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ABSTRACT

The design and installation of safe and economic foundation solutions for large projects is of great importance in contributing to commercial success. On four recent power projects in the U.K., a variety of foundation solutions have been adopted, driven largely by the particular ground conditions encountered at each location. All four projects were gas fired combined cycle power station facilities and each location provided unique challenges in both the design and installation of the foundations.

The variety of foundation soils encountered was diverse; soft alluvial peat and clay, loose to medium dense silty sands and moderately weak to moderately strong Triassic rock. Foundation solutions included shallow spread options, reinforced earth/rock fill, ground improvement and bearing piles. Various technical difficulties were overcome at each of the sites and important lessons have been learnt from these. All four power stations are similar in their design and bearing pressure requirements. The foundation solutions are all different and were selected to suit local ground conditions.

INTRODUCTION

The design and installation of safe and economic foundation solutions for large projects is of great importance in contributing to commercial success. On four recent power projects in the U.K. (Fig. 1.), a variety of different foundation solutions have been adopted, driven largely by the particular ground conditions encountered at each location. All four projects were gas fired combined cycle power station facilities, and at each location the previously developed sites provided unique challenges in both the design and installation of the foundations.

At Site A in Cheshire, north west England, much of the site was underlain by rock of moderate strength. The site was however constrained by adjacent industrial properties. This necessitated the construction of a reinforced earth and rock fill embankment with varying slope angle, founded on clay and rock, to support the cooling tower facility.

At Site B, Essex, to the east of London and less than 1km north of the River Thames, the geology comprised a sequence of alluvial peat and very soft clay underlain by gravel deposits.

Here, driven cast in-situ (DCIS) piles were adopted which were end bearing onto the underlying gravels. Some problems were encountered with necked piles, discovered during pile head preparation. These difficulties were overcome and important lessons have been learnt from using this technique in the prevailing conditions.

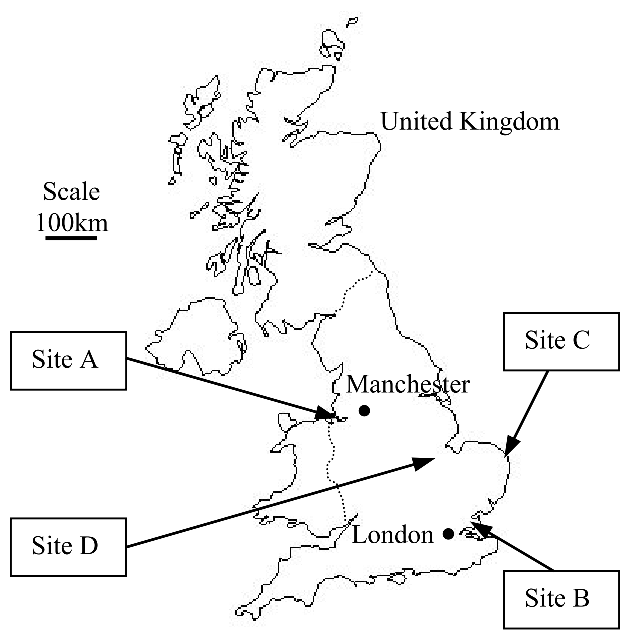

Fig. 1. Location of power station sites A to D

At Site C, situated in Norfolk, East Anglia, the underlying shallow soils comprised loose to medium dense wind-blown sands. Vibro Compaction was adopted beneath the main turbine house due to the relatively heavy static and dynamic loadings. Subsequent monitoring confirmed that the foundation settlements were as predicted.

At Site D in Lincolnshire, the site was underlain by loose to medium dense fine-grained soils of low to moderate bearing capacity. Ground improvement utilising bottom feed stone column construction and, in areas of widely spaced foundations, driven cast in-situ piling were successfully utilised. This project provided an opportunity to collect a large quantity of data on stone consumed to improvement ratio, for various bearing capacities.

All four power stations are similar in their design and bearing pressure requirements. The various foundation solutions were selected to suit local ground conditions.

FOUNDATION PERFORMANCE CRITERIA

The foundation system at each site was selected based on settlement considerations. The bearing pressures applied by equipment foundations for gas-fueled, combined cycle plants tend to be relatively low (100 to 150kPa) for most load combinations, they can reach values in excess of 200kPa for some short-duration load conditions, including those that can arise from equipment malfunction. Only bearing capacity considerations are taken into account for the short-duration load combinations because these loads are not expected to cause permanent settlement.

Due to equipment leveling requirements, strict differential settlement limitations are necessary for the long-term load combinations, which include mostly dead loads. Maximum construction settlements were set at 25mm for column footings and 50mm for structural mats to ensure satisfactory performance. Post-construction settlements were expected to be negligible.

SITE A – CHESHIRE

Overview of Site A in Cheshire

The water-cooled power station at Site A, includes one Combustion Turbine (CT), one Heat Recovery Steam Generation unit (HRSG), one Steam Turbine (ST), Air Cooled Condenser (ACC), an administration building, several tanks, and other ancillary structures and equipment.

Site Location and Regional Geological Setting

The site is located 3km south of the town of Runcorn, close to the River Mersey and adjacent to the Weaver Navigation canal.

The underlying geology comprises the solid strata of the Mercia Mudstone and Sherwood Sandstone groups of Permian and Triassic age. The region is crossed by a series of inactive, localised discontinuous faults and some regional faults. The thickness of the Permo-Triassic strata in the vicinity of the site is in excess of 1km.

Geology of Site A

The 1:50000 Scale British Geological Survey (BGS) Solid Geology map for the area indicates the site to be crossed by an inactive fault, which runs north south near the eastern side of the site. To the west of the fault is shown the Keuper Waterstone, which consists generally of a red-brown and grey-green siltstone/sandstone with mudstone beds. This is shown to be dipping at 3 to 5 degrees in a northerly direction.

To the east of the fault is shown the Lower Keuper Marl, which consists generally of red and green mudstones and siltstones. In parts of the site superficial deposits comprising sands, sandy gravels and clay with gravel were encountered to depths of 3.5m below the ground surface. (Fig. 2.)

The 1:63360 Scale BGS Drift map indicates small areas of superficial deposits at the site.

Ground water levels were generally more than 4m below the ground surface, and perched water was encountered at the soil/rock interface.

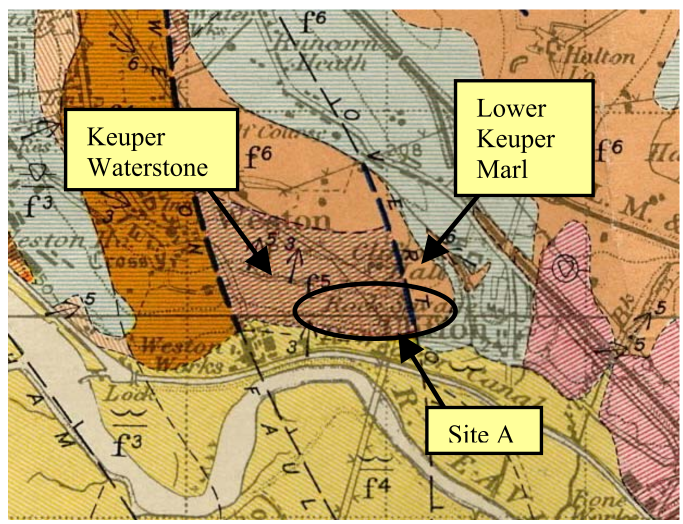

Fig. 2. Geology of Site A in Cheshire

Geotechnical Considerations and Foundation Options

The Keuper Waterstone underlying much of this site provided good bearing formation upon which to construct raft foundations. Overturning forces were only a consideration for the exhaust stack, which was constructed with an appropriately sized mass concrete base. The cooling tower facility was constructed on a part reinforced rock/earth fill slope. The fill area was on sloping ground and commenced with an unreinforced 1:2 slope at the eastern end where the site was widest. A reinforced transition slope from 1:2 to 1:1 was constructed utilising a Tensar uniaxial geogrid.

Technical Challenges

The construction of the reinforced embankment proved to be one of the most challenging aspects of the earthworks. This required precision setting out and placement of reinforcement at appropriate locations and levels, within this variable geometry embankment.

SITE B - ESSEX

Overview of Site B in Essex

The air-cooled power station includes two CTs, two HRSGs, one ST, air-cooled condensers, an administration building, several tanks, and other ancillary structures and equipment.

Site Location and Regional Geological Setting

The site is located 0.5km north of the River Thames and 3.5km south east of Corringham in Essex. The site was formally used as overflow car parking for the adjacent BP Coryton Refinery. The site lies at approximately 2m above Ordnance Datum within a large area of flat and marshy ground with many watercourses. The site is underlain by a sequence of Recent Marine and Estuarine Alluvium. Below these deposits the BGS map indicates London Clay, Woolwich Beds and Chalk at depth. No faults are indicated in the vicinity of the site. (Fig. 3.).

Geology of Site B

A sequence of Marine and Estuarine Alluvium was encountered to –12m to –15mOD. The alluvium consisted of soft organic clay, peat, silt, sand and Flood Plain gravels. The London Clay was not encountered. Underlying the alluvium river terrace deposits, Thames Gravels, comprising a thin layer of stiff clay underlain by dense to very dense sandy fine to coarse gravel, were encountered. These possess a much greater degree of consolidation than the overlying alluvium.

Ground water levels generally ranged from 0m to over 4m below the ground surface at the site.

Geotechnical Considerations and Foundation Options

The thickness of soft alluvial deposits at the site precluded the use of shallow footings for all but the smallest of instrument kiosks at the site. The site was filled to a level of +4m OD utilising a locally won fine sand capped with a layer of crusher run limestone hauled to the site using rail and road transport. This was undertaken to provide a level for the plant that offered security against future flood estimates and to provide a stable platform from which to construct the foundations and facility.

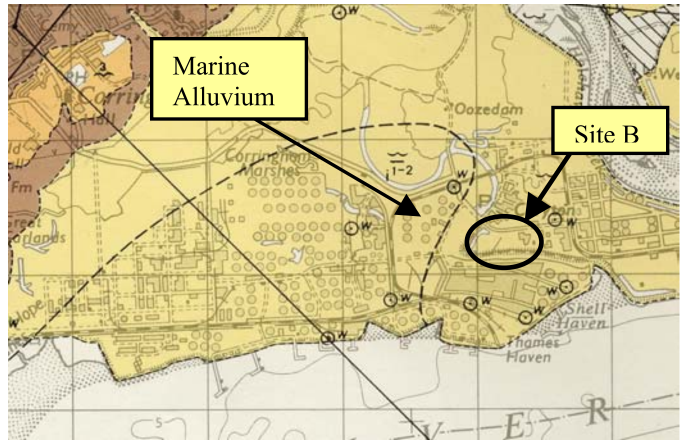

Fig. 3. Geology of Site B in Essex

A number of pile systems were trialled at the site in a development exercise (Fig. 4.). These included Continuous Flight Auger (CFA), Driven Precast, and Driven Cast In-Situ (DCIS) piles. The DCIS pile system was chosen as it offered the best balance of performance, speed, cost and flexibility for the project, enabling schedule considerations to be met. The DCIS system performed better in uplift than the Driven Precast piles and offered a higher capacity than the CFA piles, and an inherent check via driving to a set.

Fig. 4. Site investigation adjacent to a driven pile (foreground) with DCIS Piling (background) during piling trial.

The DCIS piles were 430mm diameter with a full length reinforcing cage. Performance of the pile system was of paramount importance as the piles had to perform under varying compression, tension and lateral loads depending upon which structure they were supporting. In areas of high lateral or tension load a heavier cage was used. The compression cage comprised eight T16 full length bars equally spaced on a 250mm T8 helix. The tension/lateral cage comprised eight T20 bars for the upper 7m of the pile and eight T16 bars below to the base of the pile. All the piles were driven to a set in the dense sandy gravel of the underlying Woolwich Beds. A total of over 3200 piles were installed to support all the facilities at the site. Three static compression load tests and sixteen dynamic load tests were performed on selected piles. Four lateral load tests and four tension tests were also performed. All the test results proved satisfactory performance in accordance with the specification requirements. Settlement criteria for the pile in compression were less than 10mm under working load and no more than 17mm under 1.5 times working load.

Technical Challenges

During the course of excavation of some of the deeper sumps the upper four to six metres of some piles were exposed. A few of these revealed necking – a thinning of the pile diameter – over a short length of pile (Fig. 5.). This occurrence was infrequent and in only a minority of piles did the cover to the reinforcement prove to be problematic. These were repaired to specification requirements.

Fig. 5. Necked pile showing a reduction in diameter of approximately 100mm, at Site B in Essex. Note: soil is very silty organic clay.

An in-depth investigation of the problem was undertaken by the contractor, which involved analysing all the driving records, concrete records and integrity testing all the piles on site (originally only 20% of the piles were scheduled for integrity testing). Additional high strain dynamic load tests were performed and checking of theoretical pile group performance with a defective pile was also undertaken. The conclusions of the investigation were that the occurrence of the necking only affected a minority of the piles in discrete areas of the site. The most likely cause of the necking problem was a failure to maintain a sufficient “head” of concrete in the drive tube on withdrawal, in a few cases. It is worthy of note that in very soft clay ground where pockets of organic rich material occur the “head” of concrete in the drive tube should be sufficient to counter the groundwater pressure in order to ensure the integrity of the pile shaft.

SITE C - NORFOLK

Overview of Site C in Norfolk

The once-through, water-cooled power station includes one CT, one HRSG, one ST, water intake and discharge structures and tunnels, an administration building, several tanks, a gas-insulated substation, river intake and pump house structures and other ancillary structures and equipment.

Site Location and Regional Geological Setting

The power facility is located within the South Denes industrial area approximately 2km south of the center of Great Yarmouth, Norfolk. The site is relatively low-lying; the former power station has been demolished to ground level. The main site is approximately 50m from the River Yare to the west and 50m from the North Sea to the east.

The BGS maps indicate that a sequence of Quaternary deposits of blown sands over North Denes Formation sands and gravels overly undivided shelly sands, silts and clays of the Crag group, which is of Pleistocene age. At greater depth, London Clay, the Thanet formation and Upper Chalk of Cretaceous Age is indicated. (Fig. 6.).

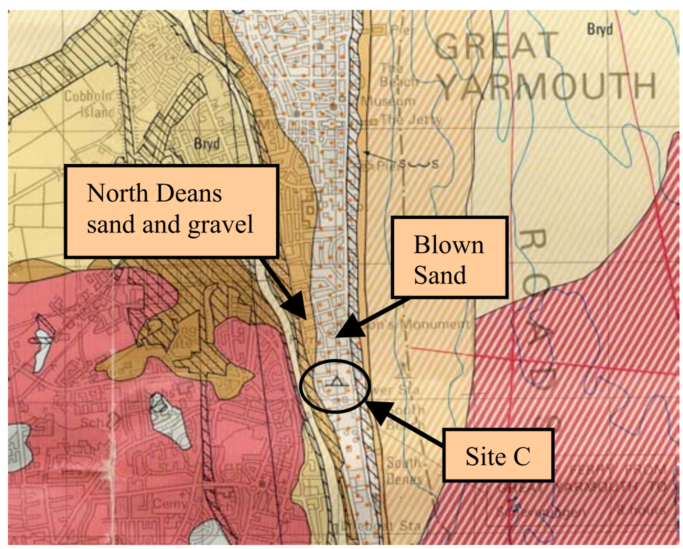

Fig. 6. Geology of Site C in Norfolk

Geology of Site C

The strata sequence at the site comprised loose made ground up to 3m deep overlying initially loose and medium dense blown sand to about 5 to 6m below ground level. Granular deposits generally continued with increasing density to about 25m below ground level. Beneath these bands of stiff to very stiff clays up to 2m thick overly further very dense sands. To the east of the site in the North Sea, the clay bands appear at a shallower depth. Groundwater levels are typically 2m below ground level on the power station site. The groundwater levels were expected to be subject to some tidal influence.

Geotechnical Considerations and Foundation Options

The site is a 'brownfield' site formerly occupied by an oil fired power station constructed in the 1950s that ceased operation in 1985. That power station was served by a cooling water intake pipe from the river Yare and a cooling water outfall pipe into the North Sea and in contrast to the air-cooled examples in this paper, this was the approach adopted for cooling for the new build.

The old intake and outfall pipe were still in existence but of inadequate capacity and in a poor structural state that prevented their reuse. In all, three pipelines were required for; cooling water intake, outfall and power cables. A number of options for these were considered involving, inter alia:

- Overhead transmission cable across the river for the power
- Open cut from the river to the site for the intake
- A combination of open cut and dredging for the outfall.

The original proposal for the project was for power cables to be run underground from the plant northwards to an existing overhead line crossing of the River Yare from where they would be routed to a connection point with the existing overhead transmission system. However a tunnelled approach offered important environmental benefits to Great Yarmouth through the removal of existing pylons to the west of the town and became a requirement of the contract.

The inlet pipe was originally proposed as open cut construction requiring the temporary construction of a sheet piled trench in conjunction with groundwater control arrangements in advance of excavation. This would have necessitated diversion of services including a large diameter deep sewer and a full range of other public utilities along with the need to maintain the highway open to traffic.

A tunnelled option removed all difficulties related to disruption and service diversions. The reuse of the tunnel-boring machine (TBM) produced additional economy.

Construction of the outfall using a single tunnelled technique had significant environmental advantages over open cut and dredging. Land works could be centred on the power station site and marine works to a limited zone around the diffuser along with a much shorter construction period. Figure 7 shows ground investigation for the outfall tunnel in progress on shore, by conventional techniques, and offshore by jack up platform.

Fig. 7. Onshore and offshore site investigation at Site C on the Norfolk Coast

The common tunnelled approach for all three cases allowed the adoption of a "single contract" approach to a tunnelling contractor. In the ground conditions identified the use of a full-face earth pressure balanced TBM, in which a segmental concrete tunnel lining is erected, was the appropriate tunnelling option.

The main powerhouse was to be built on approximately 5m depth of loose to medium dense wind-blown sands underlain by more competent sands. The main turbine house included relatively heavy and dynamic loadings. These sands, while being relatively low in fines content, had a local reputation for being difficult to compact by conventional roller methods.

A vibro compaction technique was selected as the form of ground improvement utilising a 120kW, 200kN force S-vibrator with water flush. Analysis of the soils suggested that a target relative density of 75% using the Jamiolkowski et al (1985) approach would achieve the desired total and differential settlement performance.

Technical Challenges

The seal chamber forms the interface between the site pipe work and the sea outfall. The design had to accommodate the construction requirements of the tunnel and the hydraulic requirements of the plant. A shaft diameter of 9m was chosen to suit these requirements.

The shaft was constructed through the dense water bearing sands down to a formation, 32m below ground level. It was sunk as a caisson using bolted segmental circular shaft rings within an in-situ external concrete wrap. The motive force for sinking the shaft was provided by a combination of its self-weight and hydraulic jacks. The jacks were anchored to a concrete ring beam around the shaft which itself was tied into a circular sheet piled curtain wall for stability as shown in Fig. 8.

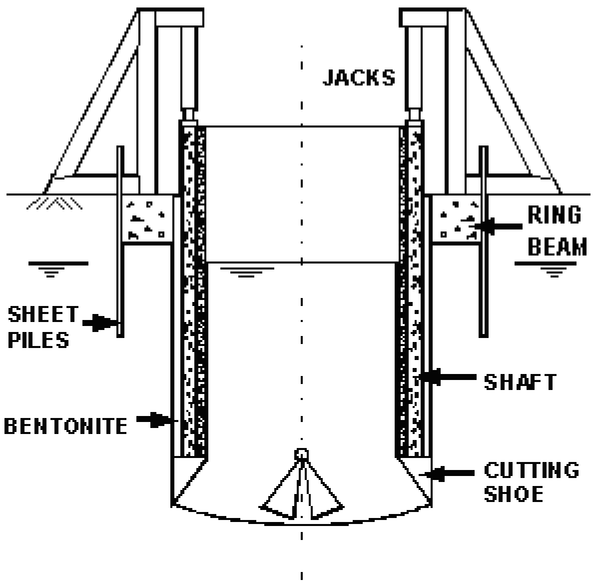

Fig. 8. Seal chamber bolted segmental caisson installation for sea outfall, Site C (after Heavey, et al., 2000)

A steel cutting shoe on the underside of the caisson was used to improve ground penetration as muck was excavated from within the caisson using a cable-operated clamshell. The maintenance of a water balance during the excavation operations is an important factor in such caisson construction. To minimize the force requirements a 50mm annular space was maintained round the shaft full of a bentonite slurry lubricant. Upon completion of the shaft, the bentonite was displaced by cement grout.

Part of the vibro compaction contract included the performance of pre-treatment CPT investigation, which revealed that locally the sands below the proposed treatment depth were less competent than were expected. However, initial vibro compaction trials had confirmed that a 2 to 4m triangular grid would compensate for the weaker deeper soils. This was confirmed by a post treatment CPT investigation. (Fig. 9.).

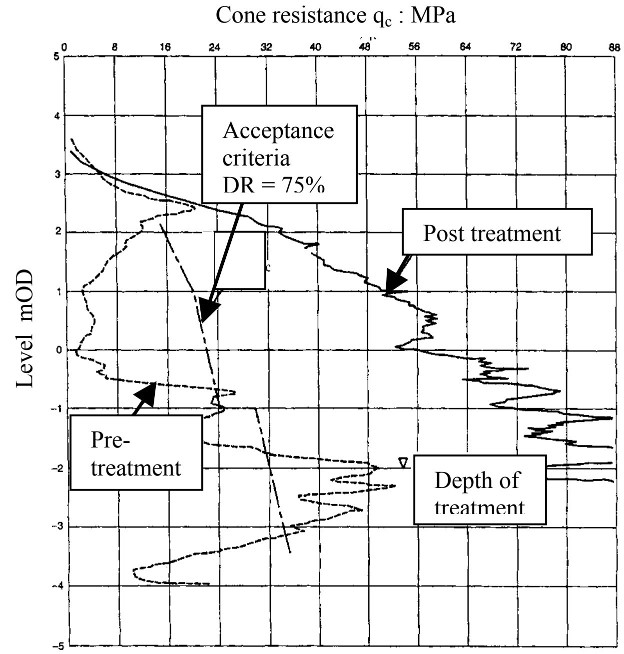

Fig. 9. Pre and post treatment CPT performance data and acceptance criteria, Site C. (after Slocombe et al., 2000)

SITE D - LINCOLNSHIRE

<u>Overview of Site D in Lincolnshire</u>

The air-cooled power station includes two CTs, two HRSGs, one ST, air-cooled condensers, an administration building, several tanks, and other ancillary structures and equipment.

<u>Site Location and Regional Geological Setting</u>

The site is located approximately 2km north east of the town of Spalding in Lincolnshire. The site lies at an elevation of approximately +4m OD. The regional geology of the area comprises the Terrington Beds (Marine Alluvium) overlying Glacial Drift and Oxford Clay of Jurassic Age. No faults are shown to cross the site.

The site is a ‘brownfield’ site formerly occupied by a British Sugar processing facility. The legacy of this former use was the presence of some areas where piled foundations and some buried reinforced concrete structures existed. The piles were left in situ since these did not impinge on the construction areas of the power station facility, however, the buried structures (sumps and basements) were removed and the excavations refilled with compacted sand.

In some areas of the site made ground, comprising brick and concrete rubble, had been used to fill an old lagoon structure. In other parts of the site lime pits had been utilised to reduce the organic by products of the former plant. These would have posed an environmental issue if the footprint of the power station had been built over them. By careful design and consideration of the available space this was avoided.

Geology of Site D

The BGS map indicates the site to be underlain by Flandrian "Terrington Beds" (marine alluvium) of Quaternary Age. These overlie mixed glacial deposits comprising Glacial Sand and Gravel and Till which lie directly on the Oxford Clay of Upper Jurassic Age. (Fig. 10.).

In areas of the site where structures had formerly been located Made Ground comprising sand or sandy clay with mixed man made material; bricks, concrete, ash etc., was encountered to depths of up to 3m below ground level overlying alluvial sand. The alluvial sand varied in condition from loose, to depths of about 7m, to medium dense, becoming very dense, below 7m. The dense and very dense sands extend to about 17m below ground level. These in turn are underlain by a very stiff grey and blue grey clay of the Oxford Clay sequence. The upper metre of the clay has probably undergone some reworking by glacial action as it typically contained gravel and cobbles of many rock types. Below this level the gravel became rare and typically comprised chalk and black igneous rock fragments.

Groundwater was encountered within the alluvial materials at depths of between 2m and 4.7m below the existing ground surface.

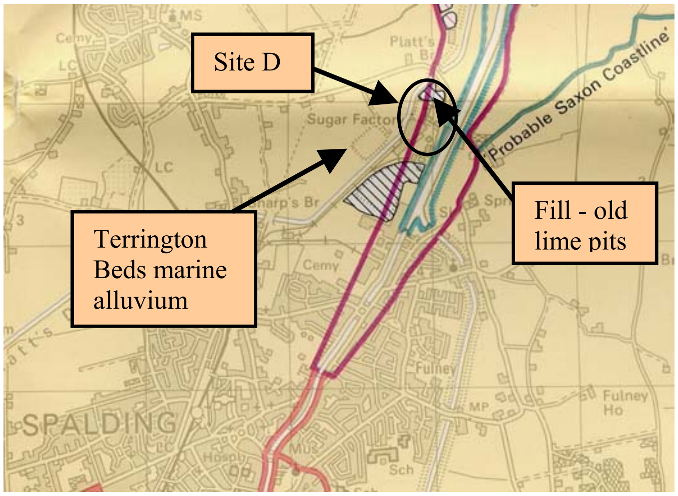

Fig. 10. Geology of site D in Lincolnshire

Geotechnical Considerations and Foundation Options

Different foundation options at this site were considered based on performance, cost and schedule. The ground conditions were reasonable, but not considered sufficient for the proposed bearing pressures. It was therefore decided to adopt a dual approach of ground improvement and bearing piles for the foundations at this site. The main site was improved using dry, bottom feed, stone columns on a regular triangular grid (Fig. 11.).

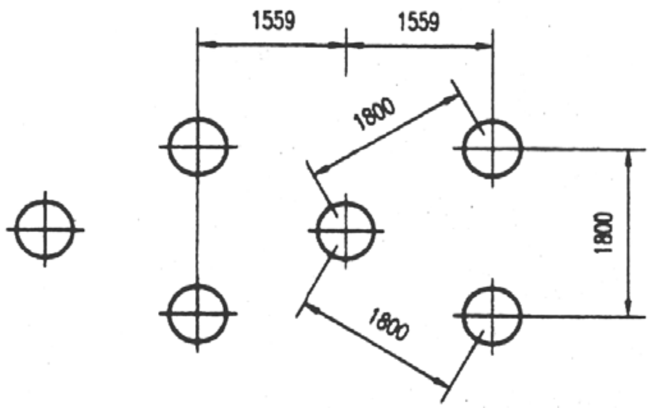

Fig. 11. Stone column layout pattern, for 150kN/m^2 bearing capacity, Site D in Lincolnshire

Bearing capacities of 150kN/m^2, 200kN/m^2 and 250kN/m^2 were required with settlement tolerance limits of 25mm for individual columns and no more than 50mm under mat foundations cast onto the columns. The stone column layout was zone tested for compliance with Specification performance requirements (Fig. 12.).

Fig. 12. Zone test on 150kN/m^2 Stone column layout

All of the power station structures, with the exception of the Air Cooled Condensers (ACC), were constructed on mat foundations built off the improved ground. In locations where the highest loads were applied the densities of the columns were increased, in accordance with the contractors design, to satisfy the bearing and total and differential settlement requirements. The centre to centre (C/C) spacing of the columns was varied in accordance with Table 1. Figure 13 illustrates the installation of columns and piles at this site.

Table 1. Stone column spacing at Site D in Lincolnshire

Bearing Pressure Requirement	Spacing C/C north/south	Spacing C/C east/west
150kN/m2	1800mm	1559mm
200kN/m2	1500mm	1299mm
250kN/m2	1300mm	1126mm

Fig. 13. Three stone column rigs undertaking ground improvement (foreground) and DCIS piling rig installing piles in ACC area (background left).

Under the ACC the structure loading is applied at discrete locations on a square grid at approximately 14m spacing. The most economic foundations for the ACC structure were therefore determined to be piles. A Driven Cast In Situ system was utilised based on a settlement performance criterion to limit differential settlement of this structure. The piles were 380mm nominal diameter of minimum length 8.25m, with full-length reinforcement of 6 T20 bars on a 250mm pitch T8 helical.

SUMMARY OF GEOLOGICAL CONDITIONS AND FOUNDATION OPTIONS

The ground conditions at the four power station sites were all geologically different. Each site had its own unique geotechnical aspects that require different foundation solutions to provide adequate bearing capacity for the proposed structures. Although the structural loading on the foundations are not considered to be large, or unusual, the structures are sensitive to differential settlement and therefore the performance of the foundations was a critical aspect of these projects.

In general the four projects were similar, the exception being the water cooling process for Site C. In this case a tunnelled solution was adopted due to environmental and technical constraints and the availability of cooling water and diffuser location. Table 2, summarises the ground conditions at each site and the foundation options utilised.

Table 2. Summary of ground conditions and foundation solutions at four recent power stations in the U.K.

Site A – Cheshire		Site B - Essex		Site C - Norfolk		Site D – Lincolnshire	
Ground conditions	Foundations	Ground conditions	Foundations	Ground conditions	Foundations	Ground conditions	Foundations
Moderately Weak Permo-Triassic rock at shallow depth	CT, ST, HRSG, Stack – Reinforced concrete raft foundations cast directly onto prepared rock surface	Alluvial clay, silt, sand and peat over dense gravel	CT, ST, HRSG, Stack – DCIS piles end bearing on dense gravel	Loose to medium dense sands becoming very dense with depth	CT, ST, HRSG, Stack – Vibro-compaction	Loose to Medium dense silty sand over dense silty sand over Oxford Clay	CT, ST, HRSG, Stack – stone columns at various spacings to provide bearing capacity
Rock as above and stiff clay on slope over rock	ACC – raft foundation cast directly on prepared rock surface and on reinforced rock fill embankment	A/A	ACC – DCIS piles end bearing on dense gravel	A/A	Water Cooling process – one pass intake shaft and tunnel discharge via marine diffuser	A/A	ACC – DCIS piles (friction and end bearing) into dense silty sand

Key: ACC (Air Cooled Condenser), ST (Steam Turbine), CT (Combustion Turbine), HRSG (Heat Recovery Steam Generation), DCIS (Driven Cast In Situ)

CONCLUSIONS

The foregoing account of the solutions adopted on four recent power projects in the U.K., indicate the variety of different foundation solutions required. These were chosen as the optimum solutions to meet the demands of the particular site conditions. Environmental considerations also impacted on the choice of foundation solutions and plant layout. Each of the locations chosen for these four gas fired combined cycle power station facilities, provided unique challenges in both the design and installation of the foundations.

The foundation soils encountered were diverse; soft alluvial peat and clay, loose to medium dense silty sands and moderately weak to moderately strong Triassic rock.

DCIS piles were adopted in the very soft alluvial materials and loose to medium dense silty sands. Stone columns and vibro compaction were used to improve silty sand and wind blown sand for raft and mat foundations. A reinforced rock fill embankment was constructed on one site to support the ACC. At one site tunnelled options were used for cable ducts and water cooling for economic optimisation and to benefit the environment.

All four power stations were similar in their design and bearing pressure requirements. Various technical challenges were overcome at each of the sites, which provides valuable information for future projects.

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