sand and used to monitor pore pressures as piles were driven.

Figure 7 shows the peak water pressures resulting from the driving of piles at various distances from the piezometers. Using pneumatic instruments, it was possible to take several readings each minute during the driving. The highest recorded pressures were observed as the piles were driven through the sand and were sustained as the pile achieved the required set. After driving, pore pressure reduced gradually with readings 35 kPa above pre-driving conditions still being recorded 20 minutes after driving the closest piles. The peak readings during the driving of the closest piles were off-scale but pressures probably far exceeded twice the overburden pressure of roughly 300 kPa.

Having established that significant water pressures were being generated and later dissipated within the Lower Sand, a bore-hole and cone penetrometer investigation was carried out in the vicinity of groups of piles that had either come to early

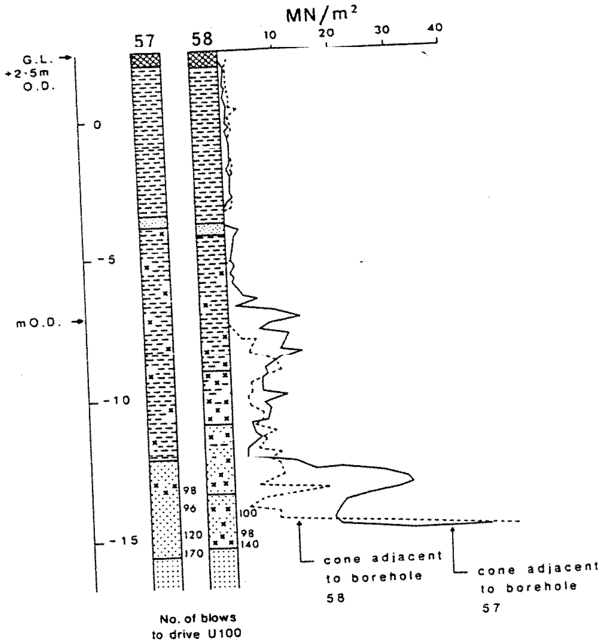

Figure 8 Ground conditions for groups of shallow (B57) and deep (B58) piles

refusal or penetrated deeply. Samples from around the pile tips were taken by piston sampler, where possible, or alternatively by using U100 sampling tubes. Simplified borehole logs and penetrometer sounding values are presented in Figure 8.

For the group of piles which reached an early set at a depth of about 14.7 m, Borehole 57 showed a change to predominantly sand at about 14.6 m. A corresponding increase in cone resistance was also recorded at that depth.

Amongst the group of piles that penetrated more deeply to about 17.5 m, the lithology in Borehole 58 became predominantly sandy from a depth of about 15.8 m but with a higher silt content than in Borehole 57. The cone resistance through the sandy layer remained low until the level at which the piles came to set.

Detailed examination of the sandy soils showed that in Borehole 57 the sand was dense and fairly uniform with D_{60}/D_{10} of about 3.0. The soils from Borehole 58 were more mixed with bands of poorly sorted sandy silt and occasional lenses of clay.

Clearly the soils around the tips of the deeper penetrating piles would be less permeable and thus more prone to the generation of high water pressures, explaining the ability of the piles to penetrate so far into the sandy soil.

It has been remarked that the measured cone resistance in the sandy layer was considerably lower adjacent to the deeply penetrating piles, although it will be recalled that earlier attempts to correlate pile driving resistance with either cone penetration resistance or SPT value had little success (see Figures 2 & 6). It is, or course, possible that cone resistances were also reduced by pore pressures in some but not all of the low permeability zones (see case reported by Appendino et al., 1979). During a recent investigation at Drax (1988) employing piezocones, significant excess pore pressure (up to 700 kN/m^2) were measured in the silts and clays overlying the Lower Sand. Such pore pressure sometimes took more than an hour to dissipate. Within the Lower Sand, measured pore pressures were typically negative due to suction induced by dilation. However, in some locations positive pore pressures up to 200 kN/m^2 were measured in material described as sand on the basis of measured friction ratios. Obviously the relationship between pile driving resistance, static soil strength, penetration test results, soil type and hence pore pressure effects are complex and it would be unwise to draw too many conclusions from one example. Certainly, at Drax, the phenomenon of negative pore pressures recorded by the piezocone was not translated into false sets on shorter piles.

Attempts were made to assess static bearing capacities for piles penetrating

	WORKING PILES		TEST PILES driven to target depth	
	No.1500 (1300 kN)	No.1316 (1100 kN)	TP19 (1300 kN)	TP21 (1100 kn)
Penetration into sand (m)	0.2	0.8	1.6	1.6
Final set blows/25mm	13	9	5	2
	Displacement, mm			
100% Working Load	4.3	4.0	6.2	6.1
Residual on removal	2.4	1.2	1.7	1.4
150% Working Load	9.8	7.5	10.6	8.6
Residual on removal	5.9	2.9	2.5	2.1

Table 1 Comparative settlements from pile tests

deeply into the 'sand', by implication, in areas where the Lower Sand contained a high proportion of silt. A series of test piles were driven alongside boreholes to a target penetration of 1.5 m into the Lower Sand unless the pile achieved its set at a higher level. Nine piles were driven to this specification and in several cases piles had not reached an acceptable set (according to the specification for working piles) before the target depth. Driving was stopped and the piles left without redriving.

The two piles exhibiting the lowest driving resistance at the target depths were selected for testing to 250 % working load and performed well within the criteria for acceptance of working piles. In Table 1, settlement figures are given for two test piles (TP19 & TP21) together with comparative results from load tests on two working piles that had achieved acceptable sets. Clearly the load capacities of the two test piles were considerably greater than was indicated by the driving resistance at the end of driving.

CONCLUSIONS

Piles driven for the construction of Drax Power Station relied for their load support on end bearing in a sandy stratum overlying Triassic sandstone. In this stratum the piles encountered variable driving resistance which did not reliably correlate with SPT values or cone penetration resistances.

Studies of pile performance supplemented by an investigation involving instrumentation, soil sampling and controlled pile testing indicated that the variable behaviour was due to the detailed grading characteristics of the sand stratum. In areas where the silt content was high, piles penetrated more deeply due, it is thought, to the generation of excess pore water pressures. After driving, these water pressures dissipated, providing the piles in such areas with much higher bearing capacities than would be predicted from dynamic driving formulae.

The process of pore water pressure generation and easy driving is a self-perpetuating one. Once pressures have been generated, continued 'easy' driving results in further large volume changes for each blow of the hammer with high pore water pressures being sustained. When new equilibrium conditions have been established it takes a large volume change to restart the process and, providing the pile has reached (and passed through) dense soil as a result of pore pressures generated earlier in the driving, further advancement of the pile will be very difficult to achieve.

The problems involved in assessing the acceptibility of driven piles under such conditions are obvious. Depending upon the specification, it may be contracturally necessary to drive and redrive piles until they reach an acceptable set according to some chosen formula. Economically it would be preferable to have dual criteria whereby piles are driven either to a set or to a target level. whichever is the shorter. However, the problem of recognising piles broken during driving should not be overlooked. Also, unfortunately the only proof of an acceptable target level is provided by preliminary investigative load testing of piles which needs to be done before a specification is written and the Drax experience shows that in some strata pile driving performance can vary markedly over short distances.

The Drax project allowed the flexibility necessary to overcome this problem. This would not always be the case on a smaller piling contract.

ACKNOWLEDGEMENTS

The authors are grateful to the CEGB for permission to publish this paper. During this work the first author (SRH) was employed by W.S. Atkins & Partners, civil design consultants for Drax Power Station Completion.

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