Performance of Reinforced Concrete Raft to Remedy 'Mushroom' Problem of Piled Embankment with Individual Pilecaps on Soft Ground

S.S. Gue, C.M. Chow & S.W. Cheah
G&P Geotechnics Sdn Bhd, Wisma G&P, 39-5 Jalan 3/146, Bandar Tasik Selatan, Kuala Lumpur, Malaysia.
gnp-geo@gnpgroup.com.my

Nik Airina & Mohd. Zulastri
PLUS Expressways Berhad, Kuala Lumpur Malaysia.

Abstract: Piled embankment with individual pilecaps was constructed in the 1980's as part of the expressway in the Northern State of Malaysia. The embankment is underlain by a thick layer of very soft compressible fine-grained soils. The original design principle of this solution was intended to rely solely on the arching of embankment materials to transfer load to pilecaps as the soft compressible subsoil between pilecaps settled under consolidation. However, a few years after the expressway was opened to traffic, the embankment continued to experience large differential settlement in the form of localised depressions that required regular maintenance and repaving. The depressions coincided with the area where there is no pilecap beneath the embankment. The protruding parts of the embankment at pilecaps with continuing settlement between pilecaps look like 'mushroom' and therefore the term is used to describe the problem. This paper presents an innovative method of using reinforced concrete (RC) raft near surface of the embankment to treat the problem and to prevent recurrence of differential settlement. A full-scale instrumented trial was carried out to verify the proposed remedial works. The instrumentation monitoring results of about two years are presented and discussed in this paper. The instrumentation results indicate that the reinforced concrete raft remedial measure is effective in reducing the total settlement and the differential settlement of the expressway embankment.

1 INTRODUCTION

Piled embankment with individual pilecaps was constructed in the 1980's as part of the expressway in the Northern State of Malaysia. The original design principle of this solution was intended to rely solely on the arching of the embankment materials to transfer the load to the pilecaps as the soft compressible subsoil between the pilecaps settled under consolidation. However, a few years after the expressway was opened to traffic, the embankment continued to experience large differential settlement in the form of localized depressions that required regular maintenance and repaving. The protruding parts of the embankment with pilecaps 'punching through' the embankment looks like 'mushroom' and therefore, the term is used to describe the problem. Figs. 1 and 2 show features of the 'mushroom' problem. Meanwhile, Fig. 3 shows the differential settlement ('mushroom') observed between the area with pilecaps and without pilecaps after excavation depth for about 300mm.

Fig. 1 'Mushrooms' observed at median of expressway. (Note: 'Mushrooms' was not observed along carriageway due to regular repaving works)

Fig. 2 'Mushrooms' and undulating surface on expressway

2 SUBSOIL CONDITIONS

The area where the 'mushroom' problems are prominent is predominantly in areas underlain by Quaternary age deposits and comprises of marine deposits such as clay, silt, sand and sea shells. The alluvium deposit mainly consists of very soft to soft silty CLAY and clayey/sandy SILT with the presence of intermittent sand layers, sea shells and some wood remnant. The deposition environment of the Quaternary deposit is believed to be from marine environment. Figure 4 shows the general geology of the site.

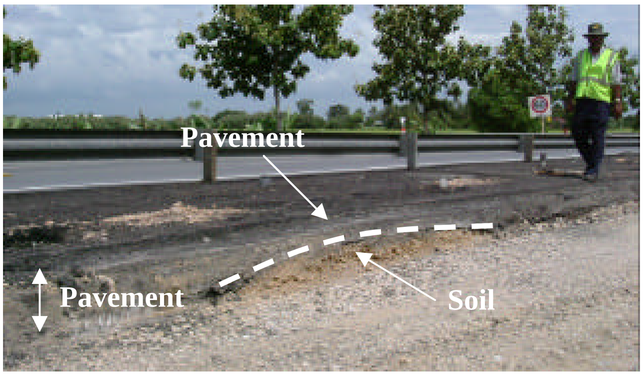

Fig. 3 Differential settlement observed after excavation to depth of about 300mm.

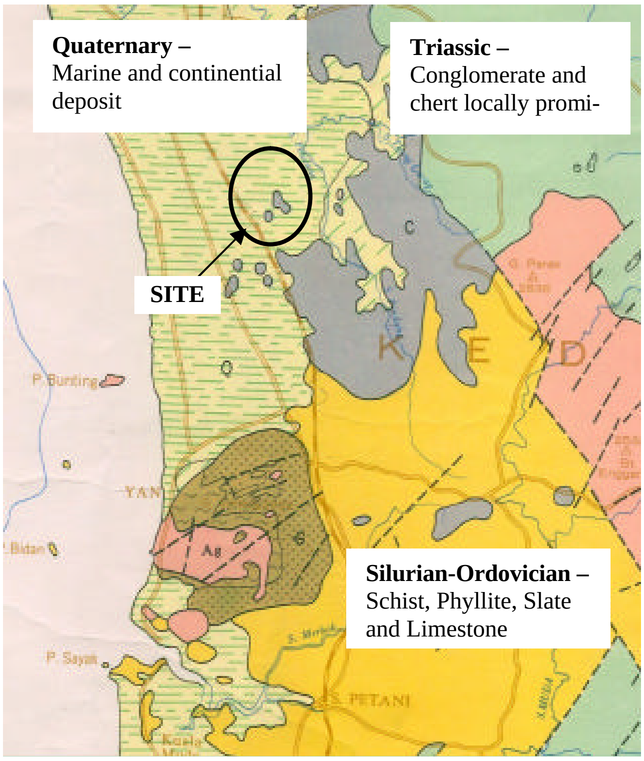

Fig. 4 General geology of site.

Table 1 Shear strength parameters of marine deposits.

Depth from OGL (m)	γ_{bulk} (kN/m^3)	γ_{dry} (kN/m^3)	ϕ' (°)	c' (kPa)	S_u* (kPa)
0 – 7.5	15.8	12.0	22	3	16.0
7.5 – 12.5					22.5
12.5 – 17.5					35.0
17.5 – 22.5					47.0

*Note: The undrained shear strength obtained from vane shear tests are corrected in accordance to recommendations by Bjerrum (1973) for stability analysis of embankments to cater for difference in rate of shearing of the subsoil in vane shear tests and in the field and strength anisotropy.

Table 2 Consolidation parameters of marine deposits.

Depth from OGL	OCR	c_v (m^2/year)	c_h (m^2/year)
0 – 2.5	7	3.0	12.0
2.5 – 7.5	1.6		
7.5 – 22.5	1.2		

Table 3 Modified critical state parameters of marine deposits.

Depth from OGL	λ*	κ*	μ*
0 – 2.5	0.18	0.05	0.007
7.5 – 12.5	0.18	0.065	0.007
12.5 – 22.5	0.22	0.075	0.0085

The original subsoil conditions of the site were obtained from a series of subsurface investigation carried out in September 2001 and October 2002 with boreholes, piezocones, Mackintosh probes, hand augers and vane shear tests. The shear strength parameters, consolidation parameters and modified critical state parameters (Vermeer & Neher 2000) for design and analysis are summarized in Tables 1, 2 and 3 respectively.

Undisturbed block sampling was also carried out at the embankment fill areas to determine the properties of the fill materials. Sieve analyses carried out have indicated that the fill materials consist of sandy or gravelly silt/clay with relatively high percentage of fines (up to a maximum of 99%). Shear box tests were also carried out and the results indicated effective stress parameters for the embankment fill materials of c' = 2kPa and ϕ' = 25°.

3 ANALYSIS OF 'MUSHROOM' PROBLEMS

The analysis of 'mushroom' problems were carried out using two-dimensional (2D) and three-dimensional (3D) PLAXIS softwares (Brinkgreve 2002 and Brinkgreve 2001), which are general finite element method (FEM) programs for geotechnical analyses to determine the possible causes of the problems. A typical FEM model adopted for the analysis is shown in Figs. 5 and 6 respectively.

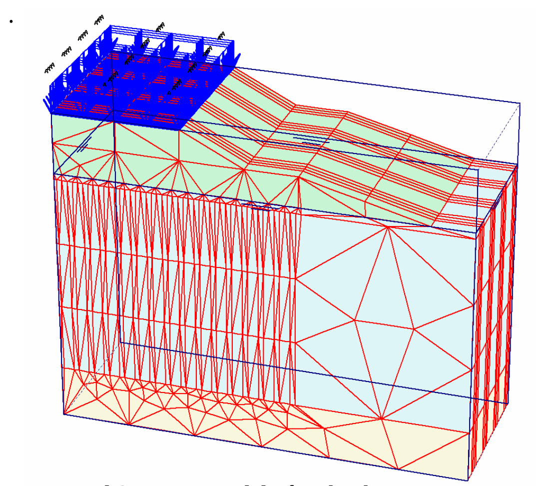

Fig. 5 Typical 3D FEM model of embankment.

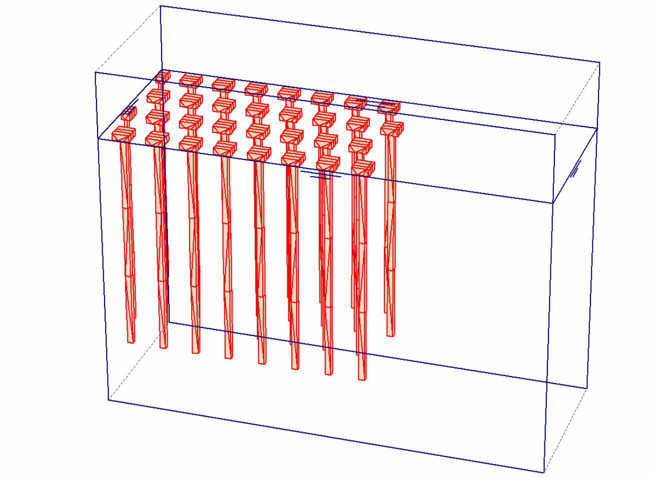

Fig. 6 Typical 3D FEM model of piles and pilecaps.

In the model, the circular spun piles beneath the embankment are modelled as linear elastic/drained material with properties defined by Young's Modulus and Poisson's ratio. The piles are assumed to penetrate into the stiff stratum. In both the 2D and 3D analyses, the soft clay subsoils are modelled using Soft Soil Creep Model which resembles the Modified Cam-Clay model with isotropic hardening. The fill material is modelled using the Hardening Soil model (Schanz et al. 2000).

Results from the analyses have shown that the differential settlement of the embankment ranges from 64mm to 156mm with angular distortion as high as high 4% (1/25). This is in excess of the recommended values of 1% (1/100) by BS8006 (1995). Typical results from the FEM analyses showing the 'mushroom' problem are shown in Figs. 7 and 8.

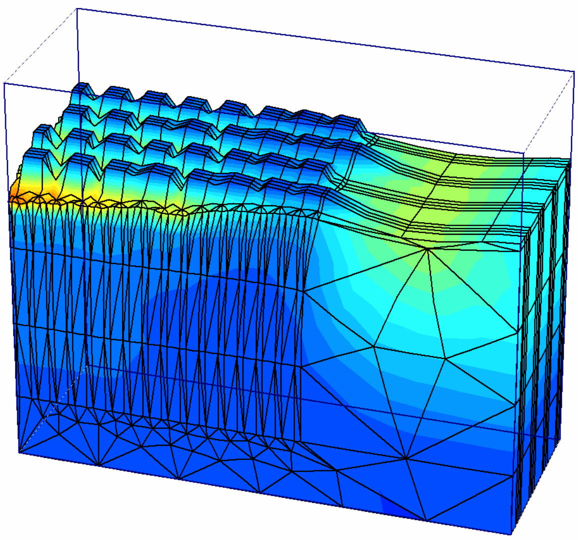

Fig. 7 Results of 3D FEM analyses showing 'mushroom' problems (top view).

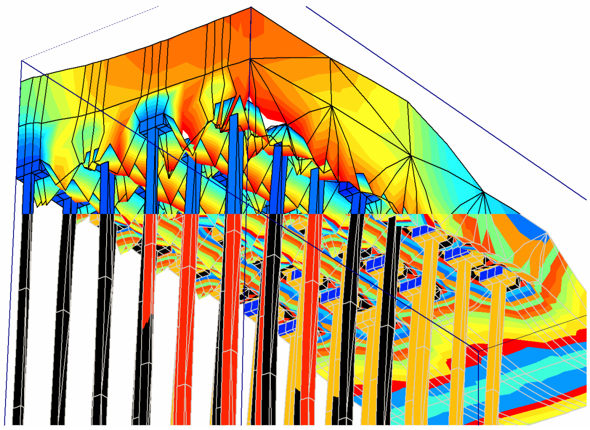

Fig. 8 Results of 3D FEM analyses showing 'mushroom' problems (bottom view).

Settlement profile along a typical section of the embankment showing the computed differential settlement and angular distortion is also plotted in Fig. 9.

In summary, results of FEM analyses have shown that the 'mushroom' problems arise due to ineffective arching mechanism influenced by the following factors:

a) Unsuitable fill materials
b) Large pile spacing to the height of fill

The FEM results are also consistent with findings from Hewlett and Randolph (1988) and Koutsabeloulis & Griffiths (1989) who showed that pile spacing (or size of voids) and properties of fill materials are important to ensure effective arching mechanism.

3 REMEDIAL DESIGN

The occurrence of the 'mushroom' problems has necessitated regular repaving works to ensure the riding comfort and safety of the expressway. However, repaving works are only short-term solution as the embankment will continue to settle due to additional loads from the pavement. Therefore, the remedial design for the 'mushroom' problems shall satisfy the following criteria:

a) Minimum disturbance to operation of the expressway.
b) Simple and fast to construct.
c) Cost effective.
d) Minimum long-term maintenance.

After reviewing all the feasible options such as high strength geogrid with granular infill (on top of pilecaps or at shallow depths) and reinforced concrete raft (on top of pilecaps or at shallow depths), it is found that reinforced concrete (RC) raft at shallow depth offers the best solution to the 'mushroom' problems based on the above criteria.

The design was carried out using FEM analyses to achieve the required long-term angular distortions of less than 1% (1/100) as recommended by BS8006 (1995). Results of FEM analyses have indicated that the angular distortion of the embankment is below 1% upon construction of the RC raft.

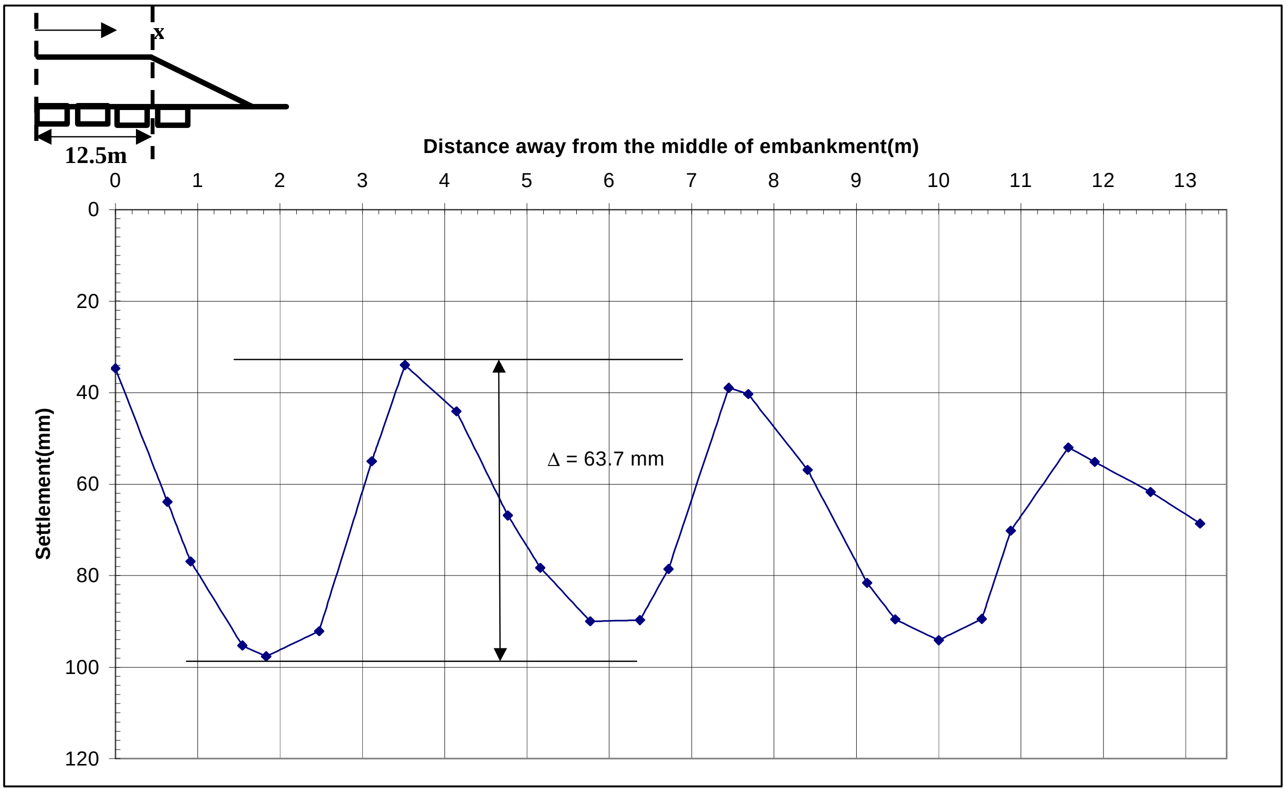

Fig. 9 Settlement profile before remedial treatment across the embankment.

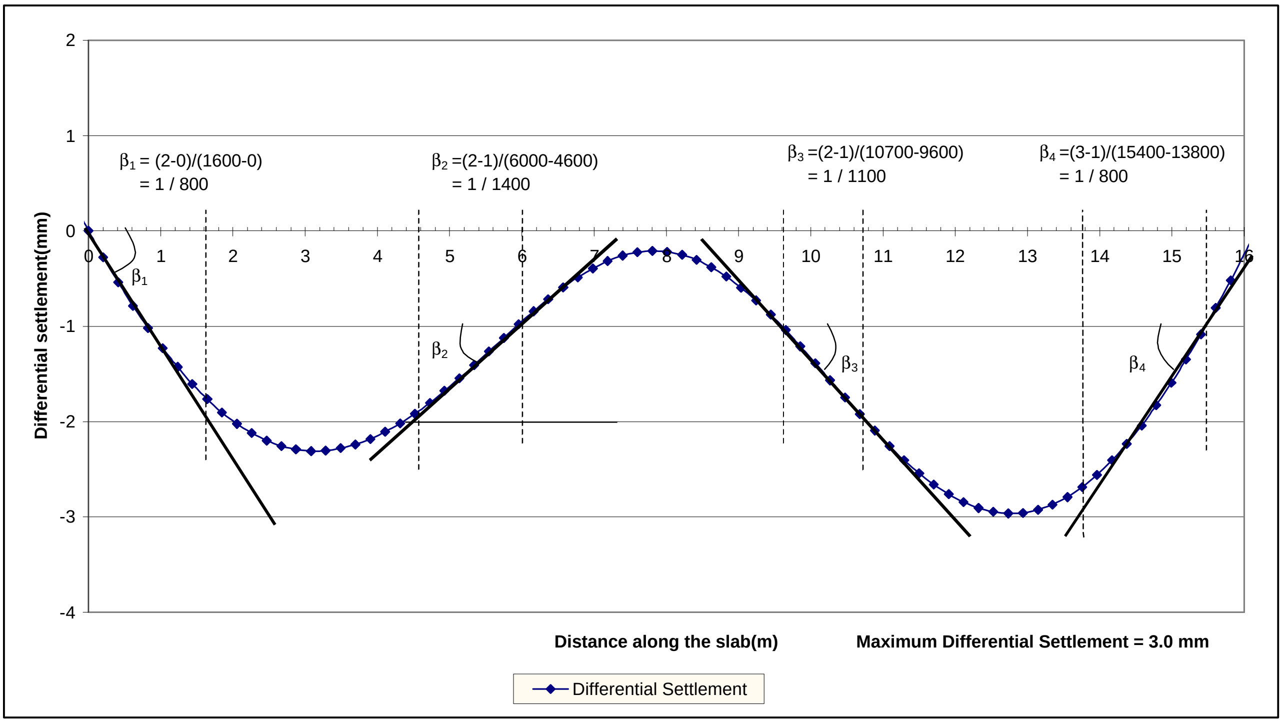

Fig. 10 Settlement profile after remedial treatment across embankment using RC raft at shallow depth
(Note: vertical scale has been exaggerated).

Fig. 10 shows typical results from the FEM analyses with the computed angular distortions and maximum differential settlement. In summary, the RC raft at shallow depth solution adopted consists of:

a) Raft thickness = 250mm to 300mm depending on embankment characteristics (height, pile spacing etc.)
b) Reinforcement required = T16 – 150mm c/c (Top & Bottom)
c) Characteristic concrete strength = $35N/mm^2$

The structural design of the RC raft is based on the bending moments obtained from the FEM analyses with an applied loading of 10kPa as traffic loading. The stages of construction simulated in the analysis are as follows:

a) Stage 0: Initial Condition of the Subsoil (before construction).
b) Stage 1: Installation of Piles and Pilecaps.
c) Stage 2: Filling of the Embankment and Consolidate for 20 years.
d) Stage 3: Construction of RC Raft.
e) Stage 4: Consolidate until Drained Condition.

It is to be noted that the reinforcement are deliberately arranged uniformly throughout the slab due to difficulties in quality control at site and the difficulties in accurately determining the position of as-built pile position. The proposed solution is subjected to a comprehensive programme of monitoring to validate its effectiveness and possible optimization of design for future implementation.

4 COSTRUCTION SEQUENCE

The RC raft solution at shallow depth essentially involves the following simple construction sequence:

a) Excavating of minimal depth for the concrete raft and wearing course. This is typically less than 500mm as the thickness of the concrete raft is approximately 300mm and thickness of wearing course is 50mm (total ~350mm) and can be easily and speedily carried out using a milling machine.
b) Laying of steel reinforcement and casting of concrete.
c) Laying of wearing course.

The simple construction sequence is very important for this site due to its location within a busy expressway. Therefore, the simple construction sequence will minimize lane closure for the construction works. In addition, the remedial solution is easy to construct and does not require specialist contractor's input. Typical construction sequence of the works for a recently completed pilot stretch is shown in Figures 11 to 16. The section of the expressway with an area of $1500m^2$ was completed in 1.5 months from milling to laying of ACWC and application of road marking. It must be noted that the laying of reinforcement, concreting works and curing time is the major time consuming activities of the work and as such, a trial using precast concrete raft has been carried out in early 2006 where the construction time has been shortened to just 2.5 weeks for an area of $2500m^2$.

Fig. 11 Milling works in progress

Fig. 12 Completed base.

Fig. 13 Laying of steel reinforcement.

Fig. 14 Concreting works in progress.

Fig. 15 View of completed RC raft.

Fig. 16 Pavement works completed and traffic reopened.

5 INSTRUMENTATION MONITORING SCHEME

An instrumentation monitoring programme consisting of the following instruments was carried out from August 2004 to April 2006 to validate the effectiveness of the RC raft remedial measures: -

a) Settlement Markers
b) Inclinometers
c) Sisterbar Embedment Strain Gauges

Fig. 17 shows the layout plan of instrumentation monitoring works.

5.1 *Settlement Markers*

Figs. 18 and 19 show the plots of settlement markers (on adjacent ground and pavement surface) and raft settlement markers (on reinforced concrete raft) at the treated and untreated bound. As shown in Figures 18 and 19, the differential settlement of the treated bound (8mm) is lesser than the differential settlement of the untreated bound (18mm) where the total settlement of the treated bounds is also lesser as compared to the untreated bounds.

Table 4 tabulates the measured maximum angular distortions of the treated bound and untreated bound respectively. The results indicate that the measured maximum angular distortions of the treated bounds are less than 1/100 as required by BS8006. The angular distortions measured to date ranges from 1/1201 to 1/2380 which is smaller than 1/100. Meanwhile, the maximum angular distortions recorded for the untreated bound is 1/658 which is significantly larger than the treated bound.

Hence, the reinforced concrete raft treatment is effective in controlling the total settlement, differential settlement and angular distortion of the expressway based on the instrumentation monitoring results.

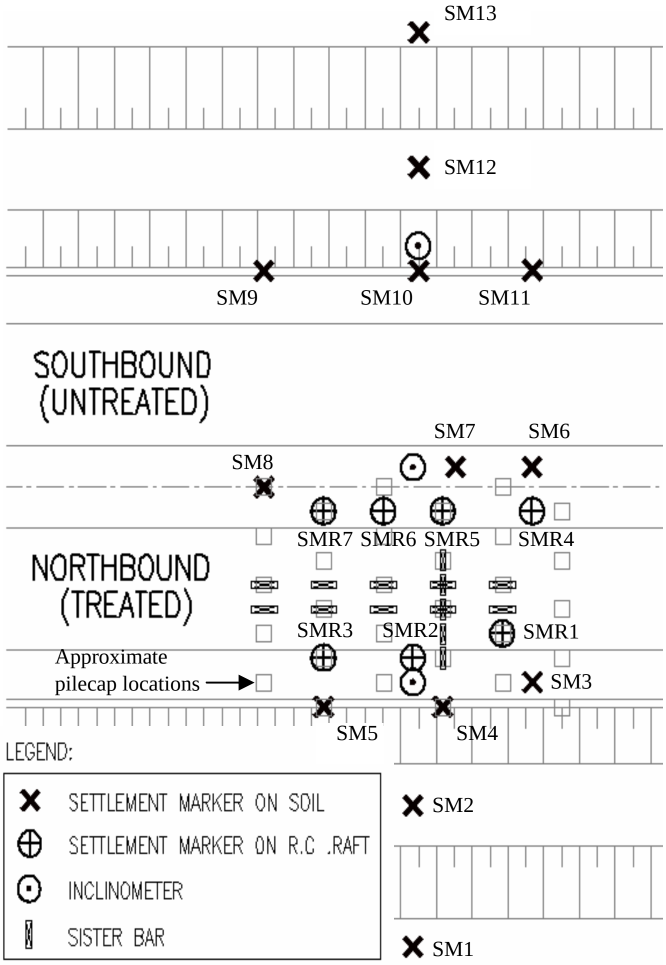

Fig. 17 Layout plan of instrumentation monitoring

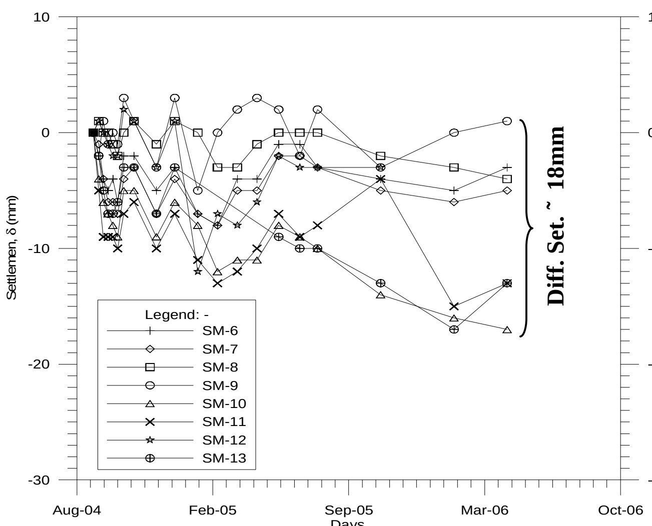

Fig. 18 Settlement markers at untreated bound

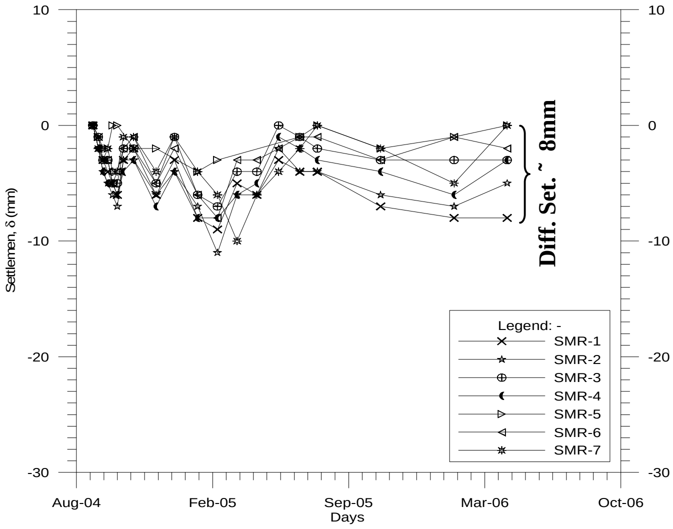

Fig. 19 Settlement markers at treated bound

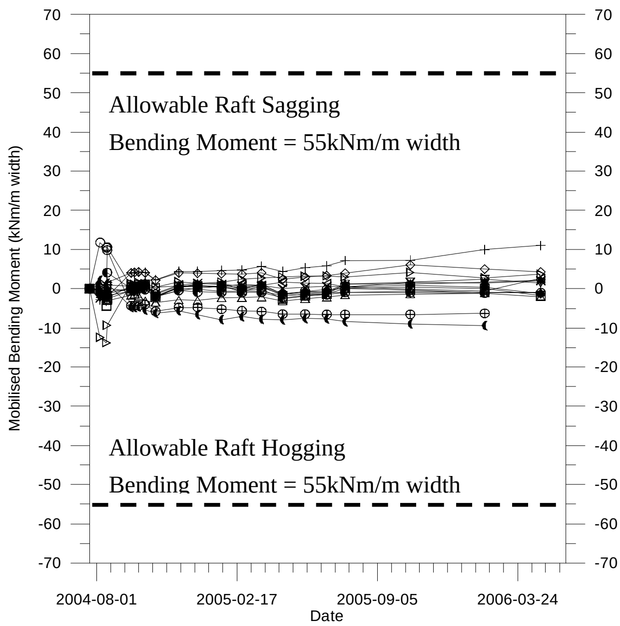

Fig. 20 Interpreted mobilized bending moment

Table 4 Measured maximum angular distortion (treated bound)

Settlement Marker	Max. Angular Distortion
SMR-01	1V : 1201H
SMR-02	1V : 1723H
SMR-03	1V : 2380H
SMR-04	1V : 1329H
SMR-05	1V : 1201H
SMR-06	1V : 1842H

5.2 *Inclinometer*

The observed displacement of the inclinometers at the end of monitoring is less than 2mm which indicates that the monitored embankment has no stability issue.

5.3 *Sisterbar Embedment Strain Gauges*

Fig. 20 shows the interpreted mobilised bending moment of reinforced (RC) concrete raft where the maximum mobilised bending moments are 11kNm/m width. The mobilised bending moment of the RC rafts are found to be lesser than the allowable raft bending moment of 55kNm/m width which indicates that the reinforced concrete raft is effective in evenly distributing the stress induced by the traffic.

Based on the monitoring results, further optimization of the design may be possible. However, the optimization carried out shall also take into consideration the serviceability limit state, i.e. differential settlement of the RC raft.

6 CONCLUSION

Piled embankment on individual pilecaps was constructed over soft compressible subsoil in the 1980's in the Northern State of Malaysia as part of the North-South Expressway. The design principle relies on arching mechanism of the embankment fill materials to transfer the loads to individual pilecaps. However, differential settlement on the expressway forming 'mushroom' has indicated that the arching mechanism is ineffective. Analyses have indicated that the ineffective arching mechanism is due to:

a) Unsuitable fill materials
b) Large pile spacing to the height of fill

An innovative method of using RC raft at shallow depth has been used to remedy the 'mushroom' problems. Besides its technical superiority as demonstrated by results of FEM analyses, the method is also attractive as it is:

a) Minimum disturbance to operation of the expressway.
b) Simple and fast to construct.
c) Cost effective.
d) Minimum long-term maintenance.

An instrumentation monitoring programme was carried out from August 2004 to April 2006 to validate the effectiveness of the RC raft remedial measure. The results of the instrumentation monitoring programme showed that the adopted RC raft remedial measure is effective in reducing the total settlement, differential settlement and angular distortion of the expressway. This shows that the RC raft is effective in evenly distributing the stress induced by the traffic.

REFERENCES

Brinkgreve, R.B.J. 2001. PLAXIS 3D, Balkema, Rotterdam.

Brinkgreve, R.B.J. 2002. PLAXIS 2D-Version 8, Balkema, Rotterdam.

British Standard Institution, BS8006: 1995: Code of Practice for Strengthened/Reinforced Soils and Other Fills.

Hewlett, W.J. & Randolph, M.A. 1988. Analysis of piled embankments, *Ground Engineering*, Vol. 21, No. 3, pp. 12-18.

Koutsabeloulis, N.C. & Griffiths, D.V. 1989. Numerical modelling of the trap door problem, *Geotechnique*, Vol. 39, No. 1, pp. 77-89.

Schanz, T., Vermeer, P.A. & Bonnier, P.G. 2000. The hardening soil model: Formulation and verification, Beyond 2000 in Computational Geotechnics – 10 Years of PLAXIS International, Balkema, Rotterdam.

Vermeer, P.A. & Neher, H.P. 2000. A soft soil model that accounts for creep, Beyond 2000 in Computational Geotechnics – 10 Years of PLAXIS International, Balkema, Rotterdam.