# EFFECT OF SOIL DISTURBANCE ON CONSOLIDATION AIDED BY PREFABRICATED VERTICAL DRAIN

**Dipanjan Basu[1] & Monica Prezzi[2]**

[1] *Purdue University. (e-mail: dbasu@purdue.edu)*
[2] *Purdue University. (e-mail: mprezzi@purdue.edu)*

**Abstract:** Soil disturbance caused by the installation of prefabricated vertical drains (PVDs) has a detrimental effect on the rate of consolidation. Finite element analyses are performed to study the effect of soil disturbance by considering the variation of hydraulic conductivity in the disturbed zone. A zone of transition between the smear and undisturbed zones, as observed in recent experiments, is included in the analysis. PVDs installed in a triangular pattern are only considered, and the actual band shape of the PVD and the hexagonal zone of influence around it are used in the analysis. Guidelines are given for using an equivalent system, where the transition zone is replaced by an expanded smear zone producing the same effect. This equivalent-system approach allows the use of existing analytical solutions that consider only the smear zone in analysis and design.

**Keywords:** consolidation, ground improvement, Prefabricated Vertical Drain (PVD), numerical, soft soil.

## INTRODUCTION

Installation of prefabricated vertical drains (PVDs) in soft clayey soil deposits is a common means by which the consolidation process in these soils is accelerated so that a rapid gain of soil strength and stiffness occurs. The installation of PVDs is done by mandrels, which disturbs the soil surrounding the PVDs. As a result of this disturbance, the hydraulic conductivity in the soil surrounding the PVD decreases, which results in delayed consolidation.

Proper quantification of soil disturbance is required to estimate the required PVD spacing for a target degree of consolidation within a specified time. Design methods (e.g., Hansbo 1981) available for PVDs capture the effect of soil disturbance by typically reducing the in situ hydraulic conductivity in the disturbed zone (also called the smear zone). The assumption made in these methods is that the hydraulic conductivity is spatially constant over the entire disturbed (smear) zone. However, it has been shown recently through laboratory and field studies (Onoue et al. 1991, Madhav et al. 1993, Indraratna and Redana 1998, Sharma and Xiao 2000) that the hydraulic conductivity typically has a spatial variation within the disturbed zone (Figure 1). In the highly disturbed smear zone immediately surrounding the PVD, the hydraulic conductivity remains spatially constant at $k_{hs}$ that is approximately 0.1-0.3 times the in situ hydraulic conductivity $k_{ho}$; between the smear and the undisturbed zones there exists a transition zone in which the hydraulic conductivity increases, approximately linearly, with increasing radial distance $r$ from the center of the PVD. The smear zone extends to about 2-3 times the radius $r_{m,eq}$ of the equivalent circular mandrel; the outer boundary of the transition zone (interfacing with the undisturbed zone), measured from the center of the drain, extends to a distance equal to approximately 6-12 $r_{m,eq}$.

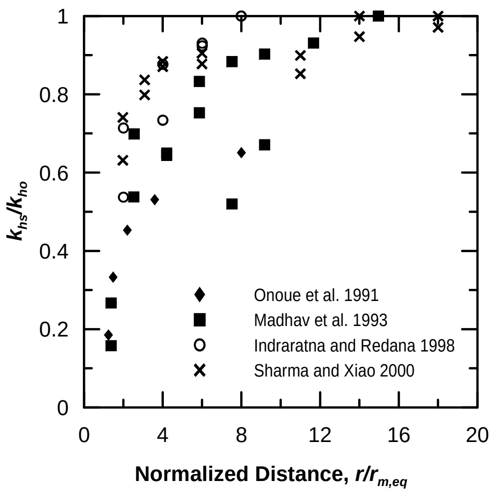


**Figure 1**. Variation of hydraulic conductivity in the disturbed zone

In this paper, we consider the spatial variability of hydraulic conductivity to investigate the effect of soil disturbance on consolidation rate of soils engineered with PVDs. We perform two-dimensional finite element (FE) analysis based on the Terzaghi-Rendulic theory of consolidation. PVDs with a typical cross sectional dimension of 100 mm × 4 mm are assumed to be installed in a triangular pattern with a center-to-center spacing $s$. The resulting unit cell is a hexagon (in plan) with each side equal to $s/\sqrt{3}$ (Figure 2). The actual hexagonal shape of the unit cell, the band shape of the PVD, and the rectangular shape of the smear and transition zones are used in the analysis. A method of replacing the transition zone by an equivalent expanded smear zone is outlined so that existing analytical solutions considering only a smear zone can be used in design.

**ANALYSIS**

The shape and size of the disturbed zone depends primarily on the mandrel shape and size. In this paper, we consider rectangular mandrels ($a \times d$), which create disturbed zones that have rectangular or nearly rectangular (e.g., elliptical) shape in plan. We assume in the analysis that the smear and transition zones are rectangular with dimensions $l_x \times l_y$ and $t_x \times t_y$, respectively (Figure 2). The size of the smear zone depends on a large extent on the smaller dimension of the mandrel (i.e., the width $d$ of the mandrel) and not on its equivalent radius $r_{m,eq}$ because, when an elongated rectangular object (mandrel) is inserted in the ground, soil is pushed mostly in the direction parallel to its shorter dimension. Assuming that the thickness of the smear zone surrounding the mandrel remains constant along the entire mandrel perimeter (Figure 2), the dimensions $l_x \times l_y$ of the smear zone can be obtained from

$$l_y = pd \tag{1}$$

$$l_x = a + (p-1)d \tag{2}$$

where $p$ is a parameter with $2 \le p \le 3$, $a$ and $d$ are the dimensions of the mandrel cross section with $a > d$. The transition zone dimensions $t_x \times t_y$ can likewise be obtained from Eqs. (1) and (2) where $l_y$ and $l_x$ are replaced by $t_y$ and $t_x$, respectively, with $p$ ranging between 6 and 12. The choice of values of $p$ for the smear and transition zones is consistent with the values found in the literature.

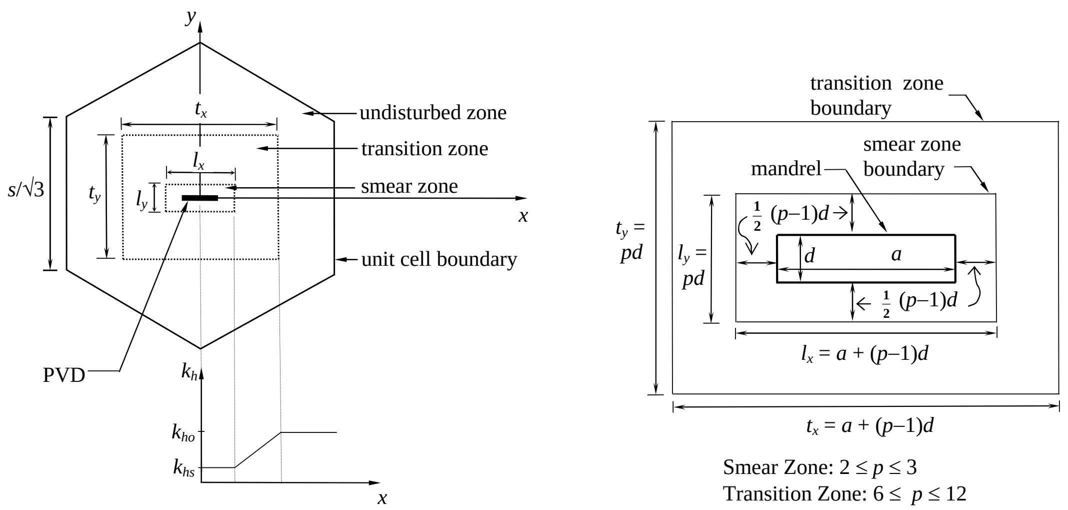


**Figure 2**. Hexagonal unit cell and rectangular disturbed zone

The hydraulic conductivity in the smear and undisturbed zones are assumed to be constants with values $k_{hs}$ and $k_{ho}$, respectively. In the transition zone, the conductivity is assumed to increase linearly from $k_{hs}$ to $k_{ho}$ as the distance from the PVD increases (Figure 2).

Finite element analysis is performed for the above domain and hydraulic conductivity profile following the Terzaghi-Rendulic differential equation for two-dimensional consolidation (see Basu and Prezzi 2007 for the details of the analysis):

$$\frac{\partial u}{\partial T} = d_{c,eq}^2 \frac{k_{hd}}{k_{ho}} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \tag{3}$$

where $k_{hd}$ is the hydraulic conductivity within the disturbed zone and $u(x, y, T)$ is the excess pore pressure at any point with coordinates $(x, y)$ at a time factor $T$. It is assumed that soil disturbance only affects the hydraulic conductivity and not the compressibility of the soil. If a finite element lies within the smear zone, then $k_{hd}$ is equal to $k_{hs}$, if the element lies in the undisturbed zone, then $k_{hd}$ is equal to $k_{ho}$, and if the element lies in the transition zone, then $k_{hd}$ is linearly interpolated between $k_{hs}$ and $k_{ho}$. The diameter of the equivalent circular unit cell is given by:

$$d_{c,eq} = \sqrt{\frac{2\sqrt{3}}{\pi}} s \tag{4}$$

The time factor $T$ is defined in this analysis as:

$$T = \frac{c_h t}{d_{c,eq}^2} \tag{5}$$

The degree of consolidation $U$ at any particular time (or time factor) is given in terms of integrals of the pore pressure over the unit cell domain as (Madhav et al. 1993):

$$U = 1 - \frac{\int_y \int_x u(x, y, T)\ dxdy}{\int_y \int_x u_{ini}\ dxdy} \tag{6}$$

where $u_{ini}$ is the initial excess pore pressure. The above integrations are performed at the Gauss points within each finite element.

## RESULTS

### Effect of Soil Disturbance

The effects of the smear and transition zones on the degree of consolidation are investigated for PVDs installed with a mandrel of 125 mm × 50 mm at 1-m spacing. The degree of disturbance, quantified in terms of $k_{hs}/k_{ho}$, is maintained constant at a value of 0.2. The smear and transition zones are assumed to extend to 2$d$ ($p$ = 2) and 12$d$ ($p$ = 12), respectively. Soil disturbance has a substantial detrimental effect on the effectiveness of the PVD in accelerating consolidation (Figure 3). Compared with the no-disturbance condition, $T$ (for $U$ = 90%) increases by 171% (from $T$ = 0.65 to 1.76), if only the smear zone is considered, and by 262% (from $T$ = 0.65 to 2.35), if both the smear and the transition zones are considered. The difference in $T$ between the cases with only the smear zone ($T$ = 1.76) and both the smear and transition zones is 34% ($T$ = 2.35).

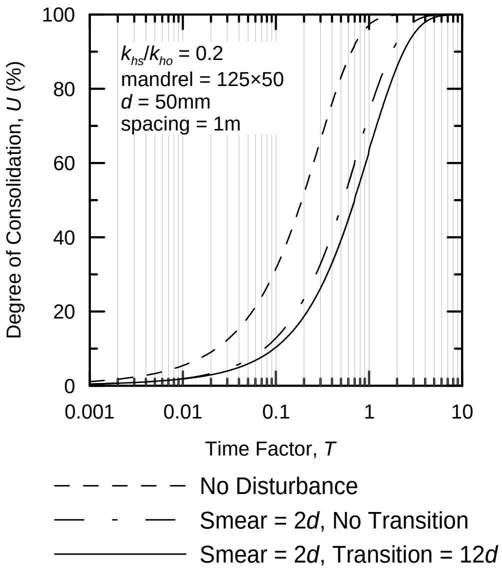


**Figure 3**. Effect of soil disturbance on consolidation rate

### Degree of Disturbance

The degree of soil disturbance is accounted for by the ratio $k_{hs}/k_{ho}$. The $k_{hs}/k_{ho}$ ratio was varied from 0.05 to 0.5 for PVDs installed with a mandrel of 125 mm × 50 mm at 1-m spacing. The smear and transition zone dimensions $l_y$ and $t_y$ were taken as 2$d$ and 12$d$, respectively. The values of $T$ corresponding to $U$ = 90% are 7.36, 4.13, 2.35, 1.69 and 1.11 for $k_{hs}/k_{ho}$ equal to 0.05, 0.1, 0.2, 0.3 and 0.5, respectively. For PVDs installed with a mandrel of 150 mm × 150 mm at 3-m spacing, the corresponding values of $T$ are 12.43, 6.76, 3.73, 2.62 and 1.7. Interestingly, the variation of $T$ with $k_{hs}/k_{ho}$, for a constant $U$, follows a power law (Figure 4). Therefore, for a given value of $U$, $T$ can be expressed in terms of $k_{hs}/k_{ho}$ as

$$T = C_1 \left( \frac{k_{hs}}{k_{ho}} \right)^{-C_2} \tag{7}$$

where $C_1$ and $C_2$ are real positive numbers.

Clearly, the degree of disturbance has a significant effect on the consolidation rate. The impact of the degree of disturbance on the consolidation rate is much more pronounced than that of the dimensions of the smear and transition zones. Therefore, the degree of disturbance needs to be predicted with greater accuracy than the extents of the zones of disturbance surrounding the PVD in order to produce a successful design.

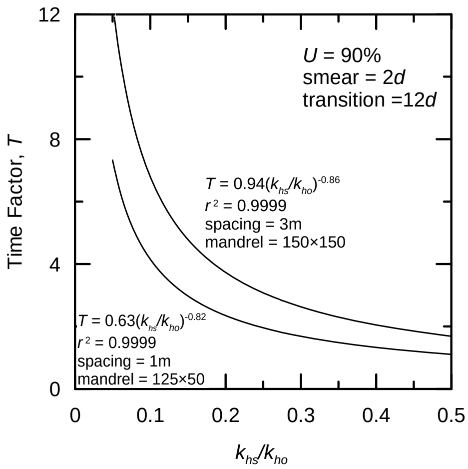


**Figure 4.** Dependence of time factor on the degree of disturbance

**Disturbed Zone Dimensions**

Two dimensions of the smear zone, corresponding to $l_y$ equal to 2*d* and 3*d*, are compared for a fixed transition zone size $t_y$ equal to 12*d* for the case of 1-m spacing and 125 mm × 25 mm mandrel with $k_{hs}/k_{ho}$ = 0.2. It was found that *T* required for 90% consolidation is equal to 2.35 and 2.55 for a smear zone size $l_y$ equal to 2*d* and 3*d*, respectively; the difference between the two cases being 8.5%.

The effect of the extent of the transition zone is studied by considering values of $t_y$ equal to 6*d* and 12*d*, with a fixed smear zone size $l_y$ equal to 2*d*. It was observed that *T* values corresponding to 90% consolidation are equal to 2.07 and 2.35 for $t_y$ equal to 6*d* and 12*d*, respectively; the difference being 13.5%.

Thus, for a given degree of disturbance, the extents of the smear and transition zones have a moderate impact on the rate of consolidation.

**Mandrel Size and Shape**

The effect of mandrel size is studied for two different PVD spacings (1 m and 3 m), with smear and transition zone dimensions $l_y$ and $t_y$ equal to 2*d* and 12*d*, respectively, and a ratio $k_{hs}/k_{ho}$ of 0.2. Four different mandrel sizes: 125 mm × 50 mm, 150 mm × 50 mm, 120 mm × 120 mm and 150 mm × 150 mm are used. Figure 5 shows the *U* versus *T* curves for the 1-m PVD spacing. The values of *T*, corresponding to *U* = 90%, are 2.35, 2.4, 3.22 and 3.23 for the four mandrel sizes mentioned above (in the same order). For 3-m spacing (not plotted), the corresponding values of *T* are 2.7, 2.75, 3.5 and 3.73, respectively.

The rate of consolidation decreases with increasing mandrel sizes, although, for practical purposes, the 150 mm × 50 mm mandrel is as effective as the 125 mm × 50 mm mandrel. The same can be stated about the 120 mm × 120 mm and 150 mm × 150 mm mandrels. However, there is a substantial difference in the consolidation rate when rectangular mandrels and square mandrels are compared. Square mandrels are less effective than rectangular mandrels because they disturb a much larger area.

**LESSONS FOR DESIGN**

**Replacement of Transition Zone by an Equivalent Smear Zone**

The transition zone is difficult to take into account in routine calculations because the existing analytical solutions (e.g., Hansbo 1981) only consider the existence of a smear zone. A way of accounting for the transition zone in design is to replace the transition zone and the smear zone with a single equivalent smear zone. In this paper, the extra length of smear zone required to replace the transition zone was determined by studying several combinations of spacings (1, 2 and 3 m) and mandrels (125 mm × 50 mm, 150 mm × 50 mm, 120 mm × 120 mm and 150 mm × 150 mm) for two different smear zone dimensions ($l_y$ = 2*d* and 3*d*), three different transition zone dimensions ($t_y$ = 6*d*, 9*d* and 12*d*) and three different values of $k_{hs}/k_{ho}$ (0.1, 0.2 and 0.3).

It was found that the extra length of the smear zone required to replace the transition zone depends only on the $k_{hs}/k_{ho}$ ratio and the size of the transition zone itself, as shown in Table 1. For example, if the original domain consists of a smear zone with $l_y$ = 2*d* and a transition zone with $t_y$ = 12*d*, then 10*d* is the length of the transition zone that needs to be replaced. Assuming a $k_{hs}/k_{ho}$ of 0.2 and referring to Table 1, the extra length of smear zone required is 0.20 × 10*d* = 2*d*. Therefore the equivalent smear zone extends to 2*d* + 2*d* = 4*d*. As can be seen in Figure 6, which shows the *U* versus *T* curves obtained for the original domain considering both smear and transition zones and the equivalent domain with a smear zone only, this procedure works quite well for all the cases considered. However, it is not applicable when there is overlap of adjacent transition zones.

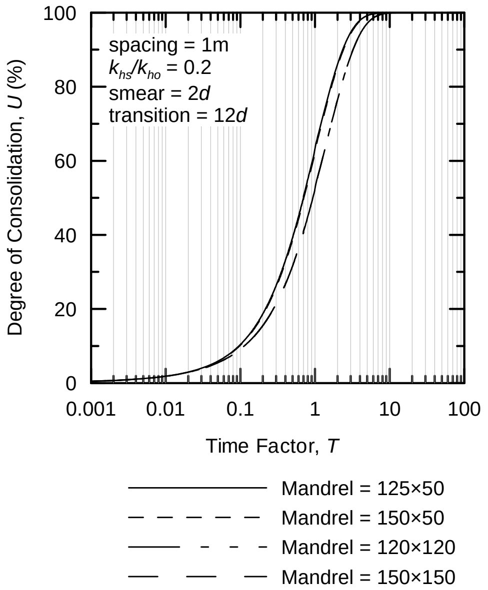


**Figure 5**. Effect of mandrel size on consolidation rate

**Table 1.** Replacement of the transition zone by an expanded smear

| $k_{hs}/k_{ho}$ | Extra length of smear zone per unit length of transition zone |
|---|---|
| 0.1 | 0.13 |
| 0.2 | 0.20 |
| 0.3 | 0.25 |

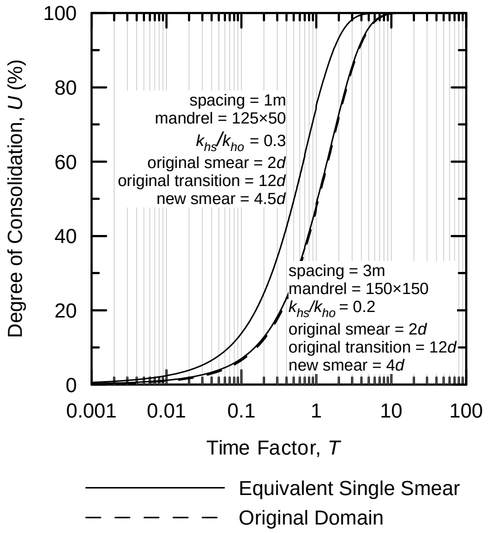


**Figure 6**. Replacement of original domain with smear and transition zones by an equivalent domain with an expanded smear zone

**Equivalent Circular Smear Zone**

For design using analytical solutions, the rectangular smear zone needs to be converted to an equivalent circle (Hansbo 1981). Two methods (A and B) can be used to do this conversion. In method A, two steps need to be followed:

1) estimate the dimensions of the rectangular smear zone ($l_x \times l_y$) from the mandrel dimensions ($a \times d$) by using Eqs. (1) and (2);

2) convert the rectangular area of the smear zone into an equivalent circle.

Alternatively, in method B, the procedure is as follows:

1) convert the rectangular mandrel with dimensions $a \times d$ to an equivalent circle to obtain the equivalent mandrel radius $r_{m,eq}$.

2) multiply $r_{m,eq}$ by the constant $p$ of Eqs. (1) and (2) to obtain the equivalent smear zone radius.

For square mandrels, both methods yield the same smear zone radius. However, for rectangular mandrels, it was found that method B always produced conservative results because of which it is recommended for use in design.

## CONCLUSIONS

In this paper, the effect of soil disturbance on the rate of consolidation of a soil deposit engineered with PVDs is studied. A standard PVD cross section of 100 mm × 4 mm and a triangular PVD installation pattern were considered. The analysis was performed using finite elements following the Terzaghi-Rendulic theory of consolidation. PVD installation creates two distinct zones of disturbance: a) a completely remolded smear zone and b) a less disturbed transition zone. The hydraulic conductivity was assumed to increase linearly in the transition zone from a low value in the smear zone to the original in situ value in the undisturbed zone. The actual hexagonal shape of the unit cell, band shape of the drain and rectangular shape of the smear and transition zones were used in the analysis.

Soil disturbance significantly reduces the PVD consolidation rate, and the transition zone, which has been neglected in most theoretical studies on the topic, has a definite impact on the consolidation process. Larger smear and transition zones result in slower consolidation rates. However, it is the degree of disturbance (i.e., the ratio of hydraulic conductivities in the smear and undisturbed zones) that affects the process the most. The mandrel size and shape also influence PVD performance.

A method of replacing the transition zone by an equivalent expanded smear zone is proposed so that the existing analytical solutions can be used. Additionally, a convenient method is proposed for converting a rectangular smear zone into an equivalent circle such that existing analytical solutions can be used in PVD design.

**Corresponding author:** Dr Dipanjan Basu, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana, 47906, United States of America. Tel: 1 765 586 5509. Email: dbasu@purdue.edu, dipan52@yahoo.com

## REFERENCES

Basu, D. & Prezzi, M. 2007. Effect of the smear and transition zones around prefabricated vertical drains installed in a triangular pattern on the rate of consolidation International Journal of Geomechanics ASCE, 7(1), 34-43.

Hansbo, S. 1981. Consolidation of fine-grained soils by prefabricated drains. Proceedings 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, 3, 677-682.

Indraratna, B. & Redana, I. W. 1998. Laboratory determination of smear zone due to vertical drain installation. Journal of Geotechnical and Geoenvironmental Engineering ASCE, 124(2), 180-184.

Madhav, M. R., Park, Y-M. & Miura, N. 1993. Modelling and study of smear zones around band shaped drains. Soils and Foundations, 33(4), 135-147.

Onoue, A., Ting, N-H., Germaine, J. T. & Whitman, R. V. 1991. Permeability of disturbed zone around vertical drains. Geotechnical Engineering Congress, Proceedings Congress of the Geotechnical Engineering Division ASCE, New York, 2, Geotechnical Special Publication 27, 879-890.

Sharma, J. S. & Xiao, D. 2000. Characterization of a smear zone around vertical drains by large-scale laboratory tests. Canadian Geotechnical Journal, 37, 1265-1271.