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Use of dry deep soil mixed columns for bridge approach embankments and piles on soft clay

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ABSTRACT: Dry Deep Soil Mixed (DDSM) ground improvement columns were constructed into soft clays to reduce settlements and lateral movements at various bridge approaches of a major project in northern New South Wales, Australia. This paper presents the analysis and design procedure of DDSM columns, and its performances obtained from field instrumentation monitoring results including total settlements and lateral movements for a bridge approach embankments. Field monitoring results revealed that the settlement and lateral movement of soft clay treated with DDSM columns reduced significantly compared to untreated clay. The results also showed that observed settlement was much lower than the predicted values both in the full depth and floating DDSM columns areas. This ground improvement technique provided a cost effective solution that allowed embankments and bridge piles to be constructed in shorter time periods, and met design settlement and lateral movement requirements at the bridge approach embankments and piles.

1 INTRODUCTION

Construction of high embankments at bridge approaches over soft clay is known to cause large total and differential settlements, lateral movement, and excess pore-water pressures. As the bridge abutments are typically supported on piles installed into very competent soil or rock with minimal settlement, differential settlement between the piled abutment and approach embankment on soft clay are difficult to avoid and may result in an abrupt change in grade on the road surface. Down drag forces due to excessive settlement and embankment induced lateral loading on the abutment piles also occur under these circumstances. The end results affect driver comfort and certainly increase maintenance costs of embankment and bridge piles, if suitable ground improvement measures are not taken over a longer transition zone (Kamruzzaman et al. 2019; Kelly and Wong, 2012).

The construction of approximately 12km dual carriageways with several bridges and culverts of a major project in northern NSW Australia have completed in early 2009. In this project, some of the bridge approach embankments are founded on soft clays up to a thickness of about 28m. The design requirements for the approach embankments are to ensure a maximum post construction settlement of 50mm in 40 years near the abutments and differential settlement of 0.5% change in grade over the transition length. Furthermore, bridge abutment piles are to ensure that down drag forces and embankment induced lateral movements are not affecting 100 years design life of the piles. Due to these stringent settlement and lateral movement requirements, the Dry Deep Soil Mixed (DDSM) column ground improvement technique was adopted to treat the soft clays at a number of bridge approaches. The principle of DDSM method is to cut a column of soft soil by rotating blades, then force cement powder into the ground and mechanically mix the cement with disturbed soil to form a soil-cement column in-situ at depths. This soil-cement column helps to increase the rate of primary consolidation settlement, reduce the post-construction settlement/lateral movement and increase the stability of the approach embankment. In this method of ground improvement, embankment load must be lesser than the apparent yield stress of the soil cement columns (Kamruzzaman et al. 2009; Chew et al. 2004). This paper presents the analyses and design procedures of DDSM columns ground treatment, and its performances obtained from field instrumentation monitoring results for a bridge approach embankments of a project in northern NSW Australia.

2 GEOTECHNICAL MODEL AND DESIGN PARAMETERS

In general, the ground consists of a firm to stiff upper alluvial crust clay layer ranging in thickness from 0.5m to 2m overlies soft estuarine Holocene clay and very stiff Pleistocene clay. The estuarine material has clay content in excess of 60%, moisture content in the range of 60% to 140%, an organic content of 2% to 5% and sensitivity of 2 to 5. The depth of the soft clay ranges from 6m to 28m. The clay has low strength, high compressibility and low permeability. Table 1 shows typical strength and compressibility properties of various geological units at the bridge approach embankment.

Table 1. Typical geotechnical model for the bridge approach embankment.

Soil type/unit	Sub-layer Thickness (m)	CR[1]	CRR[2]	OCR[3]	$C_{\alpha\varepsilon}$ (n/c)[4]	S_u (kPa)[5]
Upper crust- Unit 2b	0.5	0.35	0.05	66	0.015	26
	0.5	0.35	0.05	9.3	0.015	13
Soft clay -Unit 2a	1.0	0.35	0.05	6	0.015	13
	2.0	0.35	0.05	3.3	0.015	12
	1.0	0.35	0.05	2.3	0.015	12
	2.0	0.35	0.05	2.8	0.015	18
	2.0	0.35	0.05	2.4	0.015	20
	1.5	0.35	0.05	2.2	0.015	22
Silty Sand-Unit 2e	1.0	0.08	0.02	10	0.008	
Stiff to very stiff clay-Unit 5b	4.5	0.3	0.04	6	0.009	75
	3.0	0.3	0.04	4.5	0.009	75
	8.0	0.3	0.04	5.4	0.009	120
	12.0	0.3	0.04	4.4	0.009	150
Residual Soil-Unit 6	2.0	0.1	0.015	3.4	0.006	150

Notes: CR[1]=Compression ratio= $c_c/(1+e_0)$, RR[2]=Recompression ratio= $c_r/(1+e_0)$, OCR[3] = Over consolidation ratio $C_{\alpha\varepsilon}$[4]=Creep strain ratio= $c_\alpha/(1+e_0)$, s_u[5] = undrained shear strength

3 DSM DESIGN METHODOLOGY AND CONFIGURATIONS

The design requirements for the bridge approach embankments are shown in Figure 2. Accordingly, post construction settlement (PCS) is limited to 50mm in 40 years within the 6m approach slab of the bridge abutment. This is referred to as Zone 1. The zone behind the approach slab (i.e. Zone 2) is required to satisfy 0.5% maximum change in grade in any direction to tie in with the low embankment (i.e. so called Zone 3). Furthermore, bridge abutment piles are to ensure that down drag forces and embankment induced lateral movements are not affecting 100 years design life of the piles. Accordingly, the structural design has assumed pile lateral deformation of 20mm over 100 years.

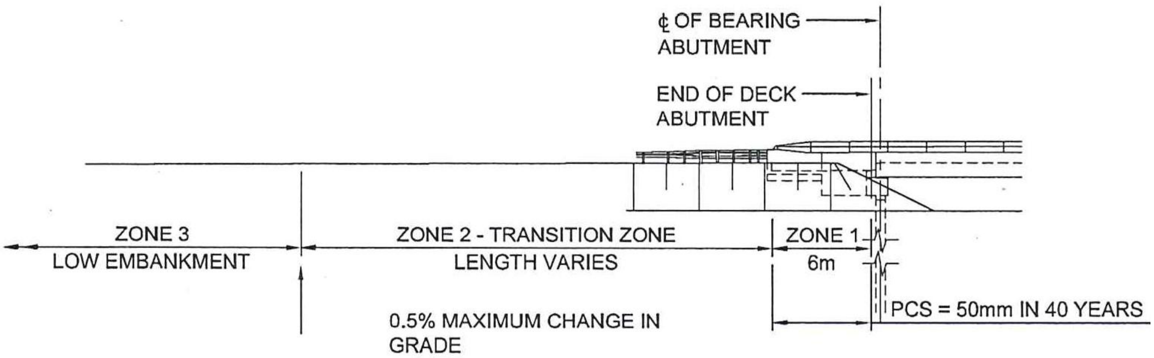


Figure 2. Schematic diagram of design requirements at the bridge approach embankment.

The design method assumes that the columns are homogeneous in geometry, strength and stiffness. The embankment loads are distributed to the columns and soil according to their relative stiffness. In accordance with SGF 4:95E (1997), the loads applied to the columns are kept to less than 75% of the theoretical ultimate column strength to prevent yielding and excessive creep. Primary and creep settlements were calculated using an equivalent block of treated ground determined from the area replacement ratio, and equivalent stiffness of the untreated soil and DSM columns (i.e. $M_{eqv}= a_rM_{col} + (1-a_r)M_{soil}$,, where M_{col} and M_{soil} are the constrained modulus of DDSM column and soil respectively, and a_r is the area replacement ratio). The design column shear strength adopted below the crest and batter were 150 and 100kPa respectively. Furthermore, the column modulus was assumed to be 200 times the design column shear strength, and the soil modulus was assumed to be 150 times the undrained shear strength of the soil. Stability of DSM treated embankment was also calculated using an equivalent undrained shear strength approach (i.e. $C_{eqv} = a_r C_{col} + (1-a_r) C_{soil,}$ where C_{col} and C_{soil} are the undrained shear strength of DSM column and soil respectively, and a_r is the area replacement ratio). Using the above methodology, settlements were calculated using an in house developed spread sheet and Finite Element program Plaxis, while stability was calculated using Slope/W program. The DDSM design parameters used in the project are summarized in Table 2.

Table 2. DDSM column design parameters.

Parameters	Value
Bulk unit weight, γ_b	20 kN/m^3
Column Shear Strength, C_{col}	$C_{col(crest)}$ = 150 kPa $C_{col(batter)}$ = 100 kPa
Area Replacement Ratio, a_r	30% (crest and batter)
Constrained modulus, M_{Col}	$M_{col(crest)}$ = 30 MPa $M_{col(batter)}$ = 20 MPa
Permeability, k	500 x permeability of untreated clay

A schematic DDSM plan and longitudinal section for the bridge approach embankment is shown in Figures 3 and 4 respectively. As can be seen, the DDSM column arrangement comprises of square and panel configurations corresponding to zones beneath the embankment crest and the embankment batter, respectively. Under the crest of the embankment, full depth and floating columns of 800mm diameter were constructed at 1.3m square centres. While, only full depth columns having in panel configuration at 2.5m centres with 100mm overlap were constructed under the batter of the embankment. All columns were constructed at an additional 0.5m depth into stiff to very stiff clay using a maximum cement powder dose of about 160kg/m^3. After leaving the installed column in-situ for a period of at least 28 days, embankment fill was placed gradually to a design height of about 6.6m.

4 SETTLEMENT ANALYSES

Settlement analyses of DDSM ground treatment for the eastern and western approaches of the bridge were carried out using the method described in section 3 above. A total of 3 months preloading period was adopted for the entire DDSM areas according to the construction programme. The analyses results are presented in Tables 3 and 4.

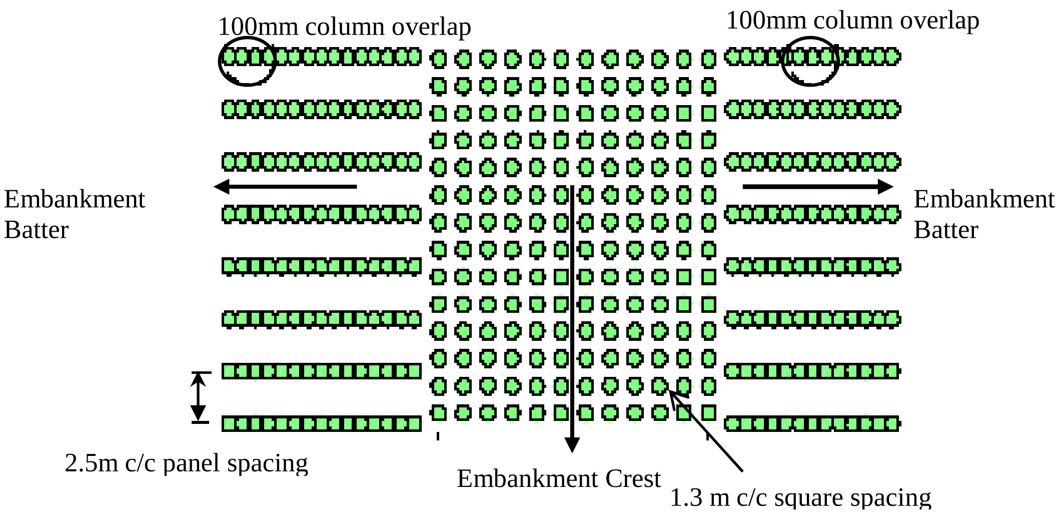


Figure 3. DDSM plan arrangement at the bridge approach embankment.

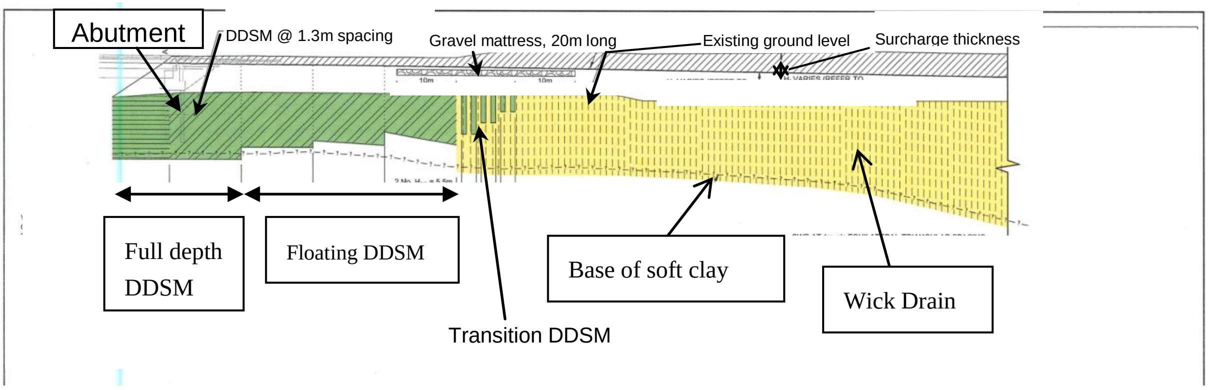


Figure 4. Bridge approach embankment long section with full depth and floating DDSM columns (wick drain design are not part of this paper)

Table 3. Summary of predicted settlement at the western approach embankment.

Chainage Analysed CH (MC30)	Total fill thickness (m)	Depth of soft clay beneath DDSM, (m)	Area replacement ratio, a_r (%)	Settlement during construction (mm)	10yr PCS (mm)	40yr PCS (mm)	100yr PCS (mm)
610	6.6	0.0 (full depth DDSM)	30 (crest and batter)	450	30	43	60
584	6.6	2.0 (floating DDSM)	30 (crest and batter)	550	55	-	-
560	6.6	3.0 (floating DDSM)	30 (crest and batter)	680	95	-	-

Table 4. Summary of predicted settlement at the eastern approach embankment.

Chainage Analysed, CH (MC30)	Total fill thickness (m)	Depth of soft clay beneath DDSM, (m)	Area replacement ratio, a_r (%)	Settlement during construction (mm)	10 yr PCS (mm)	40yr PCS (mm)	100yr PCS (mm)
760	6.0	0.0 (full depth DDSM)	30 (crest and batter)	360	30	43	60
786	6.0	2.0 (floating DDSM)	30 (crest and batter)	480	75	-	-
810	6.0	3.5 (floating DDSM)	30 (crest and batter)	560	105	-	-

5 STABILITY ANALYSES

Embankment stability checks were carried out using the Slope/W computer program, and equivalent shear strength parameters obtained from the methodology described in section 3 at different locations of both abutment approaches. Short term and long term factor of safeties are analysed considering the depth of DDSM improved ground are about 11m for the western approach and 10m for the eastern approach respectively. The results of the analyses are given in Table 5.

Table 5. Summary of stability analyses.

Abutment approach	Chainage analysed, CH (MC30)	Total fill thickness (m)	Estimated depth of treatment below batter (m)	Type of treatment	Factor of safety
Western	610	6.6	10.5	DSM	1.32 (1.57)
Eastern	760	6.0	11.5	DSM	1.43 (1.64)

Note: Factor of safety in ( ) refers to drained analysis in DDSM areas.

6 FIELD MONITORING RESULTS AND DISCUSSIONS

Series of instruments including settlement plates, extensometers, vibrating wire piezometers and inclinometers were installed to monitor the performance of DDSM treated embankments at the Western and Eastern Bridge abutments as shown in Figure 5.

6.1 *Settlements*

Settlement Plates having 500mm square size were installed at the interface between fill and existing ground surface to monitor vertical movement. The settlement plates were installed as soon as possible after construction of the access platform so that the majority of the settlement caused by the access platform was measured. Figures 6a and 6b show the settlement monitoring results for the Western and Eastern approach embankments. As can be seen in both cases, the primary consolidation settlement completed within 3 months after the full height of embankment was reached. The measured settlements were found to be lower than the predicted values as shown in Table 6. The creep settlement for DDSM treated soil is expected to be negligible. Back-analysis of the monitoring data and future projection of the settlement results also indicates that the post-construction settlement should be within the design limits.

Furthermore, the monitoring results and the future projection showed that settlements progressively reduced as the embankments approach the bridge abutments. The results confirm the effectiveness of the varying DDSM column depth design to control differential settlement and to provide a "smooth" transition from the general embankment to the bridge abutment.

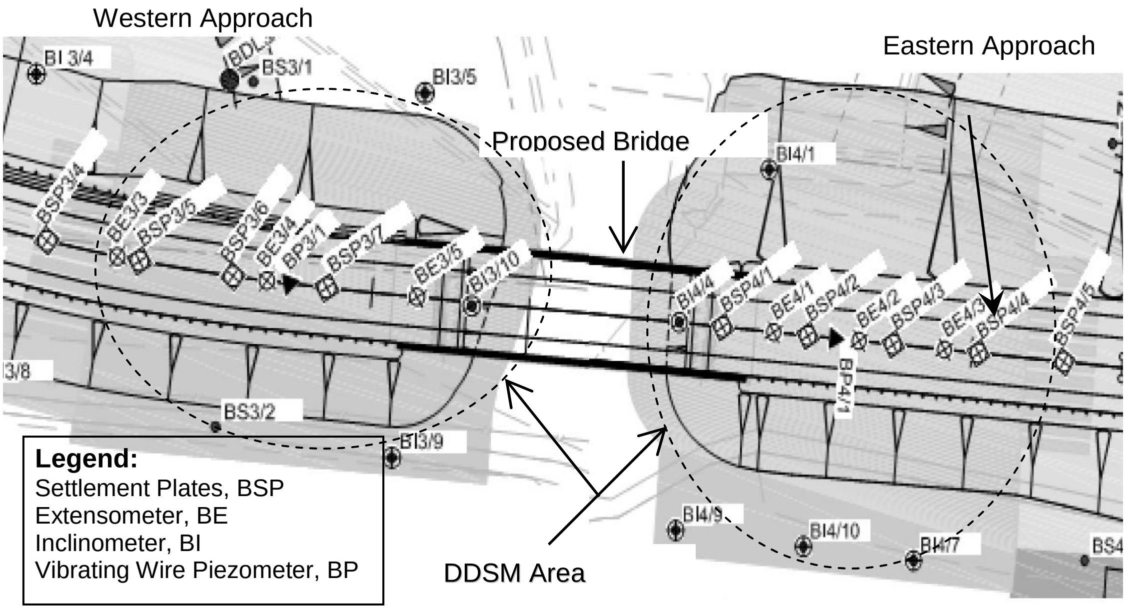
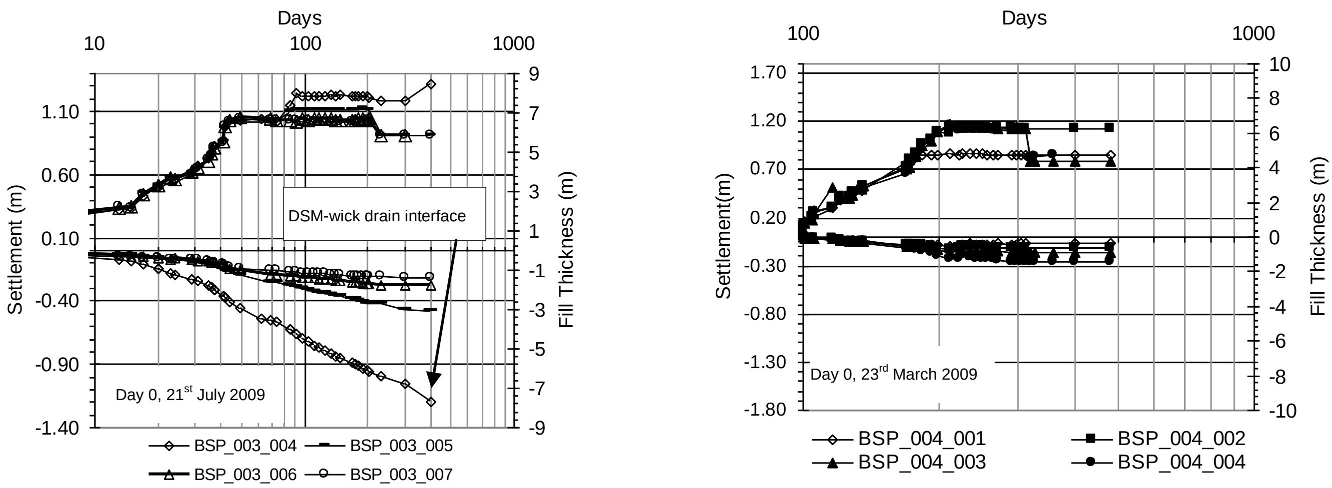


Figure 5. Instrumentation monitoring plan at the western and eastern bridge approach embankments.

Table 6. Comparison of predicted and measured settlement at bridge approaches.

Abutment Approaches	Embankment Fill Thickness (m)	Depth of Soft Clay (m)	Predicted Settlement without DDSM	Predicted Settlement with DDSM (mm)	Measured Settlement with DDSM (mm)
Western	6.6	11.0	1200	450-680	210 - 460
Eastern	6.0	11.0	1100	360-560	80 – 250



(a) (b)

Figure 6. Settlement monitoring results (a) Western bridge approach (b) Eastern bridge approach.

6.2 *Lateral Movements*

Inclinometers were installed either at the base of future batter slopes or within stability berms. They were installed in between the DSM columns once access is available and prior to earthworks filling. Figure 7 shows the maximum lateral ground movement obtained from Inclinometers BI 3/10 and BI 4/4 for the Western and Eastern approach embankments respectively.

These two particular inclinometer's results represent the ground movement just in front of the spill through abutments. Monitoring results suggest that the maximum lateral ground movements are in the range of 30 to 35mm in both cases, when embankment fill thickness reaches its maximum value. The changes of movements are found to be negligible with time, after reaching the fill thickness to its maximum height. These lateral movement results suggest that bridge piles will likely experience negligible movement in the service life, as pile lateral movements are far less than green field soil movement (i.e. likely satisfy 20mm design intent as mentioned in section 3).

In addition to the maximum lateral movement reported above, embankment stability were assessed using the ratio of maximum lateral movement to maximum settlement of the embankment crest (X_{max}/Y_{max}), which provides a better tool for assessing the plastic behaviour of the soils below the embankment. When the incremental ratio $\delta X_{max}/\delta Y_{max}$ approaches unity, it implies that the soil is undergoing undrained deformation, plastic flow is occurring and therefore imminent failure may occur (Tavenas and Leroueil, 1980). The field measurement suggests that the maximum ratio $\delta X_{max}/\delta Y_{max}$ is about 0.7 for both cases analysed as shown in Figure 7. Hence, embankment instability was not a significant concern.

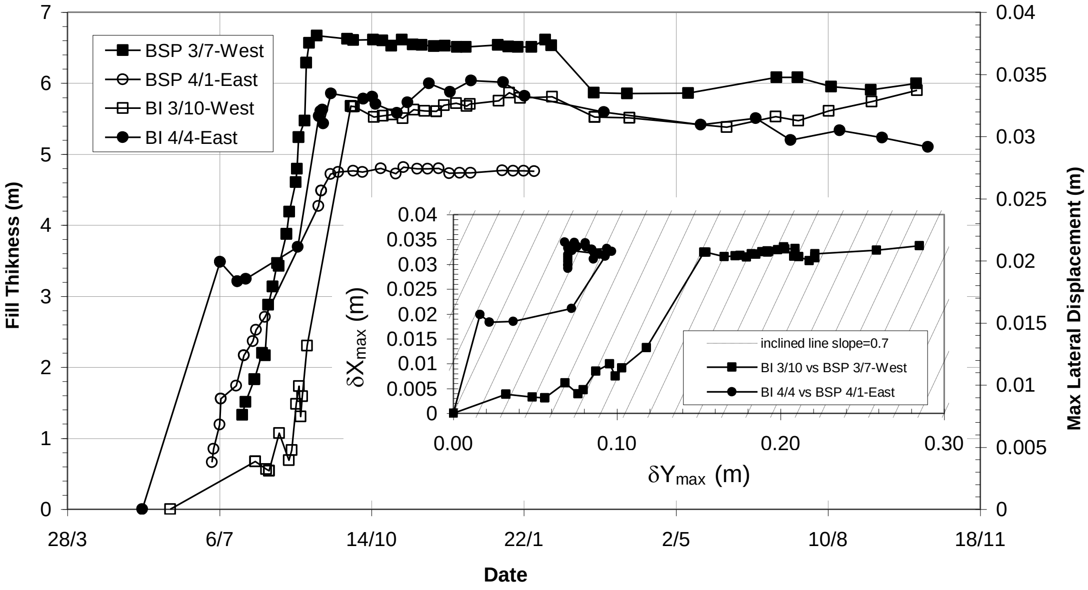


Figure 7. Lateral movement results at ECS bridge approaches.

7 CONCLUSIONS

Deep Dry Soil Mixed (DDSM) ground treatment columns have been constructed successfully for the treatment of various bridge approach embankments on soft clay of a major project in northern NSW Australia. Based on the case study presented, the following conclusions are drawn:

1. The soft clay deposits at the bridge approaches of the project have a high compressibility, low shear strength, and low permeability. Constructing highway embankments over these poor ground conditions would have resulted in large total and differential settlements at the bridge approaches if ground treatment using DDSM columns were not provided. DDSM column diameters of 800mm with a length up to 11m, and square pattern spacing of 1.3m was designed to control such settlements and lateral movements of the bridge approach embankments and piles.
2. Field monitoring results showed that the settlement and lateral movement of soft clay treated with DDSM columns reduced significantly compared to untreated clay. The results also revealed that observed settlement was much lower than the predicted values, both in full depth and floating DDSM columns areas.
3. The DDSM columns ground treatment technique allowed the construction of the embankments and bridge piles in a short period of time, with acceptable settlements at the bridge approach embankments and negligible impacts on the bridge piles. In this technique, bridge piles can be constructed ahead of embankment construction.

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