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Application of Piled Raft for Embankment in Normally Consolidated Clay

H.S.W. Chow[1], PhD, H. G. Poulos[2], DScEng, S.K. Kim[3], PhD, R. Turner[4] MEngSc, S. G. Han[5], PhD

[1]Coffey Geotechnics, Australia, Unit 8, 12 Mars Road, Lane Cove West NSW 2066; PH (612) 9911-1000; FAX (612) 9911-1001; email: helen_chow@coffey.com
[2]Coffey Geotechnics, Australia, Unit 8, 12 Mars Road, Lane Cove West NSW 2066; PH (612) 9911-1000; FAX (612) 9911-1001; email: harry_poulos@coffey.com
[3]Department of Civil Engineering, Dongguk University, Korea; email: skkimgeo@kornet.net
[4]Coffey Geotechnics, Australia, Unit 8, 12 Mars Road, Lane Cove West NSW 2066; PH (612) 9911-1000; FAX (612) 9911-1001; email: rob_turner@coffey.com
5 Hyundai Development Company, Korea; email: sghan1@kornet.net

ABSTRACT

An embankment near Busan, South Korea was designed to be constructed over a soft clay deposit with vertical drains installed. During stage construction of the embankment, excessive settlement and cracks were observed at the ground surface. Remedial design was carried out which adopted a piled raft as the foundation for the additional embankment. This paper presents the approach used for the design of a piled raft foundation for the embankment. The finite element program PLAXIS 2D was used to simulate the ground settlement during the initial construction stage and after the construction of the piled raft. Detailed design of the piled raft was carried out by the boundary element program GARP and the predicted settlement is compared with the monitoring results obtained during the embankment construction.

Keywords: analysis, embankment, soft clay, vertical drains, piled raft foundation

1 INTRODUCTION

A railway embankment was proposed to be constructed over a thick normally consolidated soft clay deposit in Busan, South Korea. The embankment was designed to have a maximum height of 12m with a batter slope of 1V:1.2H. Initial construction of the embankment adopted ground treatment techniques comprising a combination of sand compaction piles and prefabricated vertical drains. However, before embankment construction reached mid-height, cracks occurred along the centreline of the embankment at several locations, which indicated the possibility of stability failure. Based on the observations, the failure mode was circular with the arc estimated to pass approximately 10m below ground surface.

Remedial design was then carried out adopting a piled raft as the foundation for the additional embankment. A piled raft is a feasible solution for embankment construction over soft soils as it can be constructed in a timely manner without the need for extended preloading time which is required for conventional ground improvement techniques.

The use of a piled raft over thick normally consolidated soft clay deposits is often associated with problems of excessive settlement, negative skin friction development and insufficient bearing capacities (Tan et al. 2004 and 2005). Poulos (1993) performed numerical analyses on piled rafts in consolidating soils and showed that the soil surface movement due to consolidation would impose additional load on the piles which resulted in increasing the rate of settlement. Furthermore, the contact between raft and soil can be lost and result in the loads being carried by the piles alone. Applications of piled rafts on normally consolidated clay have nevertheless been proven to be effective in reducing consolidation settlement (Kakurai et al. 1987, Goad et al. 1988) in which elastic theory was employed in the design. Poulos (2007) has developed design charts for piled embankments on soft marine clay deposits, taking into account the vertical and lateral ground movements.

This paper is focused on the design approaches adopted for the piled raft foundation for the Busan railway embankment on soft clay together with a comparison between the predicted and monitoring results. Initial design for ground treatment was carried out by a third party and will not be discussed in this paper.

2 GEOTECHNICAL MODELS

The railway embankment was separated into two sections by a mountain as shown in Figure 1. Embankment site A was located at Section 1 and sites B and C were located at Section 2. The geology of site A comprised reclaimed soil underlain by approximately 14m of compressible alluvial clay. The geology of sites B and C comprised reclaimed soil underlain by approximately 28m of compressible alluvial silty clay and silty sand. Figure 2 presents the undrained shear strength profile for both sections obtained from the in-situ and laboratory tests. The undrained shear strength increases approximately linearly with depth, with values varying from 15kPa to 30kPa and 18kPa to 35kPa for Sections 1 and 2 respectively (Kim et al, 2011).

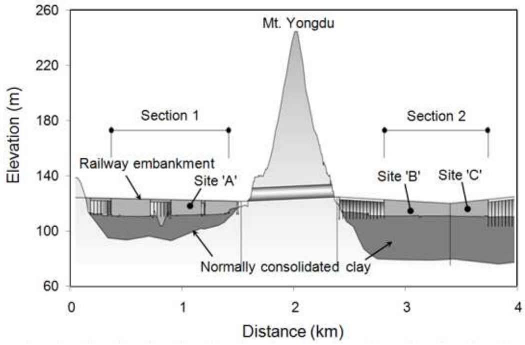
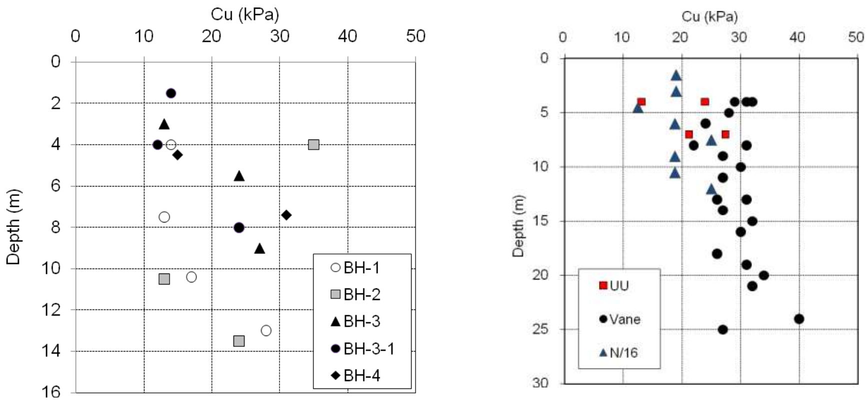


Figure 1. Profile of railway embankment



(a) Section 1 (Site A) *(b) Section 2 (Sites B and C)*

Figure 2. Undrained shear strength profile for embankment sections

3 EMBANKMENT CONSTRUCTION AND PILE LOAD TEST

3.1 Embankment construction history

Prior to the placement of embankment fill, ground improvement was undertaken, comprising of 0.7m diameter sand compaction piles with a spacing of 1.8m beneath the footprint of the batter slopes of the embankment and prefabricated vertical drains with a spacing of 1m beneath the footprint of the crest of the embankment. Table 1 summarises the embankment construction history for each site. Failure occurred when the embankment was built to half of the design height. Prior to the construction of the piled raft over the existing embankment, an additional 2m of embankment fill was placed in order to accelerate the consolidation process.

3.2 Pile load test

A series of pile load tests were performed at the embankment levels where failure occurred. A total of 7 test piles were installed at Sections 1 and 2 to obtain geotechnical information for pile design. Piles with diameters of 400mm and 450mm were installed to different depths. Results showed that the ultimate capacity of a 450mm diameter pile reached 1600kN with the pile tip founded in the upper sandy layer below the soft clay deposit.

Table 1: Embankment construction history

Embankment Section	Design Height	Height of Fill Placed (m)	Months to construct to this height	Settlement of Embankment before piled raft construction
A	10m	5m	10	1.36m
B	10m	5.5m	12	1.8m
C	12m	6m	13	2.17m

3.3 Configuration of piled raft

The adopted configuration of the piled raft foundation was comprised of a 0.4m thick concrete raft with pile diameters of 0.4m for Site A (Section 1) and 0.45m for Sites B and C (Section 2). The piles had a 3m by 3m square spacing. The piles were founded in the silty sand layer below the silty clay layer. The piled rafts have to support embankment heights of 5m at Site A, 5.3m at Site B and 7.2m at Site C. Figure 3 shows a typical configuration of piled raft foundation for the embankment at Site B. Instrumentation was installed to monitor the performance of the embankment during and after construction.

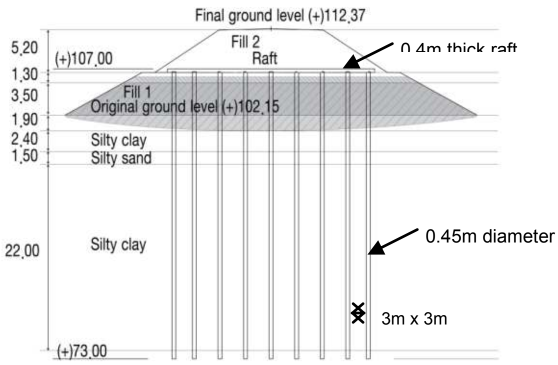


Figure 3. Configuration of piled raft for embankment at Site B

4 FOUNDATION DESIGN ISSUES AND APPROACHES

4.1 Design Issues

The design of a piled raft foundation for an embankment requires consideration of the following issues:

- Geotechnical and structural capacity of the foundation;
- Overall settlement of the foundation;
- Lateral response of the foundation;
- Possible effects of ground movement due to consolidation;
- Load-sharing between raft and piles;
- Distribution of loads along the piles.

4.2 Design Approaches

The design approaches have integrated the as-built ground improvement work in the analysis. The main analyses were carried out to obtain the following aspects of the behaviour of the foundation:

- The axial pile load capacity and pile head stiffness;
- The effect of interaction between piles and raft;
- The effect of vertical and horizontal ground movement of the embankment due to consolidation.

A variety of computer software was used to carry out the analyses, as summarised in Table 2.

Table 2: Description of analysis

Computer Software	Type of Formulation	Description of Analysis Performed
PLAXIS 2D	Finite Element	Assessment of vertical and horizontal movement of the foundation due to consolidation
CLAP	Boundary Element	Assessment of pile capacity, pile stiffness and interaction factors
GARP	Boundary Element and Finite Element	Assessment of foundation behaviour due to embankment fill and applied loads
PIES	Boundary Element	Assessment of pile head movement due to external induced vertical soil movement (i.e. consolidation)
ERCAP	Boundary Element	Assessment of pile bending moment and shear forces of the piles due to external induced lateral movement of the embankment

4.3 Analysis Procedure

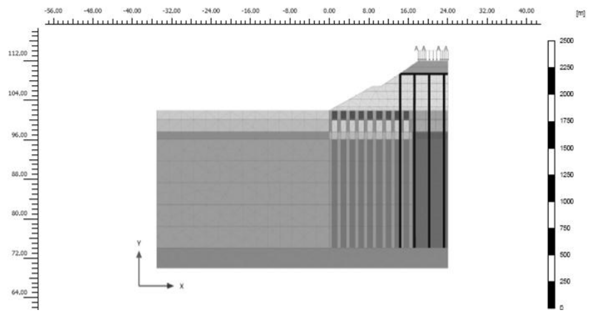
The above programs were used in the following manner:

- PLAXIS was used to obtain the vertical and horizontal movements of the foundation due to consolidation. Plane strain analysis was performed. The soft clay deposit was modelled by the soft soil model. The sand compaction piles were modelled by soil elements with 'smeared' material properties. The prefabricated vertical drains were modelled by converting the 3D axisymmetric system to an equivalent 2D plane strain system which involved the modification of the drain spacing and the permeability of the system. In the vicinity of drains, the pore pressures were reduced to the prescribed groundwater head. Due to the occurrence of large deformations, it was necessary to employ large deformation theory in the analysis, which takes into account the large structural distortion, stress changes due to finite material rotation and the effects of soil settling below the phreatic levels (Plaxis 2D Manual, 2010)
- CLAP was used to obtain the pile capacity, single pile stiffness and interaction factors between piles for input into GARP.
- GARP was used to obtain the settlement of the piled raft without considering the effect of soil movements due to consolidation. Single pile stiffness and interaction factors computed by CLAP were input into GARP.
- PIES was used to assess the pile head settlement and downdrag load caused by consolidation of the soft clay. Vertical soil movement computed by PLAXIS after the installation of the piled raft was input into PIES as the externally imposed soil movement for computation.
- ERCAP was used to assess the bending moment profile in the outer piles of the foundation. The lateral displacement profile obtained from PLAXIS after the installation of the piled raft was input into ERCAP as external-lateral soil movement.

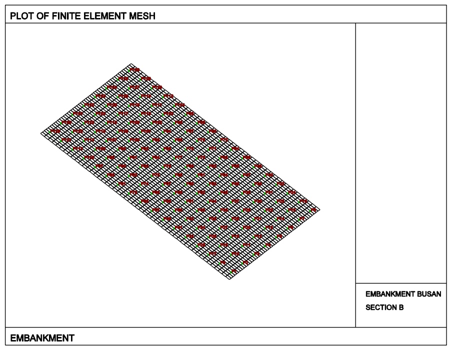
5 ANALYSIS RESULTS

Figure 4 shows the finite element meshes used for the PLAXIS and GARP analyses of the embankment at Site B. In PLAXIS, the sand compaction piles and vertical drains were modelled. The raft and piles were modelled by structural elements. The construction history of the embankment prior to the installation of piled raft was modelled to simulate the consolidation settlement and to validate the design parameters based on the monitoring data.

In GARP, a strip of the raft with a width of 50m was analysed. The analysis only considered the behaviour of the piled raft due to the embankment fill and applied loads and did not account for the effects of consolidation. The impact of soil movement due to consolidation was considered in the PIES and ERCAP analyses. Total settlement was computed by adding the settlement computed from GARP to the pile head settlement computed from PIES.



(a) *PLAXIS Analysis*

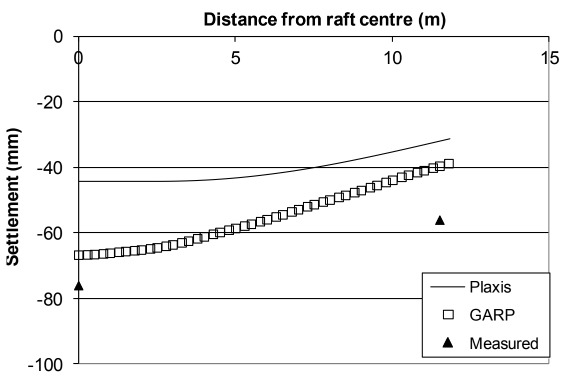


(b) *GARP Analysis*

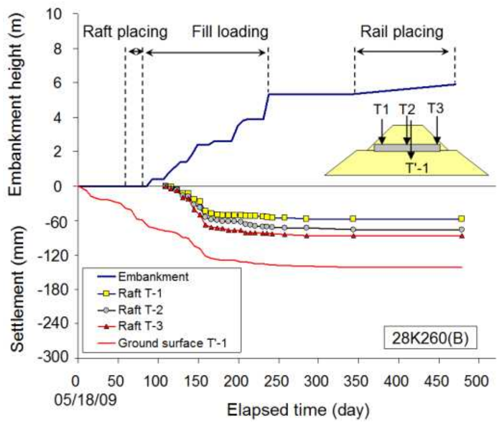
Figure 4. Finite element mesh for PLAXIS and GARP analyses of embankment at Site B

5.1 Settlement of Raft

Figure 5a shows a comparison of the raft settlement among PLAXIS, GARP and measurements for embankment at Site B. Both GARP and PLAXIS under-predicted the settlement, and this could be due to the behaviour of the piles (i.e. frictional pile vs ending bearing) which will be discussed in section 5.2. Other factors that may have contributed to the under-prediction is the continuous consolidation settlement due to the placement of additional fill and the development of excess pore pressure due to the driving of a large number of piles, which was not modelled in the GARP and PLAXIS analyses. Figure 5b presents the monitoring settlement with embankment height. The raft settlement increased with increasing embankment height and approached a constant settlement after the embankment height reached 3m. This could reflect the presence of vertical drains beneath the existing embankment which accelerated the consolidation rate. The settlement gauge T3 at the outer edge of raft was observed to settle more than at the centre of raft. This could be explained by tilting of the rod T3 which increases with increasing embankment height and results in higher settlement as expected. Despite of the discrepancy in predicted and measured settlement, it is clear that the piled raft solution adopted performed well and enabled the embankment construction to be completed successfully.



(a) Comparison of raft settlement



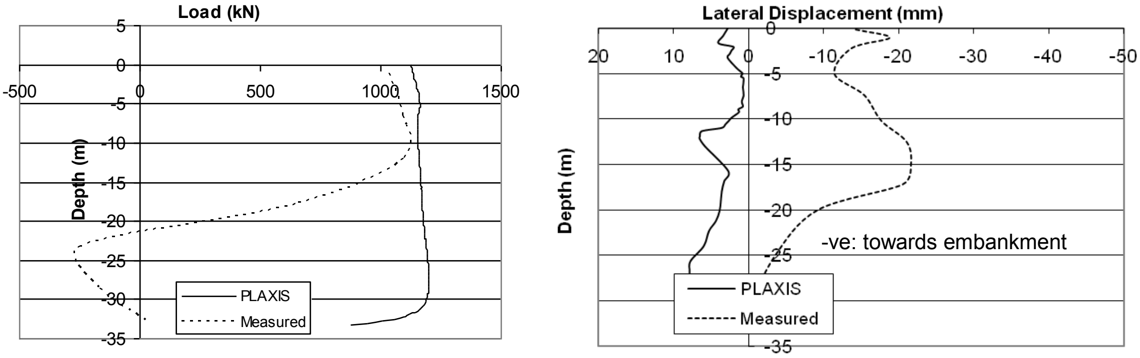
(b) Measured settlement of raft and ground with embankment height

Figure 5. Comparison between PLAXIS, GARP and measurements for Site B

5.2 Pile Load Distribution and Lateral Displacement

Figure 6a shows the comparison of axial load distribution and lateral displacement of piles. The measured tension forces below a depth of 20m indicated malfunctioning of the strain gauges and should be neglected. The measurements indicated that negative skin friction developed within the top 10m of the pile and that the load carried at the pile tip is relatively small. However, the results predicted by PLAXIS indicated that skin friction was not fully mobilised along the length of the pile and the load carried by the pile base was relatively high compared to the measurement. The differences between the measured and predicted results could be due to the founding material below the pile. The relatively small load measured at the pile base indicated the pile is founded in soft material and behaved as a friction pile, however, in PLAXIS, the piles were assumed to be end-bearing piles founded into a hard stratum below the soft clay material. This could also contribute to the differences between measured and predicted settlements, as discussed in the previous section.

Figure 6b shows the predicted and measured lateral displacement of the outermost pile. The predicted results showed a typical lateral deformation profile in which the pile is moving away from the embankment, however, measurements showed that the pile is moving towards the centre of embankment. This could possibly be due to the effects of consolidation of the underlying ground and difference in soil rigidity underneath the centre and outer part of the embankment. It should be noted that the presence of longitudinal failure cracks within the embankment, and the effect of pile driving on soil rigidity/stiffness, were not considered in the analysis.



(a) Pile load distribution (b) Lateral displacement

Figure 6. Comparison of pile behaviour between PLAXIS and measurements for Site B

6 CONCLUSION

A piled raft was used as the remedial solution for a railway embankment constructed on soft clay where stability failure occurred after ground improvement works had been conducted. Design issues and approaches adopted for the design of piled raft were outlined. The effect of ground movements due to consolidation is very important as it causes downdrag forces in piles and lead to considerable settlement of foundation.

A detailed monitoring programme was conducted and monitoring results showed that the adopted piled raft foundation performed satisfactorily. Results indicated that most of the settlement occurred during the placement of additional embankment fill over the piled raft. The vertical drains installed in the early stages contributed to the acceleration of consolidation rate. The measured and observed behaviour of the piles differed considerably, and unexpectedly, the measurements showed that the soil and pile were deforming laterally towards the embankment. The discrepancies between the measured and observed behaviour are likely to be due to some of the simplifying assumptions made in the numerical modelling procedures used for the predictions, Nevertheless, the success achieved in remediating the embankment demonstrated the potential for using the piled raft concept for embankment construction on soft ground, both for a primary design solution or a remedial works solution.

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