Proceedings of International Structural Engineering and Construction, 10(1), 2023
Innovative Theory and Practices in Structural Engineering and Construction
Edited by Karatas, A., Iranmanesh, A., Gurgun, A., Yazdani, S., and Singh, A.

ISSN: 2644-108X
www.doi.org/10.14455/ISEC.2023.10(1).INF-04

RAILWAY EMBANKMENT CONSTRUCTED ON SOFT DELTAIC DEPOSIT: LONG-TERM BEHAVIOR AND EFFECT OF TREATMENT

JOYA RANI MALLICK, SHAMONTEE AZIZ, IRAM LAMIYA HOQUE, TAMANNA-E-HAFIZ MAISHA, S.M. TAHSAN UL HAQ, and AFMS AMIN

BUET-JIDPUS, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

Railway construction over the soft soil of the active Ganges-Brahmaputra floodplain in the Padma Bridge Rail Link is the first of its kind in Bangladesh. A 2D finite element modeling using Plaxis investigated the long-term settlement behavior of ballast bottom as well as the factor of safety (FS) of this railway embankment. The contribution of cement-mixing piles (CMPs) in settlement reduction and FS improvement has been studied. Parametric study considers three train speeds, between 100–170 km/hr, and two soil profiles along different chainages: 82km+183m (Ch1) and 84km+102m (Ch2). The settlement of ballast bottom in both chainages are found higher in the long term, showing greater settlement in Ch2. Due to treatment, the short-term settlement of embankment bottom decreases by 13.8% at lower train speeds, and at 170 km/hr, the reduction increases to 18% and 16% for Ch1 and Ch2, respectively. The long-term settlement of ballast bottom is also reduced by 20% for lower speeds and 22% for a train speed of 170km/hr. CMP treatment is effective in settlement reduction, and the behavior was almost similar for both chainages, both short- and long-term. The treatment is seen to be more effective at higher train speeds. Due to treatment, increases of FS by 29–31% and 25–27% for Ch1, as well as 35–39% and 26–30% for Ch2, are obtained in the short and long term, respectively. The effect of treatment in providing stability is more prominent for Ch2 and its effect is also greater in the short term.

Keywords: Soft soil, Cement mixing pile, Settlement, Factor of safety.

1 INTRODUCTION

The construction of the Padma Bridge Rail Link (PBRL) is a challenging engineering endeavor that strives to establish connectivity over the Ganges-Brahmaputra Delta. The exceptional soft soil of this floodplain has made it difficult to attempt to build any rail track without providing sufficient strengthening to the subsoil (Hoque *et al.* 2023). Soft soil settlement characteristics can be improved by various artificial inclusions, which mainly include geogrids, geo-composites, shock mats, prefabricated vertical drains (PVDs), cement-mixing piles (CMPs), deep cement-mixed columns (DCMs), micro-piles, driven piles, vibro-concrete columns, or stone columns. These improve the bearing capacity of soft soil strata in the embankment by transferring the loads to firm layers. Some literature on railway track behavior encompasses both experimental and numerical studies on several geological strata, i.e., Bangkok soft soil (Likitlersuang *et al.* 2018), Sweden soft soil (Madshus and Kaynia 2000), Indian Marine Clay (Fulambarkar *et al.* 2021), and soft Ballina clay (Rezania *et al.* 2018). However, the soil characteristics of the Ganges-Brahmaputra floodplain significantly vary from these geological compositions, making it essential to analyze the rail track behavior under various train load conditions, as well as to assess the positive contribution of soil treatment.

In this study, the settlement behavior and safety-against-bearing failure of railway embankment constructed over soft deltaic deposits under varying train speeds have been investigated by numerical analysis in Plaxis 2D. The effect of installing CMP has been simulated in the 2D finite element model by modifying the material property of cement-treated soil, and a comparison is made on settlement behavior and the factor of safety (FS) of treated and untreated soil in the short and long term.

2 METHODOLOGY

The Padma Bridge Rail Track has a total stretch of 162 km, which consists of soft soil in several locations. In this study, two sections along chainage 82km+183m (Ch1) and 84km+102m (Ch2) were selected as representatives, having SPT N values between 2 to 8 in the soft soil layers. The Ch1 subsoil consists of three layers having a top layer of soft clay underlain by soft soil and silt with fine sand, respectively. On the other hand, the Ch2 subsoil consists of six distinctive layers having soft soil at the top four layers and silty fine to medium sand at the bottom two layers. The constructed railway embankment consists of an embankment fill, subgrade, sub-ballast, and a ballast layer.

In this study, finite element software PLAXIS 2D has been used to model the subsoil and constructed rail embankment. To properly represent the boundary conditions at infinity, the model length was defined as 60 m (x axis) and height as 30 m (y axis) so that the height and length ratios of model to embankment are greater than 4 and 3, respectively (Mestat *et al.* 2004). Only the movement along y axis was allowed on two sides of the model, the bottom was restricted for movement in both x and y directions. Following the procedure of Likitlersuang *et al.* (2018), the train load was simulated as a pseudo-static load (P) having the quantity of 68, 72.5, and 84 kN/m/m, respectively, for the three different train speeds investigated in this study: 100, 120, and 170 km/hr.

Eqs. (1) to (3) were used for the estimation of the pseudo-static loads. A detailed description of the variables in the equations, soil profile and property, and finite element modeling can be found in Aziz *et al.* (2022).

$$P = IF \text{ x } \frac{2q_r}{L} \text{ x } DF \tag{1}$$

$$IF = 1 + 5.21 \left(\frac{V}{D}\right) \tag{2}$$

$$DF = \frac{(0.061 \times S) + 13.37}{100} \tag{3}$$

Soil was defined as a "Mohr-Coulomb" material, and very fine meshes were generated. The short-term settlements at ballast bottom and embankment bottom along the centerline of the model were observed after a consolidation of 60 days and a subsequent application of train load. Whereas long term settlement was observed after a consolidation of 5,000 days. The FS against-bearing-capacity failure has also been investigated using the phi-c reduction method.

Apart from the long-term behavior of subsoil in the natural condition, this study aimed to investigate the potential of Cement Mixing Piles (CMP) as a treatment method for improving the strength and positively affecting the settlement. As the analysis was performed in Plaxis 2D, the CMP treated soil has been considered as a composite foundation having an equivalent strength index. This strength index has been calculated based on c and ϕ values of the soil and cement-mixing pile body, which is also inclusive of the triangular arrangement pattern of CMPs with pile spacing of 1.2 m and a pile diameter of 0.5 m. In this study, the final values have been obtained from the reports of the PBRL Project through personal communication where commercially available software has been used for determining the equivalent strength index (refer to Table 1). The treatment was considered up to 8.8 m and 11.5 m for Ch1 and Ch2, respectively. Figures 1(a) and 1(b) represent the long-term settlements along the whole soil profile of Ch1 and Ch2, respectively, in treated subsoil conditions induced by a train speed of 120 km/hr.

Table 1. Properties of foundation soil layers at treated condition.

	82km+ 183m (Ch1)		84km+ 102m (Ch2)			
Parameters	Soft clay	Soft Soil	Soft clay	Silty fine to medium sand	Soft soil	Soft clay
Cohesion, c (kN/m^2)	31.73	43.86	46.61	38.02	34.92	46.61
Angle of friction, φ (°)	11.41	12.88	12.29	30.04	10.95	12.29

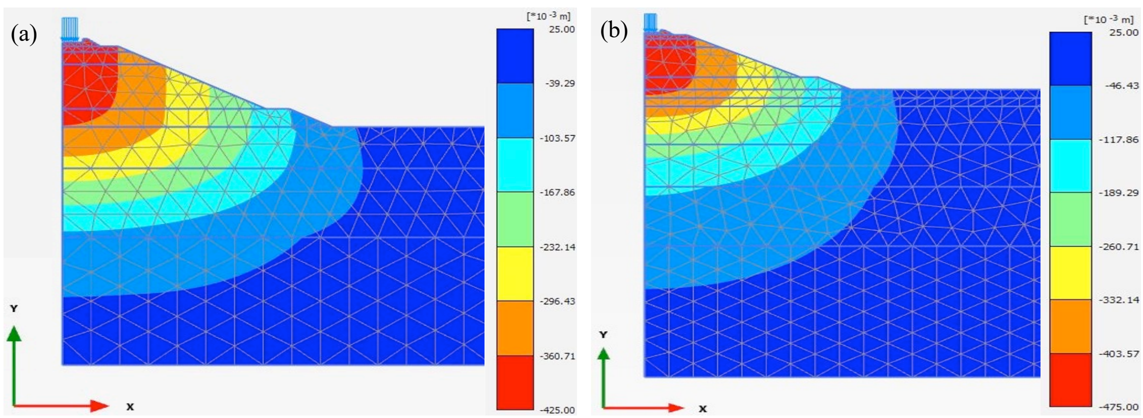

Figure 1. Long-term settlement at treated conditions for train speed of 120 km/hr: (a) Ch1 and (b) Ch2.

3 RESULTS AND DISCUSSIONS

3.1 Long-Term Behavior

3.1.1 *Settlement of ballast bottom*

Figures 2(a) and 2(b) show the settlement of the ballast bottom (BB) in the long term after a consolidation of 5,000 days. For all three speeds, the settlement increases by 16.4 cm (47.5%) and by 13 cm (29.4%) on average compared to the short-term settlement (as reported in the previous study of the authors, Aziz *et al.* 2022) for Ch1 and Ch2, respectively. The final settlement is greater for Ch2 even in the long term than it was in the short term. The existence of additional soft-soil layers extending to a greater depth may be responsible for the greater long-term settlement in Ch2. Considering the plastic strain accumulations owing to repeated train loads may have resulted in larger long-term settlements, however, it is beyond the scope of the current study.

3.1.2 *Factor of safety*

Table 2 summarizes the results for all FS and settlements. For all three train speeds, the FS is nearly 1.4 or greater for untreated conditions of Ch1 and Ch2 in long term. These FS values signify that the railway embankment is safe against bearing-capacity failure in the long term in both chainages. Comparing the long-term FS with short-term, for Ch1, the FS increases by 16–17% in untreated conditions. However, for Ch2 the increase is lower, i.e., 13%.

3.2 Effect of Treatment

3.2.1 *Effect of soil treatment in short-term settlement of embankment bottom*

As the foundation soil is treated in the form of cement-mixing piles, the settlement at the embankment bottom (EB) reduces by 13.8% for both Ch1 and Ch2 at V = 100 and 120 km/hr. However, as the train speed becomes 170 km/hr, the effect of the treatment can be considered more as the settlement reduces by 18% for Ch1 and 16% for Ch2. Figures 3(a) and 3(b) show the change of settlement along the distance from the symmetric axis.

3.2.2 *Effect of soil treatment in short-term settlement of ballast bottom*

In the case of the ballast bottom (BB), at lower train speeds, the settlement is reduced by 15.4%, and at V = 170 km/hr, it is nearly 21% for Ch1. For Ch2, the reductions are nearly 18.5% and 20.3% for lower and higher speeds, respectively. Hence, the role of treatment in settlement reduction is again more effective at higher speeds. Figures 4(a) and 4(b) show the settlement in the ballast bottom in the case of treated foundation soil.

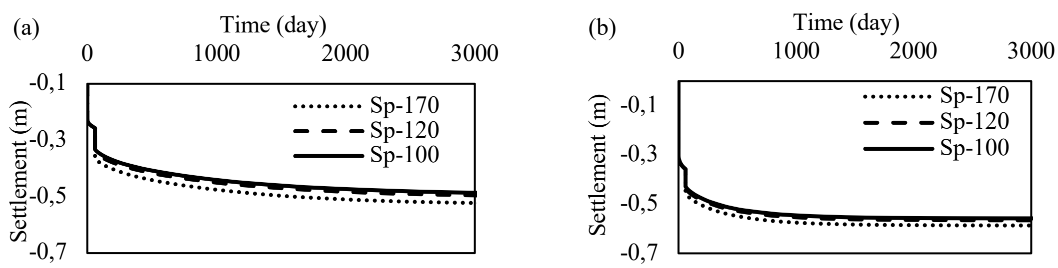

Figure 2. Long-term settlement of the ballast bottom at different train speeds for (a) Ch1 and (b) Ch2. *[Note: As settlement does not change significantly after 3000 days, the authors only presented the data till T=3000days].*

Table 2. Settlement and FS in untreated and treated conditions.

Train Speed (km/hr)	Chainage	Condition of foundation soil	Embankment bottom settlement (cm)	Ballast bottom settlement (cm)		FS (Short term)	FS (Long term)
			Short term	Short term	Long term		
100	Ch1	Untreated	27.45*	33.25*	49.30	1.225*	1.428
		Treated	23.67	28.27	39.89	1.605	1.814
	Ch2	Untreated	36.79*	42.80*	55.80	1.271*	1.434
		Treated	31.71	34.90	44.34	1.77	1.86
120	Ch1	Untreated	27.50*	34.04*	50.30	1.217*	1.416
		Treated	23.67	28.62	40.29	1.588	1.794
	Ch2	Untreated	36.81*	43.48*	55.80	1.262*	1.424
		Treated	31.71	35.20	44.75	1.744	1.825
170	Ch1	Untreated	29.2*	36.20*	53.10	1.194*	1.39
		Treated	23.85	28.50	41.40	1.543	1.736
	Ch2	Untreated	38.12*	45.31*	58.73	1.238*	1.393
		Treated	31.89	36.08	46.01	1.674	1.752

*values reported from Aziz *et al.* (2022)

3.2.3 *Effect of soil treatment in long-term settlement of ballast bottom*

At lower train speeds, the settlement due to the treatment is reduced by 19.5% and 20.2%, respectively, for Ch1 and Ch2. As the train speed increases to 170 km/hr, it becomes 22% for both the chainages. Thus, in the long term, significant improvement has not been observed for treated soils in settlement reduction compared to the short term. One potential reason for this small impact of treatment can be attributed to the soil strength parameters after treatment. The treatment provided to the soft soil in form of CMPs has significantly improved cohesion of soil, but the improvement of friction parameter is very little (maximum improvement of c and φ was observed 192% and 38%, respectively, with respect to untreated c and φ value). In the long term, soft soil's effective strength principally comes from its friction properties as the apparent cohesion becomes zero. As a result, in long term the additional strength provided by the cement mixing piles may help overcome some of the strength loss and reduce the settlement but not as much as in the short term. Hence considering long term, for soft soil, treatment schemes should be selected in such a way that it imparts higher frictional resistance.

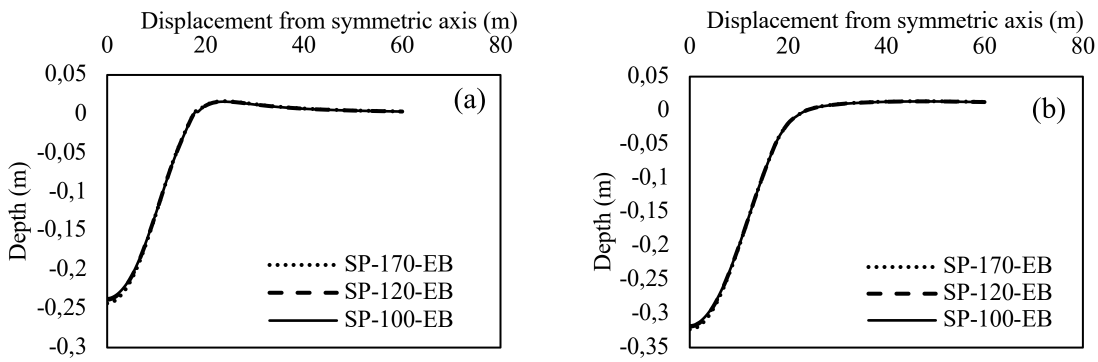

Figure 3. Settlement of embankment bottom of treated soil in the short term for (a) Ch1 and (b) Ch2.

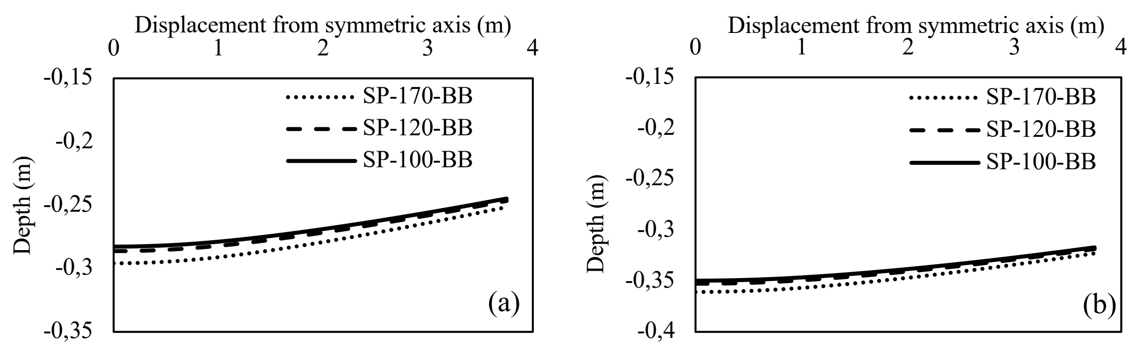

Figure 4. Settlement of ballast bottom of treated soil in the short term for (a) Ch1 and (b) Ch2.

3.2.4 *Effect of soil treatment on factor of safety*

Figures 5(a) and 5(b) show the percent increase in FS in the short and long term for treated conditions compared to the untreated one for Ch1 and Ch2.

Due to the treatment, the FS increases by 29–31% in the short term for Ch1. For Ch2, however, it increases by 35–39%. Hence, the effect of treatment is higher in Ch2 for imparting stability. A similar occurrence is noticed in the long term. However, for treated soil, the percentage increase in FS is lower in the long term than the short term for both chainages. The same analogy stated in article 3.2.3 can also be stated in support of this finding. Thus, the advantage of treatment in providing stability is greater in the short term than the long term. Similar results have been observed for the other two train speeds.

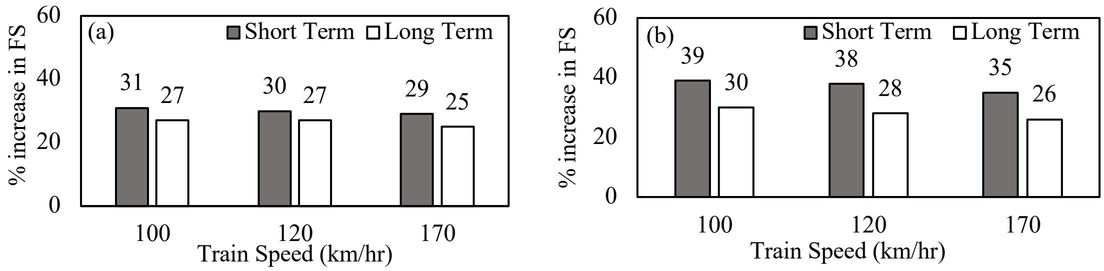

Figure 5. Percent increase in FS due to treatment in the short and long term for (a) Ch1 and (b) Ch2.

4 CONCLUSIONS

The present study encompasses the following notable conclusions.

- Long-term settlements at the ballast bottom are significantly high. Hence, treatment in the form of CMP will be helping to reduce the settlement.
- In the short, CMP treatment has been effective in the reduction of settlement values, however, it did not produce any further noticeable reduction in the long term. For the treated soil, at higher train speeds, treatments were more effective.
- In contrast to settlement reduction there was no effect of train speed in changing the FS for treated soil compared to untreated. Also, due to treatment, the increase in FS is affected due to changes in soil property and the duration of consolidation. Ch2 shows a greater increase in FS, and the effect is greater in the short term.

This study can provide valuable insight into the long-term settlement and stability behavior as well as the performance of the treated subsoil of railway embankment constructed on the soft deltaic deposits of the Ganges–Brahmaputra floodplain. Further studies in terms of strain accumulation are required to provide more insight for interpreting the long-term behavior.

Acknowledgments

The authors acknowledge Bangladesh Railway, Bangladesh Army, and Construction Supervision Consultant (CSC), PBRLP for providing technical support and information that facilitated the study during 2021–2022.

References

Aziz, S., Mallick, J. R., Hoque, I. L., Nayeem, M. A., and Amin, A. F. M. S., *Behavior of Railway Embankment Constructed on Soft Deltaic Deposits under Varying Train Speeds*, Adv. Mat. Res., Trans Tech Publications Ltd., 1174, 81-88, September, 2022.

Fulambarkar, S., Bangari, G., Manna, B., and Shahu, J. T., *Numerical Analysis of Embankment Built on Indian Marine Clay Improved with DM Column*, Int. J. Geosynth., Springer, 7(4), 95, December, 2021.

Hoque, I., L, Aziz, S., Mallick, J. R., Nayeem, M. A., Maisha, T. E. H., Hossain, F. M. Z., and Amin, A. F. M. S., *Response Analysis of a Ballasted Rail Track Constructed on Soft Soil by 3D Modeling,* Adv. Civ. Eng., Hindawi, 2023, 4290824, February, 2023.

Likitlersuang, S., Pholkainuwatra, P., Chompoorat, T., and Keawsawasvong, S., *Numerical Modelling of Railway Embankments for High-Speed Train Constructed on Soft Soil*, J. GeoEngin., Taiwan Geotechnical Society, 13(3), 149-159, September, 2018.

Madshus, C. C., and Kaynia, A., *High-Speed Railway Lines on Soft Ground: Dynamic Behavior at Critical Train Speed*, J. Sound Vib., Elsevier, 231(3), 689–701, March, 2000.

Mestat, P. H., Bourgeois, E., and Riou, Y., *Numerical Modelling of Embankments and Underground Works,* Comput. Geotech., Elsevier, 31(3), 227-236, April, 2004.

Rezania, M., Nguyen, H., Zanganeh, H., and Taiebat, M., *Numerical Analysis of Ballina Test Embankment on a Soft Structured Clay Foundation*, Comput. Geotech., 93, 61-74, January, 2018.