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Numerical Investigation of Consolidation Induced by Prefabricated Horizontal Drains (PHD) in Clayey Deposits

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Abstract In this work, the process of prefabricated horizontal drains (PHD) induced consolidation in clayey embankment fills is investigated by a numerical approach. Based on spacing parameters, the suitability of axisymmetric and plane strain conditions for modeling the drain has been studied, and the suitability zones and matching functions have been proposed. The implications of the use of elastoplastic models to simulate the behavior of in situ soil on the suitability zones and matching functions have also been studied. The numerical results were compared with the analytical unit cell solutions for axisymmetric and plane strain conditions. Further, the effect of PHD in improving the consolidation behavior of various soil types has been analyzed in terms of pore pressure dissipation and settlement. The studies showed that the drain improved ground is best modeled under axisymmetric conditions at lower spacing ratios, and plane strain conditions simulate the more distantly spaced cases. PHD was found to accelerate the consolidation process in soft soils significantly, and the effect was found to be most prominent in highly plastic soils.

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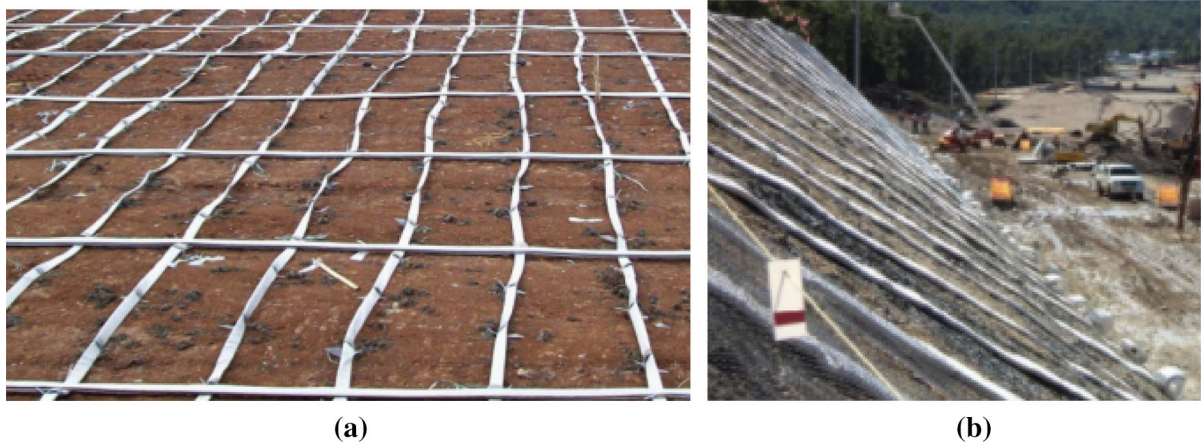e-mail: anjanabhasi@nitc.ac.in; anjanabhasi@yahoo.com

1 Introduction

Prefabricated Vertical Drain (PVD) induced consolidation is one of the most widely accepted technique to accelerate consolidation in clayey deposits (Rowe and Taechakumthorn 2008; Indraratna et al. 2012; Krishnamoorthy and Kamal 2016). There are several consolidation theories reported available in the literature about this technique (Barron 1948; Hansbo 1979; Hird et al. 1992; Tang et al. 2013; Liu et al. 2007; Huang et al. 2016). Recently, a novel idea has been developed, namely Prefabricated Horizontal Drain (PHD), which is much like Prefabricated Vertical Drain but installed horizontally (Chai et al. 2014). PHD essentially consists of an outer geotextile filter fabric which permits water flow through it, restraining the soil particles, towards an inner polymeric core, which then drains the water to designated drainage exits. The low installation cost and reduced space requirements, combined with the ease of handling and inspection, make PHD a feasible solution to many problems associated with clayey deposits. It has been successfully used as a horizontal drainage path in a system of PVDs replacing sand blankets (Fig. 1a) and

Fig. 1 Application of PHD **a** Horizontal drainage system connected to PVDs (from brochure of PT Teknindo Geosistem Unggul, Indonesia) **b** slope protection (from brochure of Specialist Site Services(SSS), Australia)

also for slope protection (Fig. 1b). PHDs can be used to accelerate the consolidation of embankments with clayey backfills, thus enhancing the scope of using clayey soil for backfills. PHDs can also be effectively used to reduce the deposition thickness of dredged soft soil deposits significantly (Chai et al. 2014).

There is a paucity of consolidation theories for studying the behavior of PHD improved clayey soils. In the case of PHD, the vertical (S_v) and horizontal (S_h) spacing between individual strips are not equal, and the region of soft soil affected by the installation of a PHD is rectangular in vertical cross-section. According to Hird et al. (1992) and Chai et al. (2001), generally, $S_v > S_h$, and using either the axisymmetric unit cell theory or the plane strain unit cell theory can cause an error in the calculation of the degree of consolidation. This work aims to investigate the degree of consolidation induced by PHDs on clayey deposits by carrying out numerical analysis based on unit cell concept (axisymmetric and plane strain) and to propose suitability zones and matching functions based on the vertical (S_v) and horizontal (S_h) spacing and the width of an individual PHD (w). The finite element analyses were performed using the Abaqus (2016) finite element program that can analyze porous media with pore pressure degree of freedom by coupled analysis based on Biot's generalized consolidation theory (1941). Further, parametric studies were carried out by varying the constitutive soil model, and the effect of different embankment soils was analyzed in terms of pore pressure dissipation and settlement.

2 Design and Analysis Aspects

The behaviour of PHD improved soil is similar to that of PVDs in many ways. The analysis of a single drain can be considered using the unit cell concept. However, since the drains are laid in layers, both horizontal and vertical spacing influence the behavior. This necessitates the formulation of new theories for the analysis of PHD induced consolidation. The field layout of PHDs approaches plane strain/axisymmetric conditions depending upon the spacing parameters and width of PHD adopted in practice. There are two factors that need to be considered in the design of a horizontal drain system. First is the smear effect, which refers to the formation of a less permeable zone in the immediate vicinity of the drain caused by the driving of the mandrel during installation. However, in the case of mixed or remolded soil and where PHDs are placed manually in layers within the soil, the smear effect need not be considered. The second aspect to be considered is the long term clogging of the drain, called the well resistance effect. The discharge capacity must be properly factored to consider this effect. However, when the discharge capacity is quite high, well resistance can be ignored.

Assuming uniform settlement along drain surface (equal strain condition) and an infinite drain discharge capacity, the degree of consolidation due to an individual drain (U_h) can be evaluated as:

$$U_h = 1 - e^{\frac{-8T_h}{\mu}} \tag{1}$$

According to Hird et al. (1992), for an axisymmetric unit cell, the time factor (T_h) in Eq. 1 can be obtained using,

$$T_h = \frac{C_h t}{4B^2} \tag{2}$$

In Eq. 1, μ is given by Eq. (3)

$$\mu = \left[\left(\frac{2}{3} \right) + \left\{ \left(\frac{2k}{BQ_w} \right) (2lz - z^2) \right\} \right] \tag{3}$$

where B = radius of unit cell; z = the vertical distance from the top surface; l = drainage length; k = permeability in the horizontal direction; and Q_w = discharge capacity of the drain per unit width.

Excess pore water pressure (u) in the radial direction (x) at a given time (t) is:

$$u = \left(\frac{\gamma_w}{2} \right) \left(\frac{\partial \varepsilon_v}{\partial t} \right) \left\{ \left(\frac{1}{k} \right) (2Bx - x^2) + \left(\frac{2B}{Q_w} \right) (2lz - z^2) \right\} \tag{4}$$

where,

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{3k(1 - U)u_0}{\gamma_w B^2} \tag{5}$$

where γ_w is the unit weight of water, and $\frac{\partial \varepsilon_v}{\partial t}$ is the volumetric strain rate.

An axisymmetric unit cell is analyzed using Hansbo (1981) equations, where time factor (T_h) in Eq. 1 is given by

$$T_h = \frac{C_h t}{D^2} \tag{6}$$

where D = diameter of dewatered soil cylinder = 2R,

For axisymmetric case, Eq. 3 is replaced by,

$$\mu = \ln\left(\frac{n}{s} \right) + \left\{ \left(\frac{k_c}{k_s} \right) \ln(s) \right\} - 0.75$$
$$+ \pi z (2l - z) \left(\frac{k_c}{q_w} \right) \left\{ 1 - \frac{\left(\frac{k_c}{k_c} \right) - 1}{\left(\frac{k_c}{k_c} \right) (n/s)^2} \right\} \tag{7}$$

$$\text{Here}, \, n = D/d_w, \, s = \left(\frac{d_s}{d_w} \right) \tag{8}$$

[d_w = diameter of drain; d_s = diameter of disturbed zone = $2r_s$; k_c = permeability of soil; k'_c = permeability of soil in disturbed zone].

Excess pore water pressure (u) in the radial direction (r) at a given time (t) for an axisymmetric case is obtained as:

$$u = \left(\frac{\gamma_w}{2k_c} \right) \left(\frac{\partial \varepsilon_v}{\partial t} \right) \left\{ r_e^2 \ln\left(\frac{r}{r_w} \right) - \left(\frac{r^2 - r_w^2}{2} \right) \right\} \tag{9}$$

where,

r_e = radius of unit cell; r_w = equivalent radius of drain.

The volumetric strain rate $\frac{\partial \varepsilon_v}{\partial t}$ can be determined as

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{2k(1 - U)u_0}{\gamma_w r_e^2 \left[\ln\left(\frac{r_e}{r_w} \right) - \frac{3}{4} + \frac{r_w^2}{r_e^2} - \frac{r_w^4}{4r_e^4} \right]} \tag{10}$$

Horizontal drains are effective in stabilizing embankments and slopes (Rahardjo et al. 2003; Nagaharaa et al. 2004; Nogami and Li 2003). Chai et al. (2014) developed a method for the consolidation analysis of dredged mud or clay soil deposits, embedded with prefabricated horizontal drains (PHDs). In the present study, analyses have been conducted adopting the method proposed by Chai et al. (2014), and the work extended to two commonly used elastoplastic models for soils (Mohr–Coulomb and Modified Cam Clay). Suitability zones and matching functions were developed for different spacing and width of PHD commonly adopted in the field.

3 Numerical Modeling

PVDs are installed vertically into the soil up to a certain depth, and therefore the horizontal spacing defines the drain alignment and pattern, which can be either square or triangular. Suitable consolidation theories were developed considering the square or triangular layout to model the PVD alignment. However, in the case of Prefabricated Horizontal Drains, horizontal and vertical spacing varies, and hence the alignment is not always symmetric. According to Chai et al. (2014), for most of the field layout of PHDs, the region of soil improved around a single PHD is rectangular in vertical cross-section. The authors indicated that the rectangular area of soil influenced by a PHD could be represented as an equivalent circular area assuming the equal area condition. The suitability of this assumption depends on the ratios (a) S_v/S_h, and (b) w/S_h. Figure 2a shows the vertical
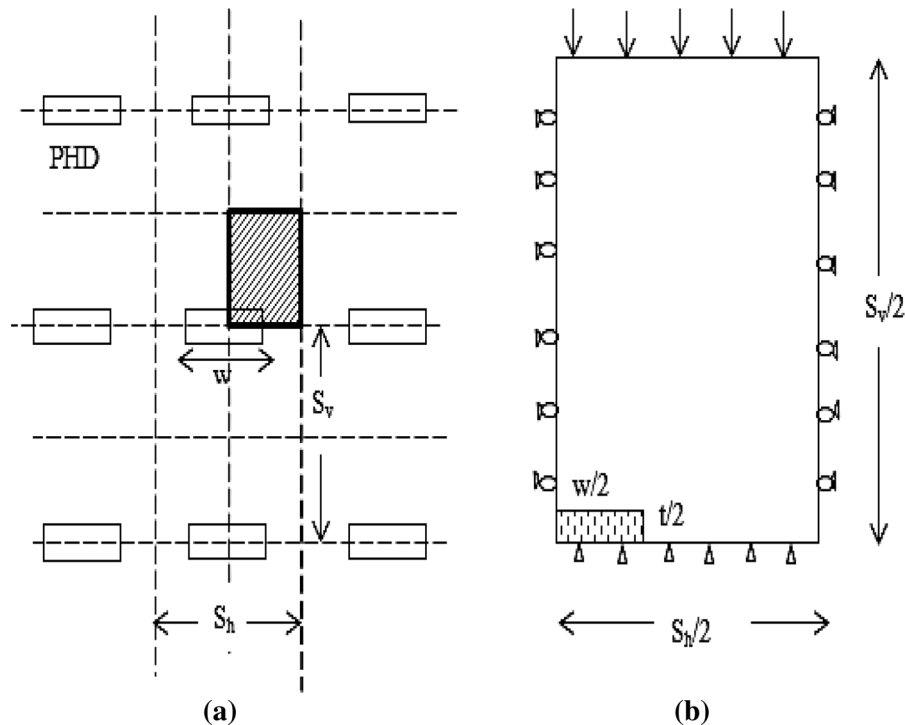
Fig. 2 Representative unit of PHD **a** Layout, **b** unit cell concept

cross-section of a soil element with PHDs, and the influence area around a PHD, forming a unit cell. For ease of analysis, a quarter of this unit cell can be represented in the analyses (Fig. 2b), and analyzed using Hansbo's solution for axisymmetric unit cell (Chai et al. 2014). However, in the case of PHDs, the assumption of an axisymmetric condition does not hold true for all cases. It depends on the spacing ratio S_v/S_h, which is denoted as VH. When S_v and S_h is approximately the same, the ratio VH assumes a value close to unity, and the condition approaches the axisymmetric condition. However, as the value of VH increases, the problem deviates significantly from being axisymmetric and can be more generalized as a plane strain condition.

Another parameter that can influence the behavior of the PHD-improved soil is the ratio of the width of PHD (w) to the horizontal spacing (S_h), which is denoted as WH. When the horizontal spacing is very less compared to the drain's width, the layer assumes a sheet-like condition, thus presuming a plane strain model.

The PHD was modeled using the simplified method proposed by Chai et al. (2001). Here, the drain is

modeled as a soil element with equivalent permeability and elasticity properties. Moreover, it assumes one-dimensional deformation for the drain. In most practical instances, the area covered by the PHDs is very large compared to the thickness of treated ground, making this assumption realistic (Chai et al. 2014). The two main design factors to be considered in prefabricated drains' discharge capacity are the smear effect and well resistance effect. The smearing effect refers to the reduced permeability zone due to the driving of the mandrel. Since PHDs are laid manually in layers, this need not be considered. The well resistance or long term clogging effect can also be ignored if the discharge capacity is greater than 100 m³/year (Chai et al. 2014).

A drain of width 100 mm and thickness of 10 mm is considered for the study. The drain's discharge capacity is assumed to be 100 m³/year, considering the long-term well resistance effect. The soil has a unit weight $\gamma = 16.5$ kN/m³, vertical permeability $k_v = 0.001$ m/day, horizontal permeability $k_h = 0.0015$ m/day, and initial void ratio $e_0 = 1.4$. It is to be noted that a stiffer drain withstands a high deformation of the surrounding soil while maintaining

sufficient flow through the core of the drain (Bergado et al. 1996; Chai et al. 2004). However, the simplified method adopted in this study does not consider the flexural stiffness parameter of the drain, which is required to analyze this effect.

The soil is assumed to have a Modulus of Elasticity (E) of 4000 kPa and Poisson's ratio (μ) 0.4, which categorizes it as medium stiff clay (Das 2002). For a detailed investigation on the suitability of the two approaches, the unit cell is modeled under both axisymmetric and plane strain conditions, for various spacing ratios VH and WH, as shown in Fig. 3a and Fig. 3b, respectively.

Considering the large area of treated ground, it is reasonable to assume one-dimensional vertical deformation of the unit cell for the numerical analysis compared to the treated soil thickness. The soil element is fixed at the bottom, restraining it from all sorts of deformations, whereas the side boundaries are restrained from a horizontal deflection. Regarding the hydraulic boundary, no drainage is allowed on either side or bottom of the soil element. At the top surface of the soil, no drainage is allowed except in the consolidation stage, during which the surface is drained, to dissipate the accumulated pore pressure. Drained conditions are assumed all around the drain considering the very high permeability of the drain. 8-noded quadrilateral, biquadratic displacement, bilinear pore pressure, reduced integration elements (CPE8RP, and CAX8RP) are used for numerical modeling.

Soils neither behave as linearly elastic nor perfectly plastic throughout the loading tenure. It changes with respect to the loading conditions and many other factors. Several researchers have hence proposed various constitutive models to describe soil behavior under different conditions, and the aspects of finite element modeling using these models for a variety of geotechnical applications (Ti et al. 2014). In the current study, the soil behavior during Prefabricated Horizontal Drain (PHD) induced consolidation is examined under three different constitutive models-Linear Elastic, Mohr–Coulomb, and Modified Cam Clay. Table 1 shows the soil properties adopted for the numerical analysis.

Since the assumption of plasticity characteristics of a drain cannot be realistic, the numerical modeling adopted a linear elastic approach for the PHD throughout the investigation. The drain was assumed to behave in a perfectly elastic manner with an Elastic Modulus (E) 4000 kPa, and Poisson's Ratio 0.4.

4 Suitability Studies

The layout of PHDs, as in Fig. 2a, shows that both horizontal and vertical spacing influence the behavior of drain improved ground under consolidation. As the spacing parameters vary, the situation cannot be generalized either to an axisymmetric or plane strain condition. Thus, to initiate the study, two spacing ratios VH and WH were defined as follows.
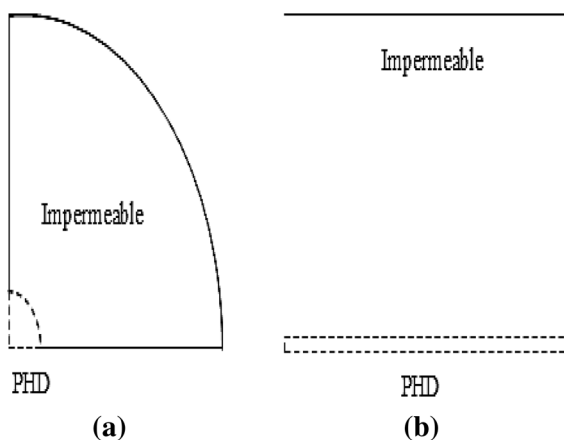

Fig. 3 Various models for analysis **a** Axisymmetric, **b** plane strain

Table 1 Soil properties used in the analyses

Properties	Value
Linear elastic	
Modulus of elasticity, E	4000 kPa
Poisson's ratio μ	0.4
Mohr–Coulomb	
Cohesion, c	3.5 kPa
Angle of internal friction, ϕ	31°
Dilatancy angle, ψ	0.1°
Modified Cam Clay	
Log plastic bulk modulus, λ	0.103
Swelling index, κ	0.006
Initial void ratio, e_0	1.4
Stress ratio, M	1.2

$$VH = \frac{S_v}{S_h} \text{ and } WH = \frac{w}{S_h} \tag{11}$$

where S_v, S_h, and w refers to the vertical spacing, horizontal spacing, and width of the drain, respectively.

In the field layout, the drain's spacing must be such that the entire soil is effectively drained under the system of PHDs. The dimensions and the draining area along the length being very much higher than the vertical cross-section; it is practically assumed that the vertical spacing is, in general, higher than horizontal spacing. Considering this, the study investigated 30 cases, where VH is varied from 1 to 6 and WH from 0.1 to 0.5. A suitability study was done on the model with these parameters. The degree of consolidation predicted from the finite element analyses using plane strain and axisymmetric unit cell models were compared with the theoretical solutions proposed by Hansbo (1979) and Hird et al. (1992). Due to the differences in basic assumptions used in various consolidation theories, the actual consolidation process cannot be directly compared with any theory or numerical modeling. Hence, to minimize error, a target matching degree of consolidation was set to be 50%. Each case was modeled under axisymmetric and plane strain conditions, and the time required for 50% consolidation(t_{50}) at mid-depth was recorded and compared with the theoretical values obtained by Hansbo (1979) and Hird et al. (1992) solution, respectively.

The coefficient of consolidation (C_v) is an important parameter that governs compressible soil's behavior, and a representative value of C_v can be determined from the properties of soil. The most established relation represents C_v as a function of permeability and compressibility coefficient, which is given by the equation:

$$c_v = \frac{k}{m_v \gamma_w} \tag{12}$$

where k = coefficient of permeability; γ_w = unit weight of water and m_v = coefficient of volume compressibility.

Chai (2001) reported that considering the coefficient of permeability (k) as constant or varying with void ratio (e) gives a higher rate of C_V values with vertical stress than the measured data. For simplicity, in the present study, the value of the coefficient of

permeability (k) has been assumed to be constant. According to Chai (2001), the coefficient of volume compressibility (m_v) for elastoplastic analysis with linear e-ln p relationship can be expressed as:

$$m_v = \frac{\lambda}{(1+e)p\prime} \tag{13}$$

Here, e = void ratio; p′ = mean effective stress; λ = slope of virgin compression curve in e-ln p′ plot.

Based on Eqs. 12 and 13, the coefficient of consolidation (C_v) could be expressed as follows (Chai et al. 2001)

$$C_v = \frac{(1+e)p\prime k}{\lambda \gamma_w} \tag{14}$$

The mean effective stress p′ at mid-depth for 50% consolidation is computed as the difference of corresponding total stress and excess pore pressure. The excess pore pressure is determined using Eqs. 4 and 5 for plane strain conditions and Eqs. 9 and 10 for axisymmetric conditions.

The soil was modeled under three constitutive laws-Linear elastic, Mohr–Coulomb, and Modified Cam Clay approach. The ratios t_a and t_p indicate the accuracy of numerical modeling (axisymmetric and plane strain, respectively) of PHD improved soil. The ratios t_a and t_p were defined as follows.

$$t_a = \frac{t_{50num}}{t_{50theo-axi}} \text{ and } t_p = \frac{t_{50num}}{t_{50theo-pl}} \tag{15}$$

t_{50num} = t_{50} obtained numerically using ABAQUS.

$t_{50theo-axi}$ = t_{50} obtained by Hansbo (1979) solution for axisymmetric conditions.

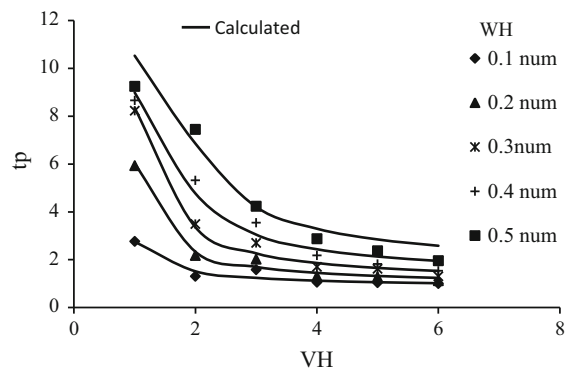$t_{50theo-pl}$ = t_{50} obtained by Hird et al. (1992) solution for plane strain conditions.

Fig. 4 t_p versus VH relations under linear elastic approach

Figures 4, 5, 6 shows the variation of t_p with VH for different WH values ranging from 0.1 to 0.5 for Linear Elastic, Mohr–Coulomb, and Modified Cam clay approach, respectively. For each value of WH (ranging from 0.1 to 0.5), the time required for 50% consolidation (t_{50}), obtained from numerical modeling is compared with the corresponding theoretical value (Hansbo 1979). It is noted that for higher values of VH, the value of t_p approaches unity, indicating a higher accuracy of plane strain modeling. Similarly, Figs. 7, 8, 9 shows the variation of t_a with VH for different WH values ranging from 0.1 to 0.5 for Linear Elastic, Mohr–Coulomb, and Modified Cam clay approach. For each value of WH (ranging from 0.1 to 0.5), t_{50} obtained from numerical modeling is compared with the corresponding theoretical value (Hird et al. 1992). From the plots, it is clear that as the spacing ratio VH reduces, the situation approaches axisymmetric condition, which is indicated by a reduction in the value of t_a, approaching unity. From the above suitability studies, a matching method was proposed to analyze PHD induced consolidation. For this, curve fitting was done to express t_a and t_p as functions of VH and WH. The coefficient of consolidation was modified by a factor which is calculated based on the relative compatibility of numerical results with theoretical values.

The proposed method for analysis of PHD induced consolidation involves the following steps.

a. For a given value of WH and VH, first identify the modeling condition to be used, from the suitability zones derived.

b. Predict the value of t_a or t_p as relevant, from the corresponding equations derived.
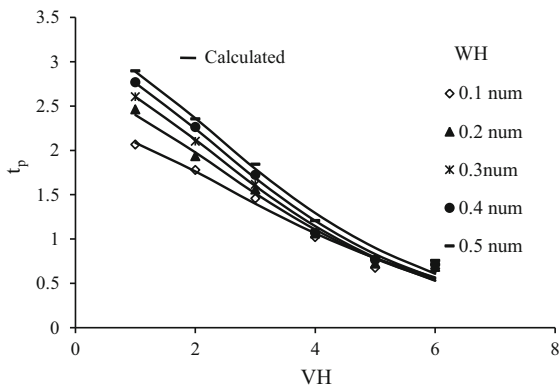

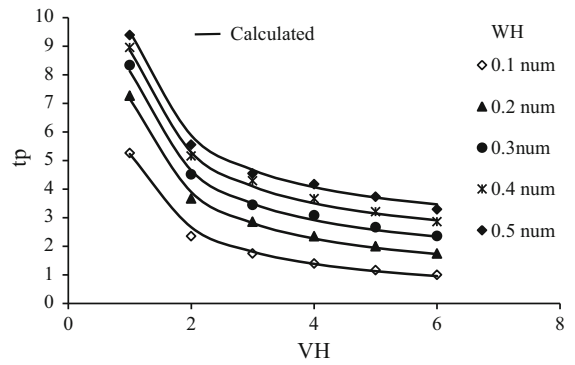**Fig. 5** t_p versus VH relations under Mohr Coulomb approach

Fig. 6 t_p versus VH relations under modified cam clay approach
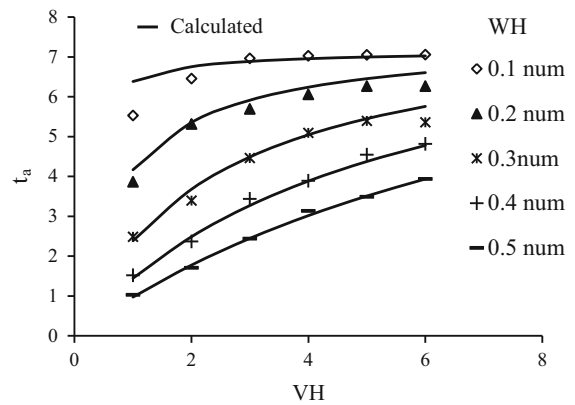

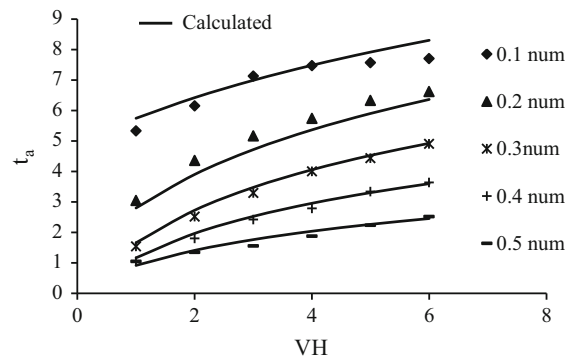**Fig. 7** t_a versus VH relations under linear elastic approach

Fig. 8 t_a versus VH relations under Mohr Coulomb approach

c. Calculate the value of equivalent coefficient of consolidation, $c' = c/t_a$ or $c'' = c/t_p$ as per the criteria.

d. Using the equivalent coefficient of consolidation, evaluate the consolidation parameters using the established axisymmetric or plane strain unit cell
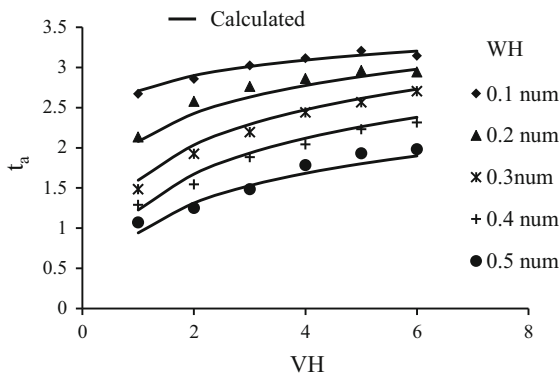
Fig. 9 t_a versus VH relations under Modified Cam Clay approach

theories (Hansbo 1979 and Hird et al. 1992, respectively).

The proposed matching equations obtained are as follows.

a. Linear Elastic

$$t_a = \frac{a(VH)}{((VH) + b)} \quad (16a)$$

$$t_p = ce^{d/VH} \quad (16b)$$

$$a = 7.07e^{11.416(WH)^2} \quad (16c)$$

$$b = 60.34(WH)^{2.69} \quad (16d)$$

$$c = 0.8122e^{2.6759(WH)^2} \quad (16e)$$

$$d = 1.088\ln(WH) + 3.63 \quad (16f)$$

Figure 7 show the compatibility of the proposed matching functions (Eq. 16a–f) for the analysis of linear elastic soil model under plane strain and axisymmetric approaches, respectively. In the same way, matching functions were also proposed for Mohr–Coulomb and Modified Cam Clay models (Eqs. 17a–f and 18a–f). From Figs. 5, 6, 8, and 9, it can be noted that these are compatible to analyse the consolidation characteristics of PHD improved soil with reasonable accuracy.

b. Mohr–Coulomb

$$t_a = a\ln[(VH) + b] \quad (17a)$$

$$t_p = ce^{-d(VH)} \quad (17b)$$

$$a = 3.791e^{-4.42(WH)^2} \quad (17c)$$

$$b = 48.61(WH)^{10.982(WH)} \quad (17d)$$

$$c = 0.922e^{1.364(WH)} \quad (17e)$$

$$d = -0.146e^{-0.339/(WH)} \quad (17f)$$

c. Modified Cam Clay

$$t_a = a(\ln(VH)) + b \quad (18a)$$

$$t_p = \frac{c}{(VH) + d} \quad (18b)$$

$$a = 0.654\sin(4.371(WH)) \quad (18c)$$

$$b = 3.525e^{-2.64(WH)} \quad (18d)$$

$$c = 7.408(WH)^{0.016/(WH)} \quad (18e)$$

$$d = 5.384(WH) - 0.434 \quad (18f)$$

The results of suitability studies show that for different spacing ratios and different soil constitutive models, either axisymmetric or plane strain analyses give more accurate and compatible results. Using this feature, based on t_a and t_p values obtained from numerical analyses, suitability zones were derived for the three different constitutive models (Figs. 10, 11 and 12). These zones can be used to identify the suitable modeling method to be adopted for the given spacing parameters.
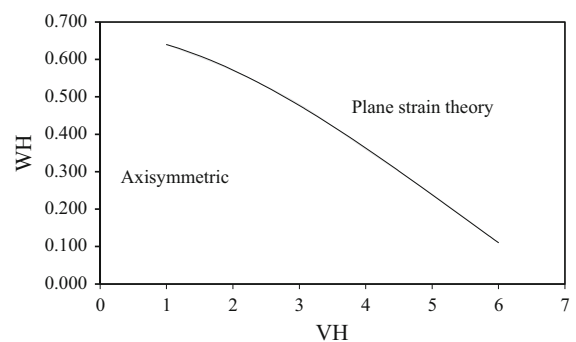

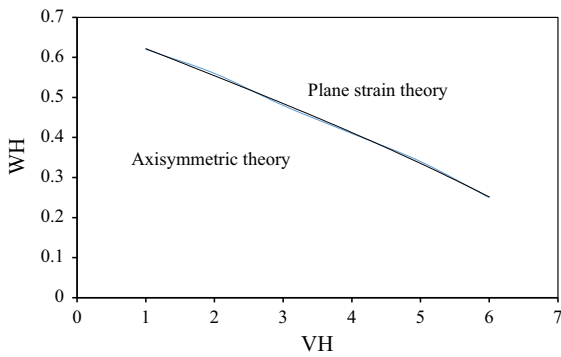**Fig. 10** Suitability zones under linear elastic approach

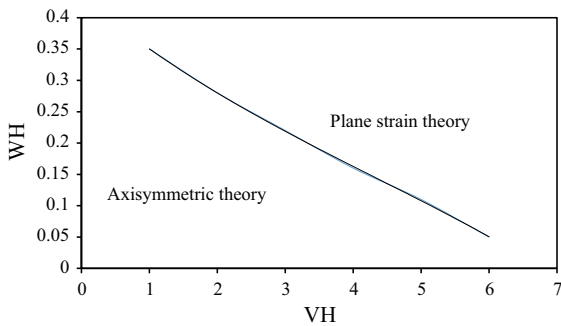**Fig. 11** Suitability zones under Mohr–Coulomb approach

Fig. 12 Suitability zones under modified cam clay approach

It is found that in general, for lower spacing ratio VH, the vertical spacing and horizontal spacing being almost equal, the drain induced soil model approaches axisymmetric condition, and hence axisymmetric modeling is suitable to analyze such situations. However, as VH and WH increase, the situation is more of a plane strain condition, as is expected due to the sheet-like layout of the drains. However, the suitability zones for each constitutive model slightly differ from each other. For the linear elastic model, at small values of WH (< 0.2), the situation is a plane strain, even for the very low value of VH. This anomaly is probably a reflection of the error caused by neglecting the plasticity parameters of the soil.

The Modified Cam Clay model is found to be most accurate in predicting soft soil behavior. Here the effect of spacing parameters on the modeling conditions is clearly observed. For high values of WH and VH, the drain behaves like a sheet, and thus the model approaches plane strain condition, which is clearly observed from the results.

5 Drain Effect Studies

The second major objective of the study was to analyze the drain effect under different conditions. The two primary influential factors considered in the analyses are the fill material properties and the drain's spacing. Three different types of fill material- namely soft silty clay, medium silty clay, and silty clay were considered in the study. Spacing ratios were selected such that the extreme cases of VH (1 and 6) and WH (0.1 and 0.5) are analyzed and compared. The drain effect was analyzed in terms of reduction in consolidation time and settlement. The two parameters defined to study the drain effect were:

$$t_i = \frac{t_{50nd}}{t_{50d}} \text{ and } u_i = \frac{u_{50nd}}{u_{50d}} \tag{19}$$

where t_{50d} and t_{50nd} refer to the time for 50% consolidation with and without drain, and u_{50d} and u_{50nd} refer to settlement at 50% consolidation with and without a drain.

The drain effect was analyzed in terms of t_i and u_i for different spacing ratios and embankment fill materials. As already mentioned, for simplicity, only the extreme cases (VH 1 and VH 6, with WH 0.1 and WH 0.5 respectively) were analyzed, so as to evaluate the maximum and minimum effect. The study was done under the Cam Clay approach since it was found to be more accurate to represent the soft soil behavior based on the studies above.

5.1 Effect of Properties of Fill Material

To study the effect of fill material, the following soils were considered-Soft Silty Clay (SSC), Medium Silty Clay (MSC), and Silty Clay (SC). Figure 13a–d shows the variation in t_i for the three types of soil, under various spacing conditions.

It can be seen that for all spacings, consolidation time is significantly reduced by the effect of PHD. However, the magnitude of drain effect changes from soil to soil. From Fig. 13, it can be seen that for a given spacing ratio VH, the effect is more pronounced in soft silty clays (SSC) and the least for silty clays (SC). Medium silty clays (MSC) show an intermediate value of t_i compared to SSC and SC. This behavior can be attributed to the increasing order of plasticity from SC to SSC. The improvement in the consolidation rate is more pronounced for highly plastic soil. This is

Fig. 13 Effect on consolidation time for three different types of embankment fill material at various drain spacing ratios **a** WH 0.1VH 1, **b** WH 0.1VH 6, **c** WH 0.5VH 1, **d** WH 0.5VH 6
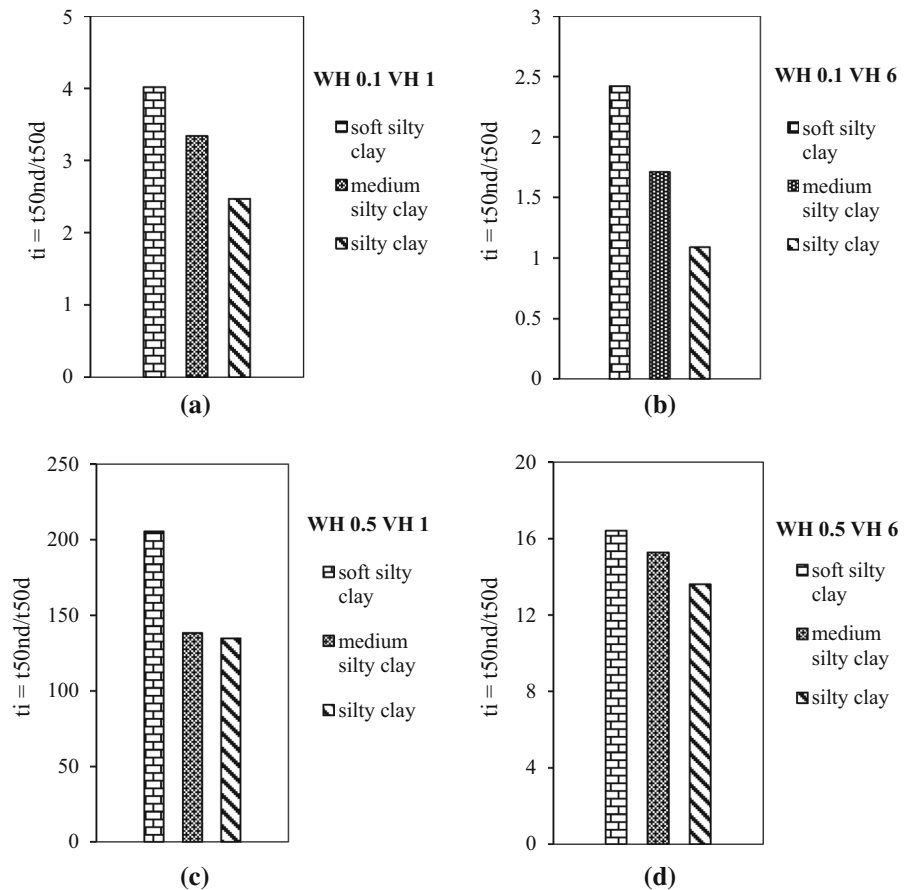
reasonably expected because, as the fines content and plasticity increases, the permeability of clay decreases. Thus, the effect of the inclusion of a very high permeable drain in such a soil will be more pronounced. The maximum reduction in t_{50} is 200 times the actual time, whereas the minimum achieved is found to be around 2.5.

The rate of consolidation is also reflected in the settlement achieved at a particular time. To analyze the effect of drain in terms of the settlement, numerical modeling was done as before, and the magnitude of settlement achieved at 50% consolidation was noted. Settlement achieved at the time when drain improved ground achieved 50% consolidation was compared. Figure 14a–d shows the variation in u_i for the three types of soils at the four extreme spacing ratios, as already explained.

It can be seen that for all spacings, both consolidation time and settlement is significantly improved by the effect of PHD. However, the magnitude of the

drain effect differs slightly from soil to soil. It can be clearly seen that for a given spacing ratio VH, the effect is more pronounced in soft silty clays (SSC), and the least for silty clays (SC). Medium silty clays (MSC) show an intermediate value of u_i compared to SSC and SC.

5.2 Effect of Drain Spacing

As discussed in the previous sections, the spacing parameters have a significant impact on the effect of the drain on the surrounding soil. As drains come closer, the effect is expected to be more. To analyze this, the previous drain effect studies were represented in a reverse manner. The three types of soils (SSC, MSC, and SC) were modeled under various spacing parameters, and the effect was analyzed in terms of consolidation time and settlement rate, using the predefined parameters t_i and u_i.

Fig. 14 Effect on settlement for three different types of embankment fill material at various drain spacing ratios **a** WH 0.1VH 1 **b** WH 0.1VH 6 **c** WH 0.5VH 1 **d** WH 0.5VH 6
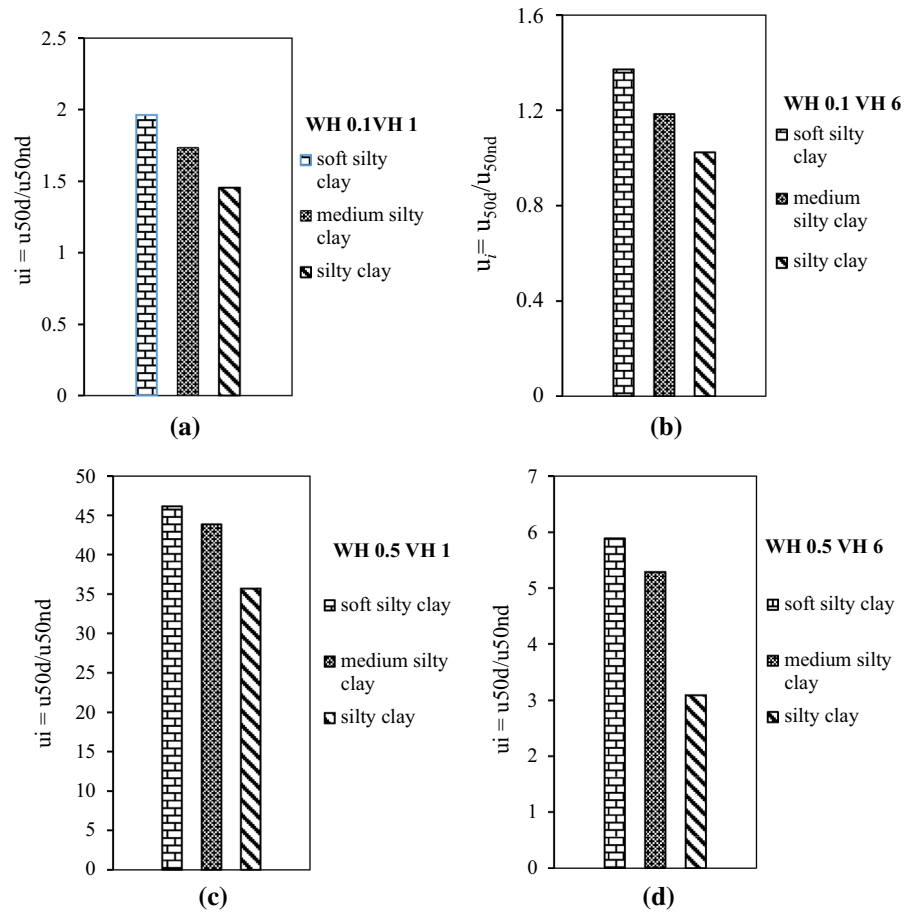
From Fig. 15a–c, it is clearly observed that the maximum drain effect is achieved when WH = 0.5 and VH = 1, and the least for WH 0.1 and VH 6. This is reasonably justified because in the former case, the drains are relatively closer and hence effectively drains water from the surrounding soil. In the latter, the drains are farther away, and the influence zones may not cover the entire area of ground, and hence, the effect of the drain will be less.

The settlement is enhanced by the inclusion of drain for all types of soils. Figure 16a–c shows the effect of the drain on soft silty clay, medium silty clay, and silty clay at various spacing ratios. As expected, the effect was maximum when the drain spacing ratio VH is least, and WH is maximum. This shows the increasing effect of drains as they come closer. With an increase in WH, the drain width relative to the horizontal spacing increases, which implies a greater draining effect from the surrounding soils, which in turn enhances the settlement.

6 Limitations and Scope for Future Study

Numerical modeling of sinusoidal buckling of Prefabricated Horizontal Drains under the significant confining stress, and the clogging of pores is a challenging study. This work addresses an approximation method based on axisymmetric and plane strain unit cell consolidation theory to model PHDs. The limitations of the present study are listed below, which can be addressed in future studies.

- As the hydraulic behavior of PHDs plays an important role in the embankment settlement, eight noded pore pressure-coupled quadrilateral elements were used to model PHD. Well resistance was neglected, as the discharge capacity of drains adopted in the analyses was significantly high (Holtz 1989; Chu et al. 2004; Indraratna et al. 2003). The problem of reduction of discharge capacity due to the deformation of PVDs by

Fig. 15 Effect on consolidation time at various drain spacing ratios for **a** Soft silty clays, **b** medium silty clays, **c** silty clays
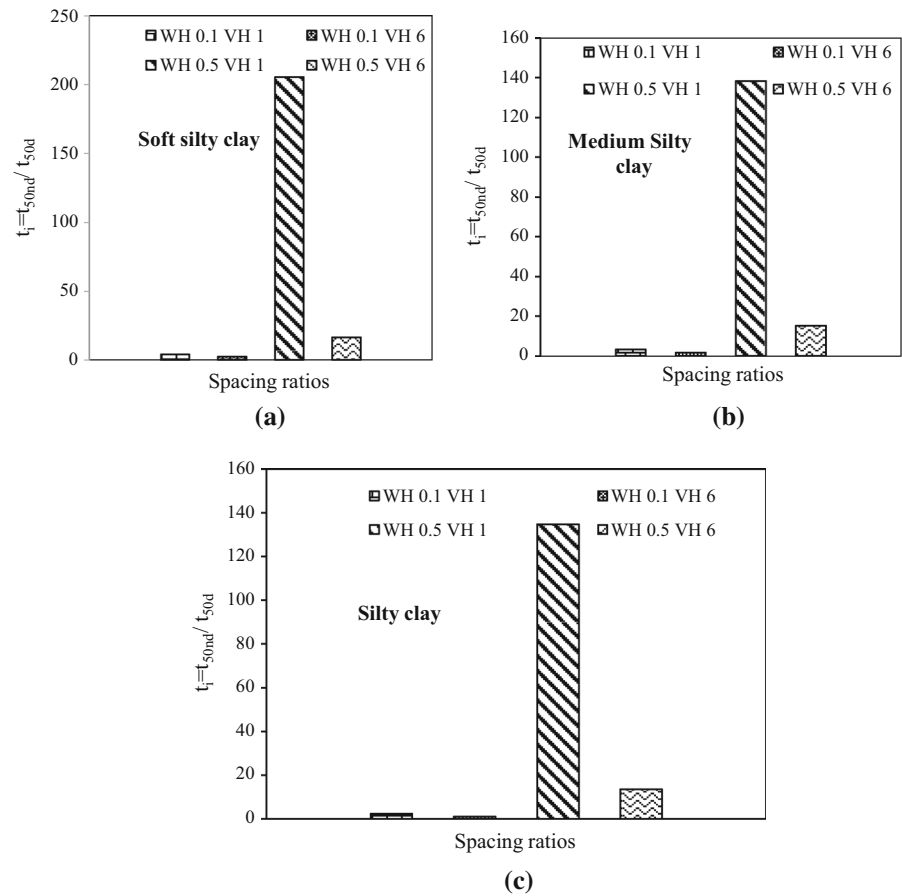

folding, kinking, and bending due to lateral confining stress and consolidation settlement of the clay layer around it has been experimentally studied by many researchers (Bergado et al. 1996; Aboshi et al. 2001; Chu et al. 2006; Tran-Nguyen et al. 2010). However, there is a paucity of numerical studies in this regard. In the case of PHDs, unlike PVDs, the effect of vertical confining stress may be significant due to the horizontal alignment of PHDs in the field. This may cause sinusoidal buckling of PHDs along its horizontal length affecting the discharge capacity. Detailed field and numerical studies are required to evaluate the potential of using PHDs in the field to accelerate the consolidation of embankments constructed with dredged mud or clayey fills.

- According to researchers (Bergado et al. 1996; Chai et al. 2004), a stiffer drain withstands a high deformation of the surrounding soil while maintaining sufficient flow through the core of the drain.

To account for these effects, flexural stiffness of drains need to be incorporated into the numerical analyses.

- Another practical problem with PHDs is the clogging of pores of the filter sleeve, which reduces the discharge capacity. Basu and Madhav (2000), using the finite difference method, studied the effect of different degrees of clogging of PVD pores on the average degree of consolidation. A Dirichlet boundary condition (excess pore pressure set to zero) was imposed on the nodes referring to PVD (no clogging). To account for clogging, Neumann boundary condition (gradient made equal to zero) was imposed on selected nodes on the PVD boundary i.e.no flow occurs across those nodes. However, the present study does not incorporate these parameters in the modeling of PHDs, which the authors recommend as a future study for a comprehensive analysis of the behavior of PHD in the field.

Fig. 16 Effect on settlement at various drain spacing ratios for **a** Soft silty clays, **b** medium silty clays, **c** silty clays

(a)

(b)

(c)
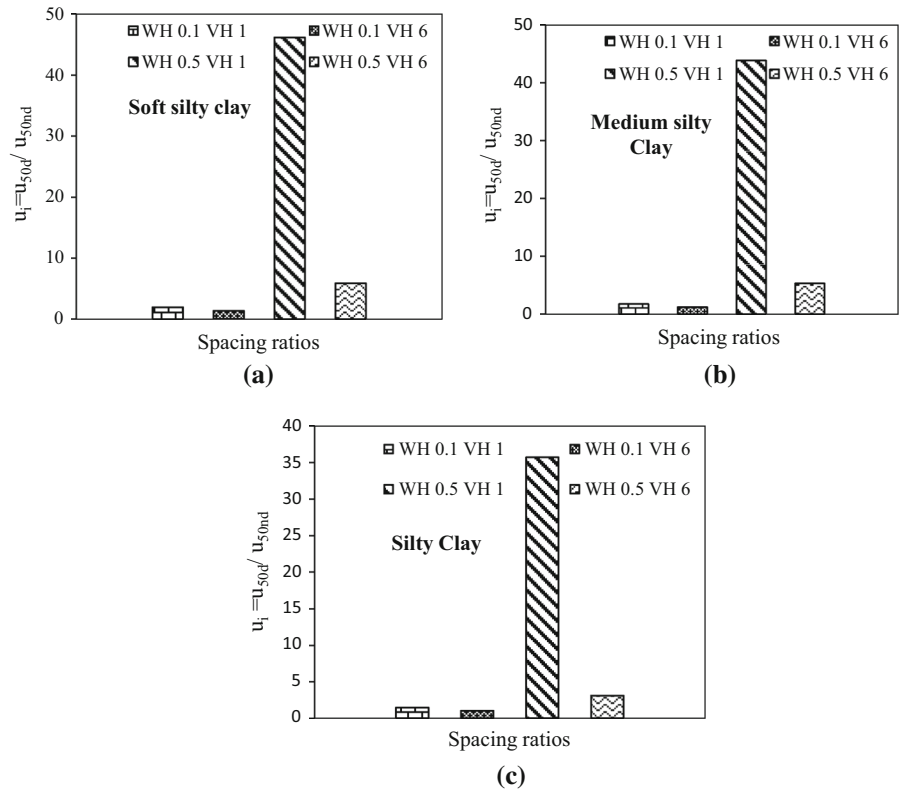
7 Conclusions

In this paper, a two-dimensional study based on coupled analysis was carried out to investigate the behavior of Prefabricated Horizontal Drain (PHD) induced consolidation in clayey embankment fills. The study adopted the simplified modeling method proposed by Chai et al. (2001), in which the drain was modeled using CPE8RP and CAX8RP elements for plane strain and axisymmetric analyses with equivalent drain permeability properties. Suitability of axisymmetric and plane strain conditions for modeling the drain was studied under varying vertical (S_v) and horizontal (S_h) spacing between individual strips. Suitability zones and matching functions in order to calculate the equivalent coefficient of consolidation of the PHD improved soil were proposed for various soil models. Based on the numerical investigations, the following conclusions can be drawn:

- The suitability of axisymmetric and plane strain modeling conditions varied with respect to the spacing parameters VH and WH. At a lower spacing ratio VH, the situation approached axisymmetric condition, and the numerical analysis yielded results matching with the established theoretical solutions. As the spacing ratio increased, the condition deviated from axisymmetric towards the plane strain approach.

- The reduction in consolidation time and acceleration in the settlement was maximum in soft silty clays as compared to medium silty clays and silty clays.

- The effect of the drain is maximum at lower values of VH, when the drains are laid at closer spacing.

- Suitability zones were derived for choosing the best-suited modeling condition to be adopted for numerical modeling of PHD improved ground, for any spacing ratios within a practical range of VH (1–6) and WH (0.1–0.5).

- Matching functions have been proposed for t_a and t_p in terms of VH and WH. Knowing t_a and t_p, the equivalent coefficient of consolidation due to PHD can be calculated for axisymmetric and plane strain conditions for the range of drain spacing ratios adopted in the field.

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