Chapter 12
Lateral Displacements of Soft Ground Treated with PVDs Under Embankment Loading

C. Abhinay Kumar, J. Y. V. Shiva Bhushan, and Madhav Madhira

Introduction

India is a country with large tracts of coastal lands consisting of highly soft soils. Soft soils are known for high water content, low undrained shear strength, low permeability, high compressibility resulting in excessive settlements that pose many geotechnical challenges. Due to their time-dependent characteristics, more time is required to complete consolidation. Improvement of soft ground is the only solution to overcome the problem of excessive deformations.

Several ground improvement techniques are available to improve the ground. Vertical drains are most commonly suited for fine-grained, inorganic high water content, low strength soils. Sand drains were used in the past but PVDs are more effective, faster to install, and economical [1]. PVD with preloading is used to get faster results by creating an artificial drainage path to the water present in the soils [2]. The disturbance caused while installing affects the performance of PVD-treated ground [3]. The rate of construction, diameter, spacing, and discharge capacity of vertical drains play important role in achieving ultimate settlements [4, 5].

Soft soil under embankment loading settles due to both consolidation and lateral deformation due to plastic flow of subsoil [3]. Treatment of soft ground with PVD along with preloading increases both the rates of vertical and horizontal consolidation. Loading rate and embankment load are the main factors that cause lateral displacements in the soil. During the construction of embankment, if the shear deformation exceeds the rate of vertical consolidation, failure of structure is likely. The present study considers the embankment loading on the PVD-treated soft ground.

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The objective of this paper is to quantify the effect on the reduction of lateral deformations at the toe of embankment alongside settlements beneath the embankment for different spacing of PVDs.

Problem Statement

An ultra-mega power project is constructed at Krishnapatnam, Nellore, Andhra Pradesh [6]. The subsoil is mostly clayey, while top soils are medium dense to very dense sand. Figure 12.1 shows the soil profile at the location which consists of very dense and medium dense sand up to 7.5 m below ground level, and a soft clayey soil is underlying which is extended up to 20 m from the surface. Table 12.1 presents the subsoil and embankment soil properties at Krishnapatnam ultra-mega power project (KUMPP) from [7]. PVDs of length 20.0 m were installed in a triangular pattern.

Construction of Embankment

Embankment of height 4 m is constructed with a base width of 33 m and with side slopes of 1 V:2H. A sand mat of 0.3 m is placed above the ground surface as a drainage layer. The rate of construction (Fig. 12.2) is small at the initial stage and rapid after 15 days of construction. Construction of embankment started from 24th day and finished by the end of 54th day after the installation of PVDs. The total period of construction is 30 days for 4 m high embankment for a design load of 68 kPa.

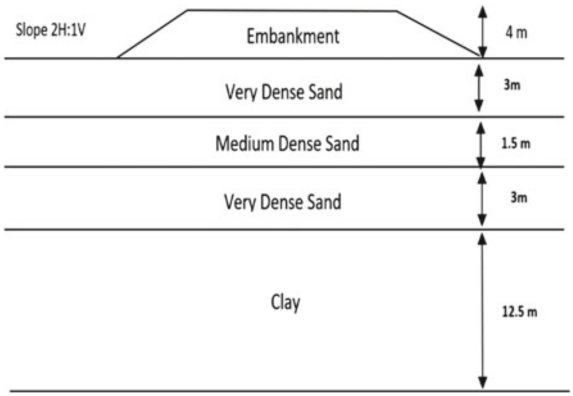

Fig. 12.1 Soil profile at KUMPP

Table. 12.1 Properties of soils

Parameter	Embankment	Very dense sand-1	Medium dense sand	Very dense sand-2	Clay
γ_{unsat} (kN/m^3)	17	17	17	17	15
γ_{sat} (kN/m^3)	19	20	20	20	17
e (void ratio)	0.5	0.5	0.5	0.5	0.5
k_x (m/day)	0.05	1.73 * 10^{-2}	1.7 * 10^{-2}	1.7 * 10^{-2}	1.6 * 10^{-6}
k_y (m/day)	0.05	4.3 * 10^{-3}	4 * 10^{-3}	4 * 10^{-3}	4 * 10^{-6}
Poisson's ratio	0.3	0.3	0.25	0.25	0.35
Deformation modulus (MPa)	30	40.6	42.1	40.6	1.059
Cohesion (kPa)	1	3	3	3	25
Angle of shearing resistance	30	41.5	36	41.5	0

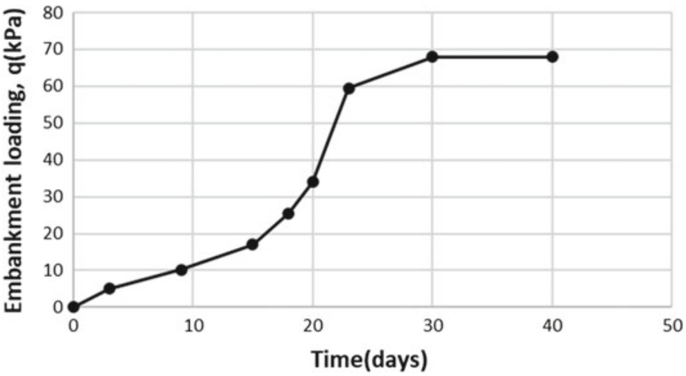

Fig. 12.2 Embankment loading with time

Finite Element Analysis

Finite element software—PLAXIS 2D, 2020—was used to analyse the problem. As the loading is symmetrical, only half the embankment and the ground were modelled for plane strain condition. Lateral boundaries are at 1.5 times the base width of an embankment. Sand layer extends from the surface to 7.5 m depth and clay layer from 7.5 to 20 m below the ground surface. Numerical analysis of the embankment with soil is conducted in plane strain model in PLAXIS 2D with 15-noded triangular elements.

Model is validated first for Terzaghi's 1D consolidation theory [8] for untreated ground. Mohr–Coulomb model is used to define the embankment and sandy soils [9]. A conventional equation given by Hird et al. [10] is used to convert axisymmetric

Table 12.2 Soil properties used in the model

Soil property	Model properties
Poisson's ratio (v)	0.3
Tangent of critical state line (M)	0.8
Coefficient of consolidation C_v (m^2/year)	0.7–1.2
Modified swelling index (λ)	0.1130
Modified creep index (κ)	0.1617

model to plane strain one as

$$\frac{k_{\mathrm{pl}}}{k_{\mathrm{ax}}} = \frac{2}{3[\ln \ln[n] + \left[\frac{k_{ax}}{r_s}\right] \ln \ln[s] - \left[\frac{3}{4}\right]} \quad (12.1)$$

where k_{pl} is the horizontal permeability of undisturbed zone in plane strain unit cell, k_{ax} is the horizontal permeability of undisturbed zone in axisymmetric unit cell, k_s is the horizontal permeability of smear zone in axisymmetric unit cell, n is the influence ratio r_e/r_w, s is the smear ratio r_e/r_w., r_e is the radius of influence zone, r_w is the equivalent radius of vertical drain, and r_s is the radius of smear zone.

Where $M = 1.73 \sin\varphi$, $\lambda = \frac{C_c}{2.3(1+e)}$, $\kappa = \frac{2C_s}{2.3(1+e)}$ and swelling or reloading index, $C_s = 0.12e^{1.13e_0}$. Model properties shown in Table 12.2 are adopted from Radhakrishnan [6].

Embankment Loading

Embankment of height 4 m and width 25 m with side slopes of 1 V:2H was constructed and a sand mat of 300 mm placed above the ground surface to drain the water (Fig. 12.3). PVDs of length 20 m were installed using a triangular pattern. The bottom boundary is fixed in both vertical and horizontal displacements, and the side boundaries are fixed in the horizontal direction while the top boundary is free.

Finite element mesh of the soft ground, embankment, and the PVDs is shown in Fig. 12.4. Finer meshing has been considered so that more precise results could be obtained. To increase the accuracy of the results, 15-noded triangular patterns are considered which provides a fourth-order interpolation.

Validation

Numerical results for Terzaghi 1D consolidation theory [8] are compared with the results from the present FE model in Fig. 12.5. The results are comparable but with some difference.

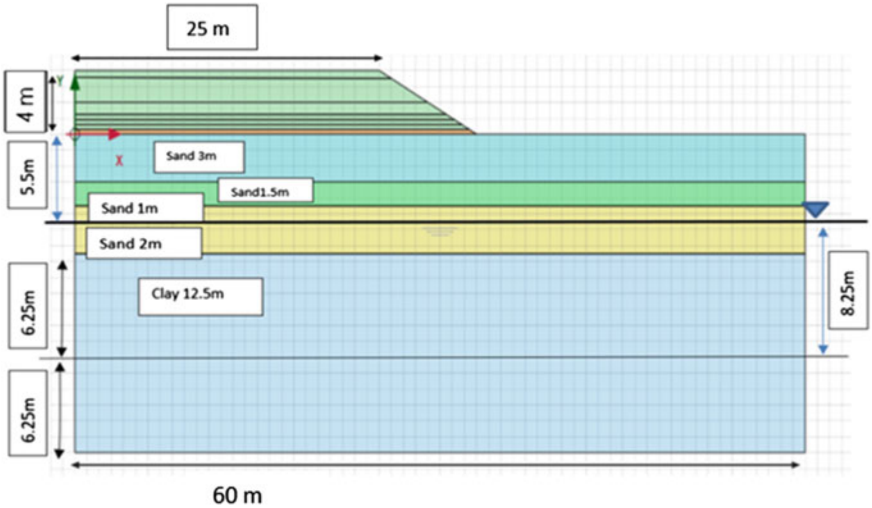

Fig. 12.3 Embankment over stratified soils

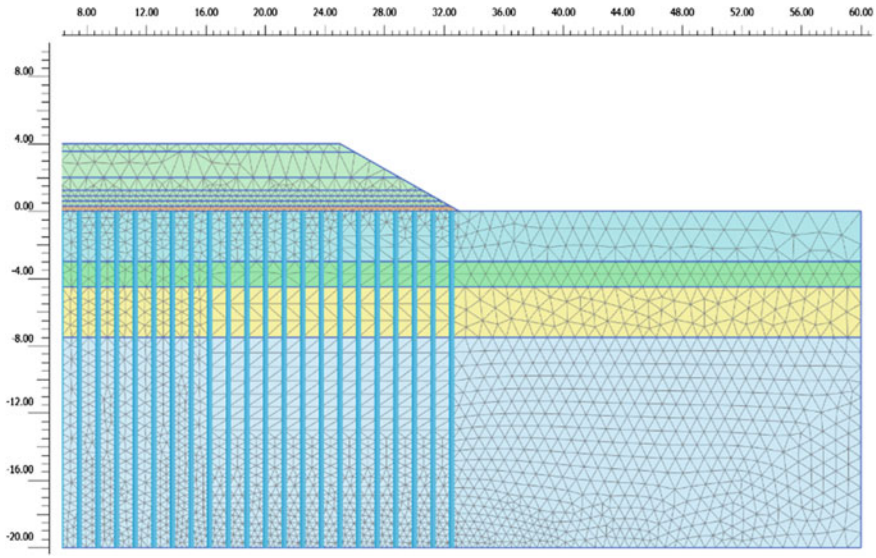

Fig. 12.4 Finite element mesh of soft ground under embankment loading

Final Settlement

Asaoka method [11] is used for interpreting and extrapolating the settlements observed in the field. The intersection points of 45° line and the plot of settlements

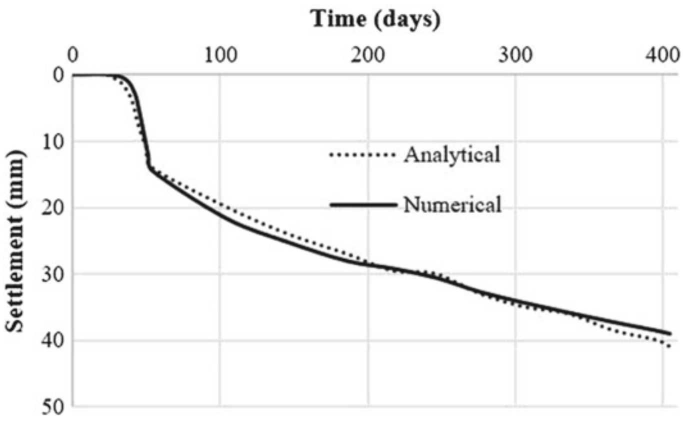

Fig. 12.5 Comparison of settlement curves with analytical solution

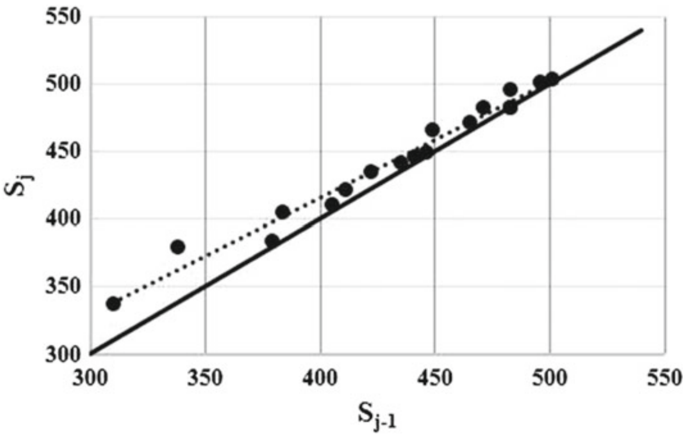

Fig. 12.6 Final settlement from Asaoka plot for 1.25 m c/c PVDs

give the final settlement. Observed results at the location for 1.25 m PVD @c/c and 2.5 m PVD spacing are analysed (Figs. 12.6 and 12.7) and final settlement (S_f) of 507 and 506 mm is obtained, respectively.

Results

Finite element models of stratified sand overlying soft clay with and without PVD are analysed and are compared to illustrate the effectiveness of PVDs on the rate and

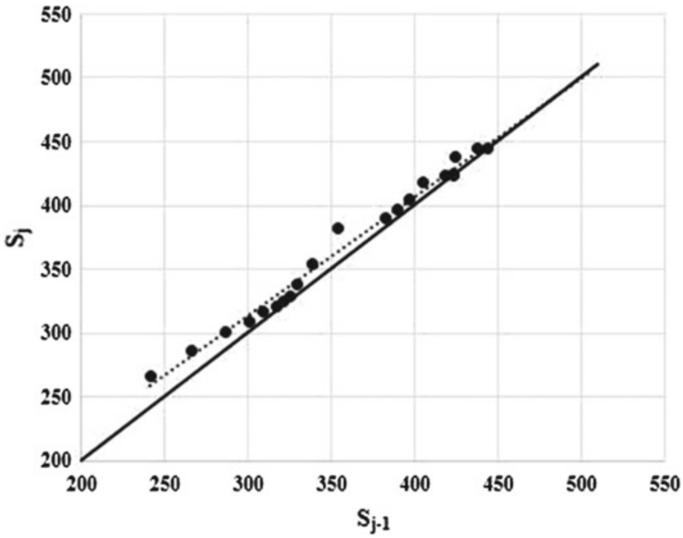

Fig. 12.7 Final settlement from Asaoka plot for 2.5 m c/c PVDs

magnitude of vertical and lateral deformations. Construction is completed at end of 54 days.

Settlements

Numerical results for the variations of surface settlements beneath the centre of embankment with time for PVD-treated soft ground for different spacing are obtained. Settlement of 507 mm is attained at 405 days for 1.25 m PVD @ c/c spacing. Deformation analysis is performed till 424 days for PVDs @ 2.5 m c/c spacing. Comparison of FEM results with measured surface settlements for PVD-treated ground @ 1.25 m c/c and 2.5 m c/c is shown in Fig. 12.8. The results predicted are comparable with the field observations.

At the end of 424 days, settlements beneath the centre of embankment for 2.5 m PVD @ c/c spacing and untreated ground are, respectively, 444 and 44 mm. Rate of consolidation is more and rapid in the case of PVD-treated ground for 1.25 m c/c spacing, in which case 99% degree of consolidation (U) is achieved in 405 days.

Based on the properties used for 1.25 and 2.5 m c/c spacing, settlements for 1.5 m PVD spacing are predicted by FEM and is shown in Fig. 12.9. A settlement of 488 mm is achieved in 405 days. With the provision of PVD treatment, 99, 96, and 87% degrees of consolidation are achieved for PVD-treated ground @1.25 m, 1.5 m, and 2.5 m c/c spacing at the end of 405 days.

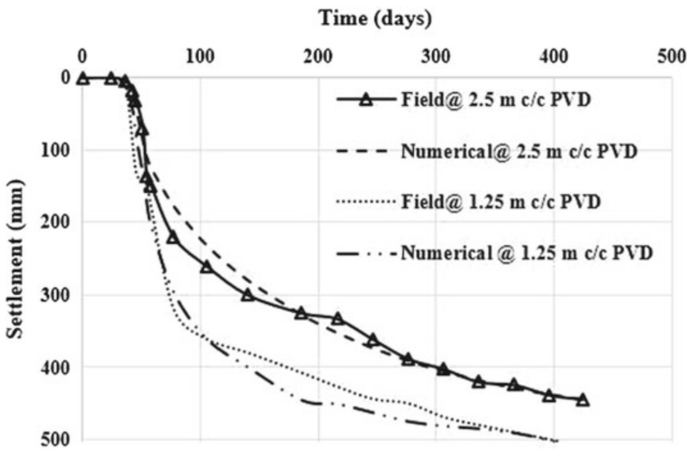

Fig. 12.8 Comparison of settlement of PVD-treated ground for different spacing

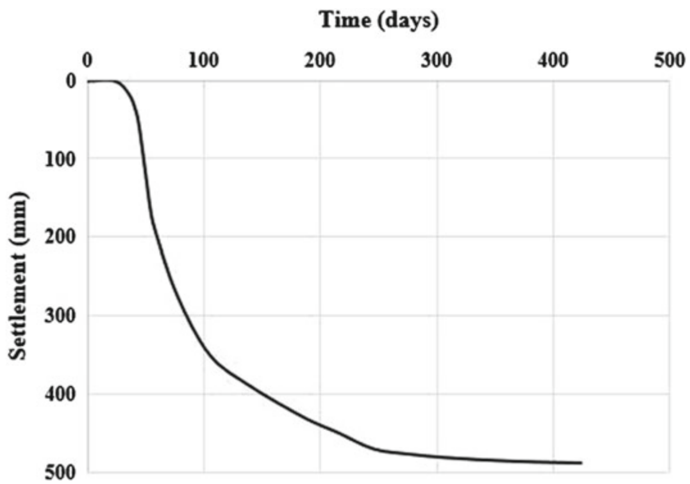

Fig. 12.9 Surface settlement with respect to time for PVD @ 1.5 m c/c

Figure 12.10 shows the surface settlement profiles beneath the embankment at the end of 405 days, obtained from FEM results. Maximum settlement for untreated, PVD-treated ground with @ 2.5 m c/c, 1.5 m c/c, and 1.25 m c/c spacing are, respectively, 41 mm, 440 mm, 488 mm, and 503 mm, while settlements attained at the toe are, respectively, 3, 121, 133, and 135 mm.

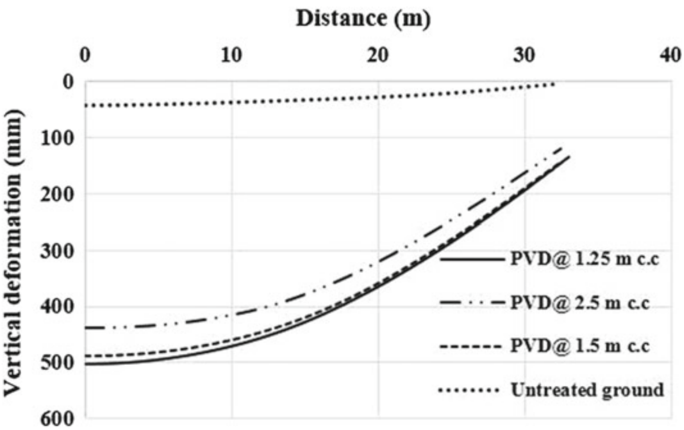

Fig. 12.10 FEM results of surface settlement profiles at the end of 405 days

Lateral Deformations

Lateral movement of soft ground at the toe of an embankment is studied by using FEM, at 405 days for PVD at different spacing. Figure 12.11 shows the variations of lateral displacements with depth. For soft ground treated with PVD, the top few metres of sandy strata deform inwards towards the embankment centerline and gradually deforms outwards and increases till the sand strata ends.

Lateral deformations at the end of 405 days are 6.92–8.18 times with respect to untreated ground for PVD with considered spacing. At depth of 7.5 m from ground

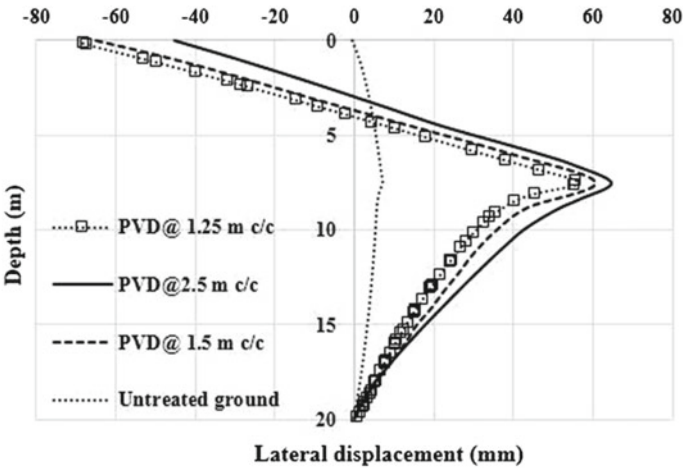

Fig. 12.11 Variation of lateral displacement at the toe of embankment with depth

in soft clay, lateral displacement is 55 mm in case of PVD-treated ground at 1.25 m c/c spacing.

Larger inward movement is seen near the top of the ground as since both the vertical and horizontal consolidations are significant. In the top layer of clay, lateral displacement variation for PVD-treated ground is large, and the difference decreases minimally as depth increases.

Conclusions

Deformations of soft ground treated with PVDs under embankment loading are analysed to study the effect of PVDs on rate of vertical and horizontal consolidation. Asaoka method is used to predict final settlements from measured settlement data for PVD-treated ground, and the results are compared with FEM findings. The results of lateral deformations of PVD-treated soft ground at various spacing are presented. It is observed that rate of settlements is higher in case of less spacing, and a gradual decrease in lateral displacements is observed with less spacing of PVD. Under embankment loading, PVD treatment of soft ground has a significant effect on the rate of lateral deformations.

References

1. Mehdizadeh A, Fakharian K (2015) Field instrumentation of a preloading project with prefabricated vertical drains. Ninth international symposium on field measurements in geomechanics FMGM Sydney, pp 453–464
2. Bergado DT, Manivannan R, Balasubramaniam AS (1996) Proposed criteria for discharge capacity of prefabricated vertical drains. Geotext Geomembr 14(9):481–505
3. Mahmoud SH, Ayman Lf, Yasser ME-M (2019) Application of PVD in soft soil for ground improvement. Int J Eng Appl Sci 6(10):68–77
4. Indraratna B, Sathananthan I, Rujikiatkamjorn C, Balasubramaniam AS (2005) Analytical and numerical modeling of soft soil stabilized by PVD incorporating vacuum preloading. Int J Geomech 5(2):114–124
5. Shui LS, Chai JC, Hong ZS, Caia FX (2002) Performance of embankments with and without reinforcement on soft subsoil. Can Geotech J 39(4):838–848
6. Radhakrishnan R (2011) Performance of pre-fabricated vertical drains & pre-loading for a major construction project. Proc IGC Kochi 357–360
7. Rajesh BG, Chukka SK, Dey A (2018) FEM of embankment resting on soft soil ground stabilized with PVD. SAGES
8. Terzaghi K (1943) Theoretical soil mechanics. Wiley, New York
9. Loganathan N, Balasubramaniam AS, Bergado DT (1993) Deformation analysis of embankment. J Geotech Eng 119(8)
10. Hird CC, Pyrah IC, Russell D, Cinicioglu F (1995) Modelling the effect of vertical drains in two-dimensional finite element analyses of embankments on the soft ground. Can Geotech J 32(5):795–807
11. Asaoka A (1978) Observational procedure of settlement prediction. Soils Found 18(4):87–101