Effect of Composite Pile Foundation System on the Behavior of Soft Ground

Dimpa Moni Kalita and S. D. Anitha Kumari

Abstract Construction of bridge approach embankment in soft ground experiences soil settlement due to different support condition of the approach embankment and the abutment. At the bridge-embankment transition zone, this difference will result in formation of bump at the bridge end. Hence, the present study focuses on developing and efficient foundation system that can minimize the bump at the bridge end. Ground improvement techniques using composite piles can be adopted to improve the soft ground. A series of numerical analysis is carried out to compare embankment system without and with composite pile made of cement-fly ash-gravel (CFG) and lime in reducing settlement. The analysis results show that settlement at the transition zone is reduced by 45% when composite piles are used as ground improvement. Performance analysis of CFG and lime pile shows that the stress carrying capacity of CFG piles is higher than lime piles. Meanwhile, the parametric study results show that pile spacing of 6 times diameter, pile length of 25 times diameter and sand as cushion material are the most optimum design parameters that can effectively smooth the bridge-embankment transition zone. Further, the effect of constant and varying pile length in the foundation system is studied. It is observed that varying length piles reduce soil settlement by approximately 25% compared to constant length piles.

Keywords Soft ground · Bridge-embankment transition zone · Composite piles

1 Introduction

An effective and well-developed transportation system has a significant role in the economic development of a country. The rapid development in the transport facilities is forcing the construction of this system on the available land which may

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be sandy, silt, clay, loamy or in general soft and weak soil. Soft ground has problems like insufficient bearing capacity, high post construction settlement, instability on excavation and embankment construction. Geotechnical engineering faces major challenge in designing and construction of highways and railways on this ground. In the bridge approach embankment system, the approach embankment rests on natural soil, whereas the bridge abutment is supported by deep piles. Therefore, the stiffness of the abutment and the embankment is different. At the bridge-embankment transition zone, this difference in stiffness will result in the formation of bump at the bridge end. Therefore, ground improvement technique should be adopted underneath the embankment to reduce the bump at the bridge end. In recent times, ground improvement technique is concerned in delivering built facilities that are environment friendly as well as financially viable. In the construction cycle, sustainable geotechnical practice can significantly improve the overall sustainability of the project. One of the sustainable techniques is to use fly ash in construction. In this study, fly ash is used in piles to form a composite pile foundation for ground improvement. The composite pile formed by the mixture of cement, fly ash and gravel will be a rigid pile which is known as cement-fly ash-gravel (CFG) pile.

So far, many researchers have investigated the behavior of composite piles as ground improvement in soft soil. Zhang et al. [1, 2] reported a case study on the performance of geosynthetic-reinforced and pile-supported embankments (GRPS) over silty clay and found that the total postconstruction settlement is reduced by 21–38.6% where 8.8–17.3% was reduced in the reinforced area and 27.5–44% in the substratum soil. An analytical solution for estimating the stress concentration ratio of GRPS embankment for high speed railways was proposed in the paper. It was reported that the combination of geosynthetics in the platform and CFG piles in the subsoil reduced the lateral displacement in the soil. Moreover, parametric study on pile length showed that change in pile length affected the stress distribution ratio. Jiang et al. [3] conducted a numerical analysis of well-monitored pile slab supports (PSS) embankment with CFG piles in the foundation. They observed that the cushion reduced shear force in slab by 28% and maximum bending moment by 17%. They also mentioned that increase in the pile stiffness by 10 times reduced the maximum settlement, differential settlement and lateral displacement of the embankment by 50%, 67% and 84%, respectively. Xiao et al. [4] studied the effect of CFG piles on the abutment piles for different ground replacement ratio and reported that increase in ground replacement ratio reduced the axial force, normal contact pressure, bending moment and horizontal displacement of abutment piles. Wei and Bian [5] analyzed the dynamic performance of CFG pile-supported bridge embankment with constant length and varying length pile and observed that multistage improvement strategy using varying length CFG piles gave better result in reducing settlement compared to constant length pile.

As per the study conducted on existing literature, researchers have mainly focused on reducing soft ground settlement by using geosynthetic-reinforcement and pile-supported embankment. Limited researches were carried out to compare the effect of lime and CFG pile-supported embankment with various cushion material. The present study is focused on the effects of lime and CFG pile as ground reinforcement for reducing the soft ground settlement. Moreover, the effect of design parameters on the embankment performance is also studied to obtain the most feasible foundation system and compared its performance with varying length pile foundation system.

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2 Methodology

Three-dimensional numerical model of the bridge approach embankment is analyzed using numerical methods. FEM software ABAQUS was used for modeling the system. The model consists of embankment, abutment, sand cushion, composite piles and abutment piles. The modeled embankment is resting on subsoil consisting of two layers: silty clay and clay. Mohr–Coulomb failure criterion is adopted for the soil layers and material parameters used are tabulated in Table 1. The parameters and material properties used in modeling the piles are mentioned in Table 2. For analysis, a length of 10 m for CFG and lime piles and 17 m for the abutment piles are used. The position of abutment piles and composite piles with spacing in longitudinal and transverse direction is shown in Fig. 1. The model is analyzed for self-weight of the embankment, i.e., 120 KN/m^2.

Table 1 Material properties of geomaterial [4]

Material	Height H (m)	Density γ (kN/m^3)	Young's modulus, E (kN/m^2)	Poisson ratio, μ	Friction angle °	Cohesion c (kN/m^2)	Dilation angle, ψ°
Silty clay	7	19.1	9×10^3	0.33	12	35	0.1
Clay	13	19.5	15.3×10^3	0.33	30	8.3	1
Embankment	6	20	80×10^3	0.3	30	15	4
Sand cushion	0.5	20	100×10^3	0.3	35	0	7

Table 2 Material properties of elastic piles [4, 6]

Material	Diameter, D (m)	Density γ (kN/m^3)	Young's modulus, E (kN/m^2)	Poisson ratio, μ
Abutment pile	0.96	24.52	70×10^6	0.2
CFG pile	0.48	14.72	35×10^6	0.25
Lime pile	0.48	19.62	15×10^6	0.25

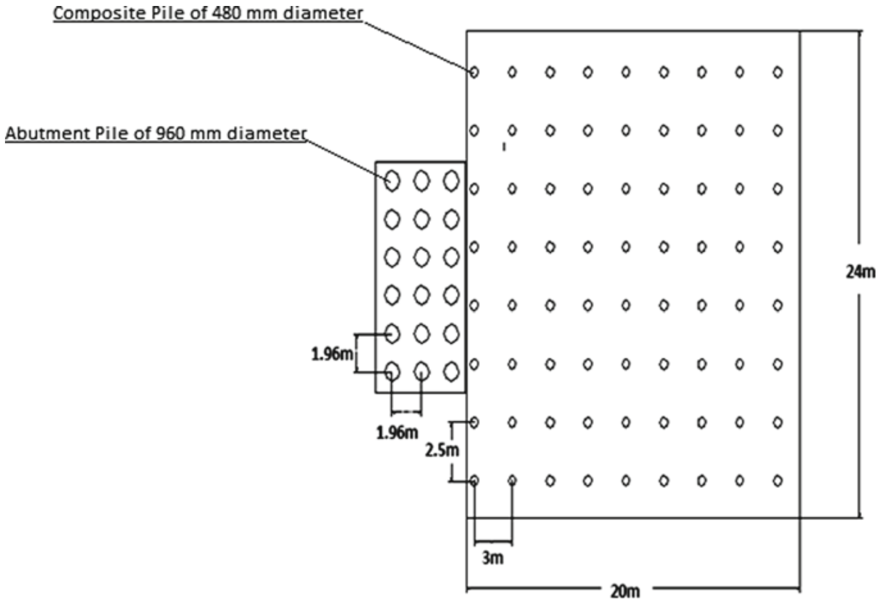


Fig. 1 Top view of the composite pile foundation

3 Analysis of Bridge Approach Embankment System

The bridge approach embankment system is analyzed for two different cases. In the first case, the bridge approach embankment system is analyzed for the embankment without and with composite pile foundation underneath the embankment. In the second case, the bridge approach embankment system is analyzed for CFG pile composite foundation and lime pile composite foundation to obtain the most suitable pile material.

3.1 Bridge Approach Embankment with and Without Composite Piles

The numerical model of the bridge approach embankment is analyzed for two models; (i) without composite pile foundation and (ii) with CFG pile composite foundation. It is observed that the soil without any composite piles underneath the embankment undergoes settlement in the cushion as well as in the soil. Figure 2a and b compares the magnitude of settlement in the embankment system without and with composite pile foundation. The stress in the cushion is 75.54 kPa and settlement is 79.64 mm for the embankment system without composite pile foundation at the bridge-embankment transition zone. In the case of CFG pile foundation, the stress in the cushion is

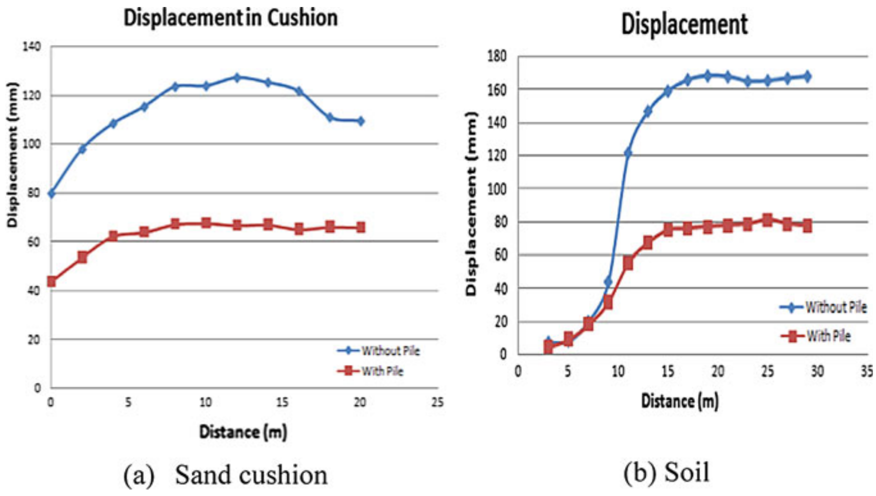


Fig. 2 Comparison of displacements for embankment with and without composite piles

69.68 kPa and settlement is 43.67 mm. It is also observed that as the distance from the transition zone increases, the stress and displacement in the cushion also increase gradually. Comparing the stress for both the cases, it is observed that the stress in embankment system without pile is 8% more in the bridge-embankment transition zone and 33% more at a distance of 10 m from the transition zone compared to embankment with composite pile. In Fig. 2a, the displacement increases up to a certain length for the embankment system with reinforced CFG piles and then it becomes almost constant. The increase in the settlement is due to the load from the embankment which is stabilized when CFG piles are used. Thus, CFG piles have effectively stabilizes the subsoil. In Fig. 2b, settlement at the extreme end of the soil in longitudinal and transverse directions is zero as no load is acting at that point. whereas near the bridge-embankment transition zone, the dead load of the embankment produces an impact on the underlying soil that results in settlement. Comparing the settlement for both the cases in cushion and soil, it is observed that CFG pile foundation underneath the embankment can effectively reduce the cushion and soil settlements by approximately 45% and soil settlement by 54%, respectively.

3.2 Comparison of CFG and Lime Piles in Composite Pile Foundation

The three-dimensional model of the bridge approach embankment is analyzed for two different pile foundation system; (i) CFG pile foundation and (ii) lime pile foundation under static loading. The embankment system with CFG pile foundation, the maximum stress obtained from the numerical analysis at the pile top is 29.86 kPa,

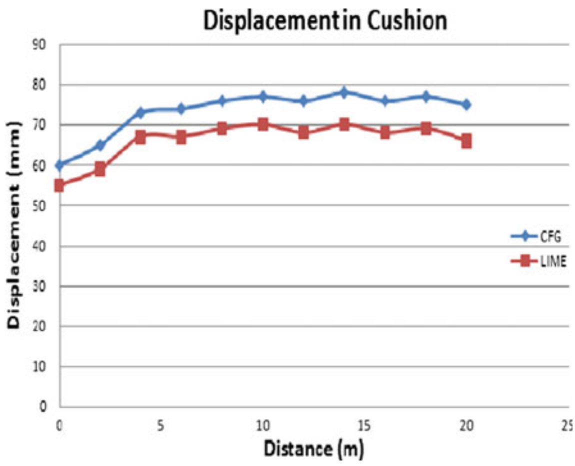


Fig. 3 Settlement comparisons for CFG and lime pile foundation

and for lime pile foundation system, it is 23.47 kPa. Thus, the initial stress generated on the CFG piles is 21% more compared to lime piles. But it is observed that the stress throughout the pile length is reducing gradually along the depth of the pile. The total percentage of stress transferred to the lower depth of CFG piles is 45% and to the lower depth of lime piles is 65%. This indicates that smaller depth of CFG for pile can carry more stress compared to lime pile. However, the displacement at the bridge-embankment transition zone is 60 mm for CFG pile foundation and 55 mm for lime pile foundation. Figure 3 shows the displacement comparison for CFG and lime pile in cushion. Therefore, further analysis on the design parameters needs to be studied to obtain the most effective pile material.

4 Parametric Studies

In this study, the three-dimensional numerical model of the bridge approach embankment is analyzed for various influencing parameters. In order to obtain the most suitable pile material, analysis of CFG and lime pile foundation is done for different pile spacing in each model. With the most suitable pile material and pile spacing, further analysis on the effect of pile length and the behavior of cushion materials is studied.

4.1 Effect of Pile Spacing

The effect of pile spacing on the overall performance is studied by considering 14 different configurations. The 14 different configuration includes seven CFG piles and seven lime piles and are compared for pile spacing of 2D, 3D, 4D, 5D, 6D, 7D and 8D, where D is the diameter of the pile, i.e., 480 mm. Figure 4a and b shows the displacement comparisons for different spacing with CFG piles and lime pile respectively. It has been observed that pile spacing between 2D–4D performs very well in reducing settlement as the piles are very compactly placed and the performance of 8D spacing is not satisfactory. Therefore, the performance of 5D, 6D and 7D is compared. At the bridge-embankment transition zone, soil settlements are 34 mm, 37 mm and 41 mm for 5D, 6D and 7D spacing, respectively, with CFG pile foundation. The lime pile foundation soil settlements obtained are 52 mm, 58 mm and 65 mm for 5D, 6D and 7D spacing. This indicated that CFG piles give better results in reducing settlement compared to lime pile at the transition zone. Moreover, it has been observed that in 7D pile spacingm the displacement is varying alternately which indicates that this pile spacing is not able to improve the soft soil much. The settlement for both CFG and lime foundation in 5D and 6D shows uniform variation and is approximately same. Therefore, 6D spacing is considered as the optimum pile spacing for this foundation system. However, in the transition zone, settlement of 37 mm with 6D spacing will not minimize the bump at the bridge end completely. So, further investigation on the effect of pile length needs to be studied.

4.2 Effect of Pile Length

Figure 5a and b shows the displacement for different pile depth in sand cushion and soil respectively. The influence of CFG pile composite foundation is analyzed with pile lengths of 8 m, 10 m, 12 m and 14 m. At the bridge-embankment transition zone, cushion displacement observed for 8 m, 10 m, 12 m and 14 m pile length is 45.93 mm, 42.34 mm, 34.66 mm and 32.3 mm, respectively. The soil displacement observed for 8 m, 10 m, 12 m and 14 m pile length is 41 mm, 37 mm, 34 mm and 32 mm, respectively. It is observed that higher the length of pile, lower is the displacement at the bridge-embankment transition zone. Comparing the displacements for different pile length, CFG pile of length 12 m and 14 m shows approximately the same settlement at the bride end. Therefore, an effective pile foundation system is modeled with a pile depth of 12 m.

4.3 Effect of Cushion Material

The three-dimensional model of the bridge approach embankment system is analyzed for two different load transfer medium; sand cushion and concrete slab. Figure 6a and b shows displacement in sand cushion and soil respectively for different cushion materials. At the bridge-embankment transition zone, the settlement in sand cushion is 34 mm and the settlement in concrete slab is 27 mm. It indicates that when a concrete slab is used as load transfer medium, the cushion settlement gets reduced by 23%. Result shows that the maximum settlement in sand cushion is 52 mm and in

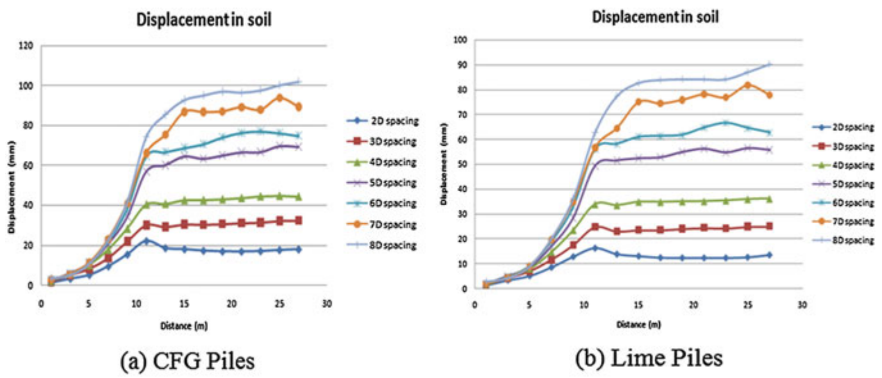


Fig. 4 Displacement comparison for different pile spacing

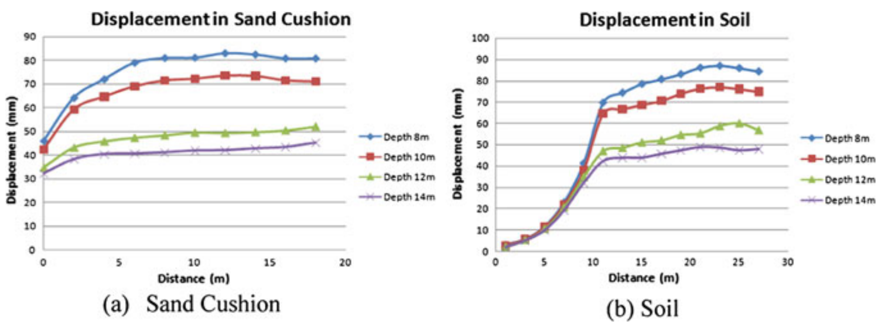


Fig. 5 Displacement for different pile length

concrete slab is 42 mm. But settlement of a concrete slab by 27 mm and 42 mm will result in cracking at the concrete surface. Thus to prevent cracking in the concrete slab, it is required to provide proper reinforcement design at the transition zone. The present study is not focused on designing an optimum-reinforced concrete slab therefore; sand is taken as the most suitable cushion material to carry the load transfer mechanism in the embankment system.

4.4 Comparison of Constant Length and Varying Length Pile in Foundation

Based on the results obtained from the parametric studies, a foundation system with constant length pile is designed. The study focuses on the performance of soft ground reinforced by constant and varying lengths CFG pile foundation system. Figure 7a and b shows the 2D view of constant length and varying length pile foundation system

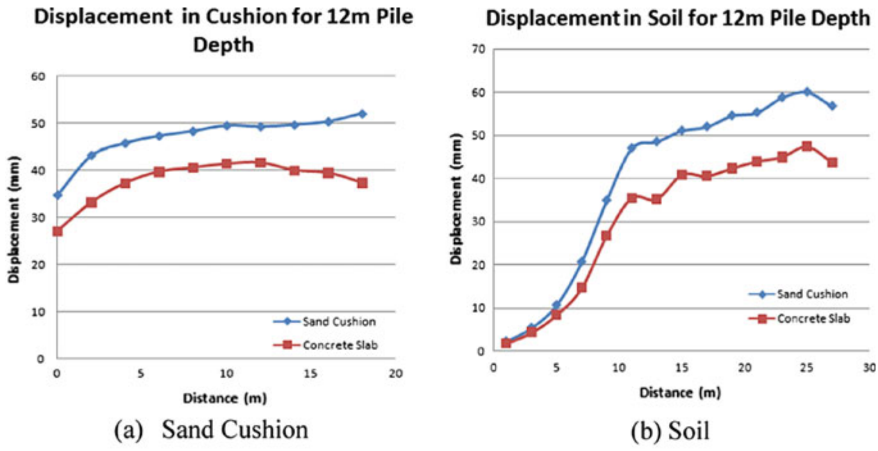


Fig. 6 Displacement for different cushion material

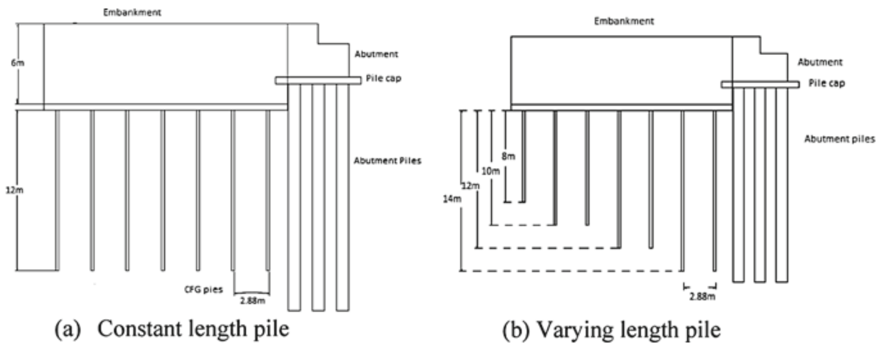
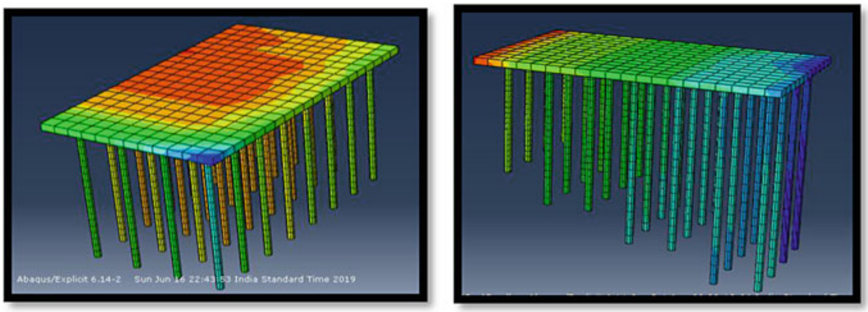


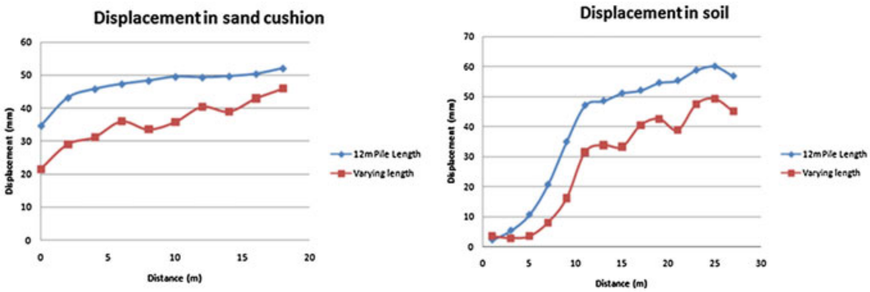
Fig. 7 Two-dimensional view of the composite pile foundation system

used for analysis. The numerical model with constant length and varying length pile is shown in Fig. 8a and b respectively. Figure 9a and b compares the displacement for constant length and varying length pile in cushion and in soil respectively. Results show that at the transition zone, displacement in sand cushion is 34 mm for constant length piles and 22 mm for varying length piles and in the soil is 35 mm for constant length piles and 16 mm for varying length piles. Varying length pile foundation reduces settlement at the bridge-embankment transition zone by 25% compared to constant length pile foundation.



(a) Constant length pile (b) Varying length pile

Fig. 8 Numerical model of the composite pile foundation system



(a) Sand Cushion (b) Soil

Fig. 9 Settlement comparison of constant and varying length pile foundation system

5 Conclusions

The behavior of soft ground reinforced by CFG and lime pile in a bridge approach embankment system is compared. Results obtained from the analysis indicate that shorter span of CFG pile can carry more stress therefore; the stress carrying capacity of CFG pile is more compared to lime piles. The displacement at the bridge transition zone is minimized when CFG piles are used in the foundation compared to lime piles. In order to get the most optimum design parameters, the influence of pile spacing, pile length and cushion material is analyzed. It has been observed that pile spacing of 6 times diameter, pile length of 25 times diameter and sand as cushion are the most feasible parameters in a foundation system. Further, the performance of constant length and varying length piles is compared to understand the effect on the behavior of the foundation system. The analysis indicates that for a smooth bridge-embankment transition zone, a foundation system with varying pile length shows better response against settlement compared to constant length pile in a foundation resting on soft ground. Thus, it is recommended to adopt a pile length of 14 m for a distance of

4.5 m from the bridge-embankment transition zone, i.e., three times its distance in the varying length pile foundation system.

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