February 1998

Laboratory determination of smear zone due to vertical drain installation

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

I. W. Redana
University of Wollongong

LABORATORY DETERMINATION OF SMEAR ZONE DUE TO VERTICAL DRAIN INSTALLATION

By B. Indraratna,[1] Member, ASCE, and I. W. Redana[2]

ABSTRACT: This paper is mainly concerned with a laboratory study to investigate the effect of smear due to vertical drain installation. The extent of the smear zone around a vertical drain was studied utilizing a large-scale consolidometer apparatus. The test results reveal that a significant reduction in the horizontal permeability takes place toward the central drain, whereas the vertical permeability remains relatively unchanged. The radius of the smear zone was estimated to be a factor of four to five times the radius of the central drain (mandrel), and the measured ratio of horizontal to vertical permeability approached unity at the drain-soil interface. The laboratory measured settlements are subsequently compared with the predictions based on the theory of Hansbo and the finite element method. It is of relevance to note that the inclusion of the correct variation of permeability ratios of the smear zone in the plane strain finite element analysis improves the accuracy of settlement predictions.

INTRODUCTION

The installation of vertical drains by means of a mandrel causes significant remolding of the subsoil, especially in the immediate vicinity of the mandrel. Thus, a zone of smear will be developed with reduced permeability and increased compressibility. As remolding retards the consolidation process of the subsoil, it has to be considered in any theoretical solution. Barron (1948) suggested the concept of reduced permeability, which is equivalent to lowering the overall value of the coefficient of consolidation. Hansbo (1979) also introduced a zone of smear in the vicinity of the drain with a reduced value of permeability.

In the present research, a large-scale consolidometer (Indraratna and Redana 1995) was utilized to examine the actual reduction of soil permeability, and to assess the extent of the smear zone around a mandrel driven vertical drain. By sampling the soil around the vertical drain, the smear zone could be quantified by the measured change in permeability. In the present study, the laboratory findings have been incorporated in a finite element model to predict the corresponding consolidation settlements under a given load. The numerical results indicate that accurate predictions can be obtained once the smear effects are included in the model, and also that the Hansbo (1981) theory underestimates settlements in the long run.

The three-dimensional (3D) axisymmetric modeling of vertical drains is considerably more time consuming than the two-dimensional plane strain modeling. Indraratna and Redana (1997) have shown in a previous study that the plane strain analysis is accurate, once the relevant geometric parameters are transformed from the axisymmetric to the plane strain condition. In contrast to 3D modeling, a plane strain analysis can incorporate a large number of vertical drains in a finite element model simulated in a personal computer environment.

APPARATUS

The schematic illustration of the large-scale radial drainage consolidometer is given in Fig. 1, where the main body of the cell consists of two half sections made of stainless steel (450 mm in internal diameter and 950 mm in height). The friction along the cell boundary is reduced by placing a 1.5 mm thick Teflon sheet around the internal cell boundary. The loading system with a capacity of 1,200 kN can be applied by an air jack compressor system via a piston. The axial displacement transducer is usually placed at the top of this piston to measure the settlements. To measure the excess pore-water pressures, six diaphragm type piezometers complete with wiring can be connected to a 10-channel switch box for signal conditioning, and the subsequent readings can be observed via a digital voltmeter. Volume changes during the test are monitored using a burette drainage tube system. The cell is also equipped with a specially designed steel hoist from which a synthetic vertical drain can be inserted along the central axis of the cell.

TEST SAMPLE

As it was not feasible to obtain one undisturbed sample for the large consolidometer apparatus, reconstituted alluvial clay from Sydney, Australia was used to make large samples. The clay size particles (<2 μm) accounted for about 40%–50% of

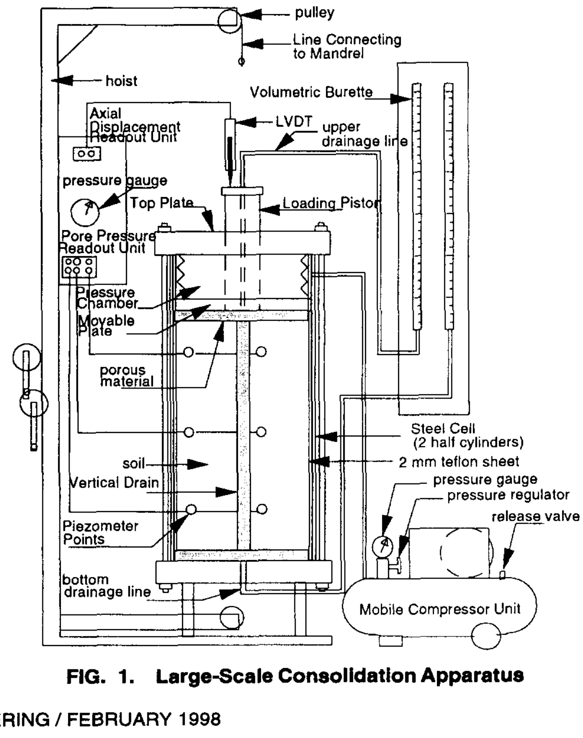

FIG. 1. Large-Scale Consolidation Apparatus

[1]Sr. Lect., Dept. of Civ. and Min. Engrg., Univ. of Wollongong, Northfields Ave., Wollongong, NSW 2522, Australia.
[2]PhD Student, Dept. of Civ. and Min. Engrg., Univ. of Wollongong, Northfields Ave., Wollongong, NSW 2522, Australia.

Note. Discussion open until July 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on December 16, 1996. This technical note is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 124, No. 2, February, 1998. ©ASCE, ISSN 1090-0241/98/0002-0180–0184/$4.00 + $.50 per page. Technical Note No. 14770.

TABLE 1. Soil Properties of Reconstituted Clay Sample

Soil properties (1)	Reconstituted clay (2)
Clay content (%)	40-50
Silt content (%)	45-60
Water content, w (%)	40
Liquid limit, w_L (%)	70
Plastic limit, w_P (%)	30
Plasticity index, PI (%)	40
Unit weight (t/m^3)	1.7
Specific gravity, G_s	2.6

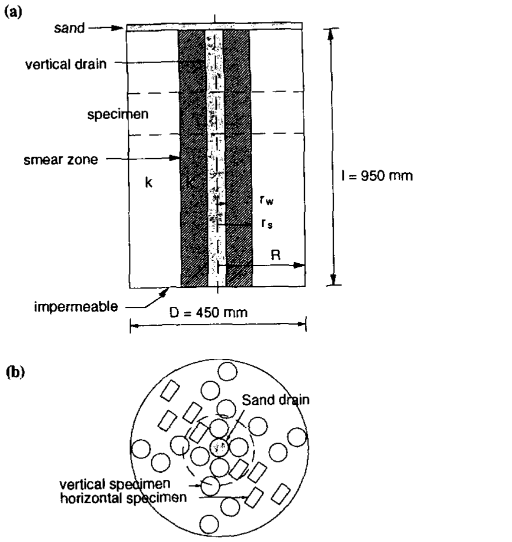

FIG. 2. Schematic Diagram: (a) Section of Test Equipment Showing Central Drain and Associated Smear; (b) Locations of Small Specimens Obtained to Determine Consolidation and Permeability Characteristics

the specimen, and particles smaller than silt size (<6 μm) constituted about 90% of the specimen. Selected geotechnical properties of the sample are shown in Table 1. On the basis of the Casagrande Plasticity Chart, the reconstituted clay could be categorized as CH (high plasticity clay).

TEST PROCEDURE

Clay was thoroughly mixed with water before placing it into the large cylinder, and subsequently the soil was placed and compacted in layers. To reduce friction between the side wall of the cylinder and the soil, a Teflon sheet was laid around the inner periphery of the cell. After specimen preparation, filter material and a sand mat of about 5 cm thick were put on the surface of the compacted clay. The loading device was set and an initial preconsolidation pressure of 20 kPa was applied prior to the installation of the central drain.

The vertical sand drain was installed by using a specially designed "pipe" mandrel and hoist (pulley system). The diameter of the mandrel was 50 mm and its thickness was 2 mm. After the sand was poured into the pipe, it was gradually withdrawn by the hoist while applying light vibration to the pipe as well as compacting the sand using an external (inner) rod. The vertical drain thus formed can be regarded as a sand compaction pile (SCP).

After installation of the sand compaction pile in the large cell, small specimens were collected from different locations within the cell at known radial distances by using a specially designed tube sampler [Fig. 2(b)]. The samples were subjected to one-dimensional consolidation using conventional (50 mm diameter) oedometers in order to study the variation in soil

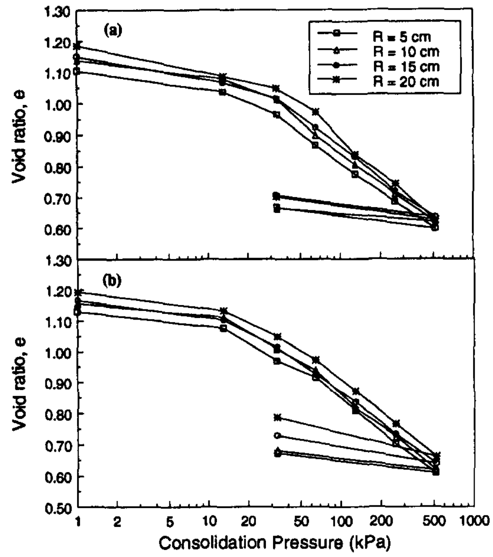

FIG. 3. Void Ratio against Pressure Relationship for: (a) Vertical Specimen; (b) Horizontal Specimen

properties close to and away from the central drain. It is postulated that the compressibility and permeability characteristics of the smear zone near the sand drain would be significantly different from the rest of the clay unaffected by the installation of the SCP. The horizontal and vertical compressibility and permeability characteristics were measured for the specimens recovered from the cell, as indicated in Fig. 2(b).

To investigate the effect of a vertical drain on settlements, separate samples were prepared in the large-scale consolidometer with the central drain, and were loaded axially in increments of 50, 100, and 200 kPa to promote radial consolidation. A schematic section of the vertical drain and associated smear in the large-scale consolidometer is illustrated in Fig. 2(a). The corresponding settlement behavior was recorded and plotted.

TEST RESULTS AND ANALYSIS

As mention earlier, the extent of the smear zone associated with the vertical sand drain installation was investigated by evaluating the compressibility and permeability parameters close to and away from the vertical drain. The following section describes the oedometer consolidation behavior of the small specimens that were obtained from the large cell after the drain installation [Fig. 2(b)].

Fig. 3 shows the relationship of the void ratio against the applied consolidation pressure for samples obtained at different radial distances (R) from the axis of the drain. It is observed that the void ratio decreases toward the vicinity of the central drain, which confirms that the effect of smear (compaction) is greatest near the drain boundary. Due to the significant reduction of the horizontal permeability in the vicinity of the drain [Fig. 4(a)], it is clear that the radius of the smear zone can be taken to be 100 mm or estimated to be a factor of four to five times the radius of the drain (mandrel).

The variation of the horizontal and vertical coefficient of permeability (k_h and k_v) for various mean applied consolidation pressures is plotted in Fig. 4. The magnitudes of the coefficients of permeability k_v and k_h are calculated by the Terzaghi consolidation theory, where the coefficients of consolidation (c_v and c_h) are determined on the basis of the Casagrande "log time" method. In the smear zone, although it is seen that the coefficient of horizontal permeability (k_h') becomes smaller toward the drain, the vertical permeability (k_v') is almost unchanged even at the drain interface.

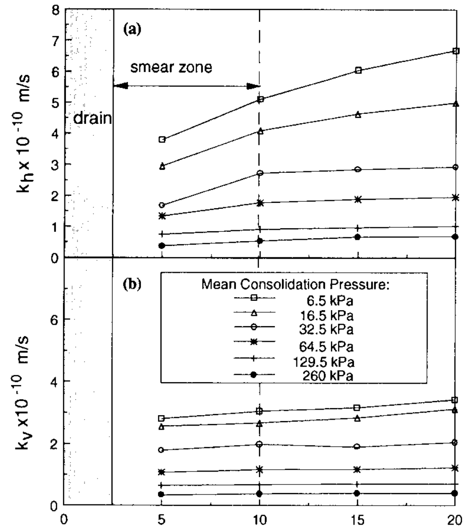

FIG. 4. Permeability along Radial Distance from Central Drain: (a) Horizontal; (b) Vertical

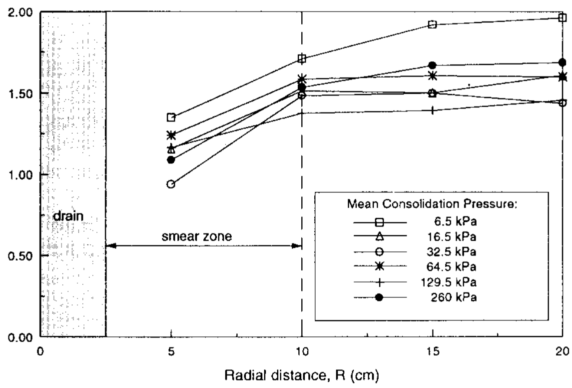

FIG. 5. Ratio of k_h/k_v along Radial Distance from Central Drain

As discussed previously, the coefficient of permeability, k (Fig. 4), was obtained (back-calculated) using the Terzaghi one-dimensional consolidation theory. Tavenas et al. (1983a) have stated that this indirect method of determining k is not accurate because of the assumptions of constant modulus of deformability (m) and constant coefficient of consolidation (c_v) during the reduction of void ratio (e) upon loading. Tavenas et al. (1983a) suggest the determination of permeability using the triaxial or modified oedometer apparatus. However, in the present study, the actual magnitude of k is not critical in determining the extent of smearing. The smear zone is characterized by the significantly decreased permeability toward the drain, in relation to the higher permeability of the soil that is unaffected by drain installation. In other words, it is the kind of variation of k with radial distance (i.e., the shape of the graph in Fig. 4) that is important to detect smear, rather than the actual magnitude of k. The writers have, therefore, proposed a dimensionless ratio k_h/k_v (Fig. 5) to eliminate the previously mentioned ambiguity inherent in Terzaghi's method. The method of obtaining k_h and k_v is not critical, as long as the same laboratory approach is consistently followed for determining both k_h and k_v.

The change in k_h/k_v ratio along the radial distance from the central drain is plotted in Fig. 5. The value of k_h'/k_v' in the smear zone varies between 0.9 and 1.3, with an average of 1.15. Hansbo (1987) argued that for extensive smearing, the horizontal permeability coefficient in the smear zone (k_h') should approach that of the vertical permeability coefficient (k_v'), thus suggesting that the ratio k_h'/k_v' could approach 1. The experimental results of the current study seem to be in agreement with Hansbo (1987). For the applied consolidation pressures, it is observed that the value of k_h/k_v varies between 1.4 and 1.9, with an average of 1.63 in the undisturbed zone. Shogaki et al. (1995) reported that the average values of k_h/k_v were in the range of 1.36–1.57 for undisturbed isotropic soil samples taken from the Hokkaido to Chugoku region in Japan. Tavenas et al. (1983b) reported that for the soil tested in a conventional oedometer, the k_h/k_v ratio was found to vary between 0.91 and 1.42 for intact natural clays, and from 1.2 to 1.3 for Matagami varved clay. Bergado et al. (1991) conducted a thorough laboratory study on the development of the smear zone in soft Bangkok clay, and they reported that the horizontal permeability coefficient of the undisturbed zone to the smear zone varied between 1.5 and 2, with an average of 1.75. The ratio of k_h'/k_v' was found to be almost unity within the smear zone.

The settlement behavior of clay under loading was predicted using the analytical approach of Hansbo (1981) and by the finite element method (CRISP). The finite element discretization of the consolidation cell is shown in Fig. 6, and the results are discussed later. The variation if k_h/k_v within the consolidation cell, as explained earlier, was incorporated to represent the effect of smear in the predictions. The settlement of the large-scale consolidometer sample without smear was predicted from the Terzaghi one-dimensional theory ($C_c = 0.34$, $C_r = 0.14$, $c_v = 1.5 \times 10^{-8}$ m²/s, and $k_v = 2.25 \times 10^{-10}$ m/s). A maximum past pressure (σ_p') of 20 kPa was assumed based on previous oedometer consolidation data. The stress distribution within the cell was determined based on the theory of elasticity (Boussinesq analysis). The radius of the smear zone was estimated to be 100 mm on the basis of the large-scale experimental results shown in Fig. 5.

Following the Hansbo (1981) analytical method for axisymmetric flow, the average degree of consolidation $\bar{U}_h$ on a horizontal plane at a depth z and at time t was predicted from

$$\bar{U}_h = 1 - \exp\left(-\frac{8T_h}{\mu}\right) \quad (1)$$

where

- $\mu = \ln(n/s) + (k_h/k_h')\ln(s) - 0.75$ (smear effect only)
- $\mu = \ln(n) - 0.75$ (both smear and well resistance ignored)

In the previous equations, $n = R/r_w$ and $s = r_s/r_w$; R = radius of influence, r_s = radius of smear, and r_w = radius of drain well (see also Fig. 2); k_h = horizontal coefficient of permeability; and k_h' = horizontal coefficient of permeability in smear zone.

A plane strain finite element analysis was also employed to predict the settlement behavior of the soil, where the numerical analysis based on the modified Cam-clay model (Roscoe and Burland 1968) was incorporated in the finite element code, CRISP92. The discretized finite element mesh for the soil cell (Fig. 6) is composed of six-node linear strain triangular elements with three pore-pressure nodes. Because of symmetry, it is sufficient to consider one half of the unit cell. The clay layer is characterized by drained conditions at the upper boundaries only. The applied piston loading was simulated by applying incremental vertical loads to the upper boundary. The excess pore-water pressures were set to zero along the drain boundary to simulate complete dissipation, thus the effect of well resistance was neglected. The axisymmetric permeability ratios (Fig. 5) were converted to plane strain equivalents based on the detailed analytical formulation described elsewhere by

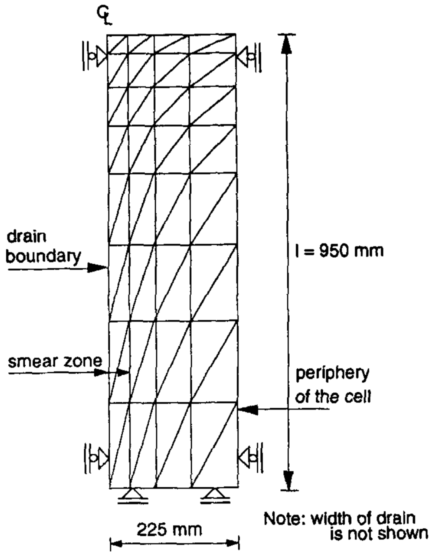

FIG. 6. Finite Element Discretization for Plane Strain Analysis of Soil in Large-Scale Consolidometer

TABLE 2. Stresses within Large-Scale Consolidometer

Depth (m) (1)	σ'_h (kPa) (2)	σ'_v (kPa) (3)	u (kPa) (4)	p'_c (kPa) (5)
0	0	0	0	30
0.15	12	21	1.5	20
0.45	14	23	4.5	23
0.95	16	28	9.5	27

Note: σ'_v, σ'_h = vertical and horizontal effective pressures; u = pore water pressure; and p'_c = isotropic preconsolidation pressure.

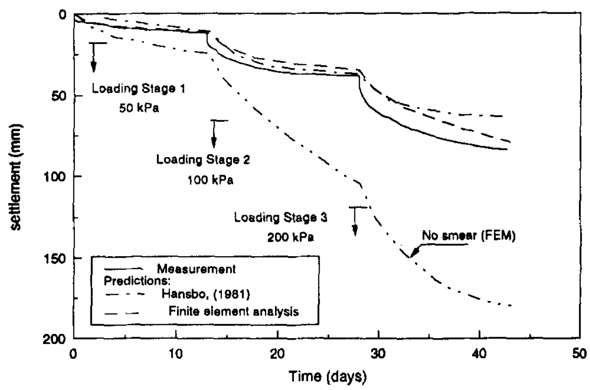

FIG. 7. Consolidation Settlement of Soil Stabilized with Sand Drain As Measured in Large-Scale Consolidometer Incorporating Smear Effect

Indraratna and Redana (1997). Only a summary of the important governing equations is given next.

The ratio of the equivalent plane strain permeability (k_{hp}) to the axisymmetric permeability (k_h) without smear effect is given by

$$\frac{k_{hp}}{k_h} = \frac{0.67}{[\ln(n) - 0.75]} \tag{2}$$

where parameter n is the same as defined earlier in Hansbo (1981) theory. Subsequently, the equivalent (plane strain) permeability in the smear zone (k'_{hp}) can be determined by the following expression:

$$\frac{k'_{hp}}{k_{hp}} = \frac{\beta}{\left[\ln\left(\frac{n}{s}\right) + \left(\frac{k_h}{k'_h}\right)\ln(s) - 0.75 - \alpha\right]} \tag{3}$$

where α and β = parameters based on geometry of smear zone and vertical drains (Indraratna and Redana 1997).

The Cam-clay parameters for the soil cell are chosen as measured in the laboratory and are as follows: gradients of volume against log pressure relations for consolidation and swelling, λ = 0.15 and κ = 0.05, respectively; slope of the critical state line based on effective stress, M = 1.1; void ratio at unit consolidation pressure, e_{cs} = 1.55; Poisson's ratio ν = 0.25; and unit weight of soil γ_s = 17 kN/m^3. The extent of the smear zone and the associated permeability parameters were determined by large-scale consolidometer tests, as described earlier. In the smear zone, the average, converted (plane strain) permeability $\bar{k}'_{hp} = 3.52 \times 10^{-12}$ m/s, while outside the smear zone, the mean converted value of permeability $\bar{k}_{hp} = 1.66 \times 10^{-10}$ m/s, for the range of applied consolidation pressures. The stress levels at various depths within the consolidation cell (Table 2) were incorporated in the finite element code, CRISP.

The finite element predictions are also compared with the Hansbo (1981) theory, as illustrated in Fig. 7, together with the laboratory measurements. As shown in Fig. 7, the Hansbo (1981) theory underestimates settlements, particularly during the final loading stage. This is not surprising, because in Hansbo's theory, the ratio of vertical to horizontal permeability is assumed to be unity throughout the smear zone. The finite element analysis incorporating the laboratory permeability ratios provides a good agreement with the measured data and is more appropriate to predict the long-term settlements. If the effect of the smear is not included in the predictions, the conventional time-settlement curve becomes considerably below the actual settlement response (Fig. 7). However, as the time period is increased substantially (greater than, say, three months), the settlement curve without smear converges toward the settlement prediction with smear. This implies that the effect of smear is mainly a concern during the short-intermediate term.

CONCLUSIONS

The effect of smear due to the installation of a vertical sand compaction pile was investigated in the laboratory, using a large-scale consolidometer. By measuring the variation of the horizontal permeability close to and away from the centrally installed drain, the extent of the smear zone could be determined. The smear zone radius was estimated to be about 100 mm, which was a factor of four to five times the radius of the central drain (mandrel). At the drain-soil interface, the measured ratio of horizontal to vertical permeability approached unity. This implies that the original assumption made by Hansbo (1981) with regard to $k'_h/k'_v = 1$ for the whole smear zone would, in general, underestimate the settlements. The inclusion of the correct variation of the permeability ratios (i.e., as a function of the radial distance from the central drain) in the finite element method is a more realistic tool for predicting settlements.

APPENDIX. REFERENCES

Barron, R. A. (1948). "Consolidation of fine-grained soils by drain wells." *Trans., ASCE*, 113, 718–742.

Bergado, D. T., Asakami, H., Alfaro, M. C., and Balasubramaniam, A. S. (1991). "Smear effects of vertical drains on soft Bangkok clay." *J. Geotech. Engrg.*, ASCE, 117(10), 1509–1530.

Hansbo, S. (1979). "Consolidation of clay by band shaped prefabricated drains." *Ground Engrg.*, 12(5), 16–25.

Hansbo, S. (1981). "Consolidation of fine-grained soils by prefabricated drains." *Proc., 10th Int. Conf. on Soil Mech. and Found. Engrg.*,

Publications Committee of ICSMFE, ed., A. A. Balkema, Rotterdam, The Netherlands, Vol. 3, 677–682.
Hansbo, S. (1987). "Design aspects of vertical drains and lime column installation." *Proc., 9th Southeast Asian Geotech. Conf.*, Organizing Committee, SEAGS (ed.), Bangkok, Thailand, Vol. 2, section 8, 1–12.
Indraratna, B., and Redana, I. W. (1995). "Large-scale, radial drainage consolidometer with central drain facility." *Australian Geomech.*, 2(December), 103–105.
Indraratna, B., and Redana, I. W. (1997). "Plane strain modeling of smear effects associated with vertical drains." *J. Geotech. Engrg.*, ASCE, 123(5), 474–478.
Roscoe, K. H., and Burland, J. B. (1968). "On the generalized stress strain behavior of wet clay." *Engineering plasticity*. Cambridge University Press, Cambridge, U.K., 535–609.
Shogaki, T., Moro, H., Masaharu, M., Kaneko, M., Kogure, K., and Sudho, T. (1995). "Effect of sample disturbance on consolidation parameters of anisotropic clays." *Proc., Int. Symp. on Compression and Consolidation of Clayey Soils*. H. Yoshikuni and O. Kusakabe, eds., A. A. Balkema, Rotterdam, The Netherlands, Vol. 1, 561–566.
Tavenas, F., Jean, P., and Leroueil, S. (1983a). "The permeability of natural soft clays, part 1: Methods of laboratory measurement." *Can. Geotech. J.*, 20(November), 629–644.
Tavenas, F., Jean, P., and Leroueil, S. (1983b). "The permeability of natural soft clays, part 2: Permeability characteristics." *Can. Geotech. J.*, 20(November), 645–660.