Recent advances in soft ground improvement - from bumpy rides to rapid transit

B Indraratna  
*University of Wollongong*, indra@uow.edu.au

A S. Balasubramaniam  
*Griffith University*

C Rujikiatkamjorn  
*University of Wollongong*, cholacha@uow.edu.au

R Zhong  
*University of Wollongong*, rzhong@uow.edu.au

Follow this and additional works at: [https://ro.uow.edu.au/eispapers](https://ro.uow.edu.au/eispapers)
Recent advances in soft ground improvement - from bumpy rides to rapid transit

Abstract
Much of the world’s essential infrastructure is built along congested coastal belts that are composed of highly compressible and weak soils up to significant depths. Soft alluvial and marine clay deposits have very low bearing capacity and excessive settlement characteristics, with obvious design and maintenance implications on tall structures and large commercial buildings, as well as port and transport infrastructure. Stabilising these soft soils before commencing construction is essential for both long term and short term stability. Pre-construction consolidation of soft soils through the application of a surcharge load alone often takes too long, apart from which, the load required to achieve more than 90% consolidation of these mostly low lying, permeable, and very thick clay deposits can be excessively high over a prolonged period. A system of vertical drains combined with vacuum pressure and surcharge preloading has become an attractive ground improvement alternative in terms of both cost and effectiveness. This technique accelerates consolidation by promoting rapid radial flow which decreases the excess pore pressure while increasing the effective stress. Over the past 15 years, the authors have developed numerous experimental, analytical, and numerical approaches that simulate the mechanics of prefabricated vertical drains (PVDs) and vacuum preloading, including two-dimensional and three-dimensional analyses, and more comprehensive design methods. These recent techniques have been applied to various real life projects in Australia and Southeast Asia. Some of the new design concepts include the role of overlapping smear zones due to PVD-mandrel penetration, pore pressure prediction based on the elliptical cavity expansion theory, and the rise and fall of pore pressure via prefabricated vertical drain (PVD) under cyclic loads with a new constitutive model for soft soils under cyclic loads. These recent advances enable greater accuracy in the prediction of excess pore water pressure, and lateral and vertical displacement of the stabilised ground. As a rigid inclusion, the stone column can provide reinforcement to the soft soils apart from shortening the drainage path for the dissipation of excess pore water pressure. Factors such as arching, clogging and smear effects were included in a numerical solution developed recently by the authors and the simulation results showed a good agreement with field test results. This lecture note presents an overview of the theoretical and practical developments and salient findings of soft ground improvement via PVD, vacuum preloading, as well as stone columns, with applications to selected case studies in Australia, Thailand, and China.

Disciplines
Engineering | Science and Technology Studies

Publication Details

This conference paper is available at Research Online: https://ro.uow.edu.au/eispapers/3766
ABSTRACT: Much of the world’s essential infrastructure is built along congested coastal belts that are composed of highly compressible and weak soils up to significant depths. Soft alluvial and marine clay deposits have very low bearing capacity and excessive settlement characteristics, with obvious design and maintenance implications on tall structures and large commercial buildings, as well as port and transport infrastructure. Stabilising these soft soils before commencing construction is essential for both long term and short term stability. Pre-construction consolidation of soft soils through the application of a surcharge load alone often takes too long, apart from which, the load required to achieve more than 90% consolidation of these mostly low lying, permeable, and very thick clay deposits can be excessively high over a prolonged period. A system of vertical drains combined with vacuum pressure and surcharge preloading has become an attractive ground improvement alternative in terms of both cost and effectiveness. This technique accelerates consolidation by promoting rapid radial flow which decreases the excess pore pressure while increasing the effective stress.

Over the past 15 years, the authors have developed numerous experimental, analytical, and numerical approaches that simulate the mechanics of prefabricated vertical drains (PVDs) and vacuum preloading, including two-dimensional and three-dimensional analyses, and more comprehensive design methods. These recent techniques have been applied to various real life projects in Australia and Southeast Asia. Some of the new design concepts include the role of overlapping smear zones due to PVD-mandrel penetration, pore pressure prediction based on the elliptical cavity expansion theory, and the rise and fall of pore pressure via prefabricated vertical drain (PVD) under cyclic loads with a new constitutive model for soft soils under cyclic loads. These recent advances enable greater accuracy in the prediction of excess pore water pressure, and lateral and vertical displacement of the stabilised ground.

As a rigid inclusion, the stone column can provide reinforcement to the soft soils apart from shortening the drainage path for the dissipation of excess pore water pressure. Factors such as arching, clogging and smear effects were included in a numerical solution developed recently by the authors and the simulation results showed a good agreement with field test results.

This lecture note presents an overview of the theoretical and practical developments and salient findings of soft ground improvement via PVD, vacuum preloading, as well as stone columns, with applications to selected case studies in Australia, Thailand, and China.

Keywords: surcharge preloading, vacuum preloading, PVD, cyclic load, constitutive model, stone column
South Wales. The low bearing capacity and high compressibility of these deposits affects the long term stability of buildings, roads, rail tracks, and other forms of major infrastructure (Johnson 1970). Therefore, it is imperative to stabilise these soils before commencing construction to prevent unacceptable differential settlement. However, attempts to improve deep bearing strata may not commensurate with the overall cost of the infrastructure (Bo et al. 2003). In the past, various types of vertical drains such as sand drains, sand compaction piles, PVDs (geo-synthetic), stone columns, and gravel piles have commonly been used. Certain types of granular piles and deep stone columns may indeed significantly enhance the intensity of the soil. However, because of the minimum risk of damage to utilities from lateral ground movement and a significant reduction in the price of flexible PVDs over the years, they have often been used to more conventional the original compacted sand drains, gravel piles stone columns etc. Their installation can significantly reduce the preloading period by decreasing the length of the drainage path, sometimes by a factor of 10 or more. More significantly, PVDs can be installed quicker with minimum environmental implications and quarrying requirements.

Preloading (surcharge embankment) is one of the most successful techniques for improving the shear strength of low-lying areas because it loads the ground surface to induce a greater part of the ultimate settlement that it is expected to bear after construction (Richart 1957; Indraratna and Redana 2000; Indraratna et al. 2005a). In order to control the development of excess pore pressure, a surcharge embankment is usually raised as a multi-stage exercise, with rest periods between the loading stages (Jamiołkowski et al. 1983). Since most compressible low-lying soils have very low permeability and are often thick, a lengthy time period is usually needed to achieve the desired primary degree of consolidation (>95%). In these instances, the height of the surcharge can be excessive from an economic perspective and stability consolidation (Indraratna et al. 1994). One drawback of this surcharge technique is that the preload should be applied for a sufficiently long period, which may at times become impractical due to stringent construction schedules and deadlines. When PVDs combined with surcharge preloading is applied, vertical drains provide a much shorter drainage path in a radial direction which reduces the required preload period significantly. PVDs are cost effective and can be readily installed in moderate to highly compressible soils (up to 40m deep) that are normally consolidated or lightly over-consolidated. PVDs do not offer particular advantages if installed in heavily over-consolidated clays.

Apart from the method of drainage and PVDs combined with surcharge preloading, vacuum pressure has been used to enhance the efficiency of PVD when a desired degree of consolidation is required over a relatively short time period. Negative pore pressures (suction) distributed along the drains and on the surface of the ground accelerate consolidation, reduce lateral displacement, and increase the effective stress. This allows the height of the surcharge embankment to be reduced to prevent any instability and lateral movement in the soil. Today, PVDs combined with vacuum preloading are being used more and more in practical ground improvement all over the world.

Aside from PVDs, stone columns can be adopted to improve the soft soils in two aspects. Firstly, the radial drainage paths are created due to the porosity of the stone aggregates, which speed up the time-dependent consolidation. In addition to smear zone induced by installation, another factor which could adversely affect the performance is the clogging caused by the soil particles moving into the pores of stones. Secondly, the arching effect can occur due to the greater column stiffness compared to the surrounding soils. To ensure the high accuracy of the predictions of stone column behaviour, it is of significance to develop a solution which considers those factors.

This lecture includes selected salient aspects of more than 20 years of active research conducted at the University of Wollongong in the area of soft soil stabilisation using PVDs, vacuum preloading as well as stone columns, undoubtedly a vital Australian contribution to the field of soft soil improvement worldwide, plus offering a significant component of higher education training through almost a dozen doctoral studies to date, promoting the advancement of current industry practices in infrastructure development in coastal and low lying areas.

**PRINCIPLES OF VACUUM CONSOLIDATION VIA PVDS**

The vacuum preloading method for vertical drains was arguably first introduced in Sweden by Kjellman (1942). Since then, it has been used extensively to accelerate the consolidation of soft ground worldwide, for instance at the Philadelphia International Airport, USA; Tianjin port, China; North South Expressway, Malaysia; Reclamation world in Singapore and Hong Kong, China; Suvarnabhumi Second Bangkok International
Airports of Hong Kong, Thailand; Balina Bypass New South Wales and the Port of Brisbane, Queensland in Australia, among many other projects (Holtan 1965; Choa 1990; Jacob et al. 1994; Bergado et al. 2002; Chu et al. 2000; Yan and Chu 2003). When a high surcharge load is needed to achieve the desired undrained shear strength, and this cost becomes substantial due to an excessively high embankment and a long preloading period in order to achieve 95% or more consolidation, the optimum solution is to adapt to a combined vacuum and fill surcharge approach. In very soft clays where a high surcharge embankment cannot be constructed without affecting stability (large lateral movement) or having to work within a tight construction schedule, the application of vacuum pressure is quite often the most appropriate choice.

This PVD coupled system is designed to distribute the vacuum (suction) pressure to deep layers of the subsoil to increase the consolidation rate of reclaimed land and deep estuarine plains (e.g. Indraratna et al. 2005b; Chu et al. 2000). The mechanism for vacuum preloading can be explained by the spring analogy (Figure 1) described by Chu and Yan (2005), where the effective stress increases directly due to the suction (negative) pressure, while the total stress remains the same. This is in the context of conventional case surcharge preloading.

The general characteristics of vacuum preloading compared to conventional preloading are as follows (Qian et al. 1992; Indraratna and Chu 2005):

- The effective stress related to suction pressure increases isotropically, whereby the corresponding lateral movement is compressive. Consequently, the risk of shear failure can be minimised even at a higher rate of embankment construction, although any ‘inward’ movement towards the embankment toe should be carefully monitored to avoid excessively high tensile stresses.
- The vacuum head can propagate to a greater depth of subsoil via the PVD system and the suction can propagate beyond the tips of the drain and the boundary of the PVD.
- Assuming on air leaks and depending on the efficiency of the vacuum system used in the field, the volume of surcharge fill can be decreased to achieve the same degree of consolidation.
- Since the height of the surcharge can be reduced, the maximum excess pore pressure generated by vacuum preloading is less than the conventional surcharge method (Figure 2).
- With the applied vacuum pressure, the inevitable unsaturated condition at the soil-drain interface may be partially compensated for.
- With field vacuum consolidation, the confining stress applied to a soil element may consist of two parts: (a) vacuum pressure and (b) lateral earth pressure (Chai 2005). Chai et al. (2008) demonstrated the possibility of improving clayey deposits by combining the cap-drain with a vacuum and the surface or subsurface soil as a sealing layer, in lieu of an air tight sheet on the ground surface. However, the efficiency of the method depends on preventing the surface sand from being affected by the pressure from pervious layers of sand and discontinuities in the ground.

It is essential with vacuum assisted preloading that some horizontal drains be placed in transverse and longitudinal directions after installing the sand blanket, in order to uniformly distribute the surface suction. All vertical and lateral drains can then be connected to the edge of a peripheral Bentonite slurry trench, which is normally sealed by an impervious membrane system (Figure 3a). The trenches can then be filled with water or Bentonite slurry to improve the intact sealing of the membrane around the boundary of the treated zone. The vacuum pumps are then connected to the prefabricated discharge system extending from the trenches. The suction head generated by the vacuum pump helps dissipate the excess pore water pressure via the PVDs.

![Spring analogy of vacuum consolidation process](image-url)
When a reclaimed area has to be sub-divided into a number of sections to facilitate installation of the membrane (e.g. Port of Brisbane, as shown in Figure), vacuum preloading can only be effectively carried out in one section at a time. Vacuum preloading can become cumbersome over a very large area because the suction head may not be sustained due to the pressure of sand layers, or because it is too close to a marine boundary, in which case a cut off wall will often be used. An alternative method is to apply the vacuum directly to the individual PVD with flexible tubes without using a membrane. Here, each PVD is connected directly to the collector drain (Figure 3b). Unlike the membrane system where an air leak can affect the entire PVD system, in this membrane-less system, each drain acts independently. However, installing an extensive tubing system for a large number of PVDs can increase the time and cost of installation (Seah 2006).

Apart from the obvious inherent characteristics of these two vacuum systems, their effectiveness depends entirely on the properties of the soil, the thickness of the clay, the drain spacing, the type and geometry of PVDs, and the mechanical design and capacity of the vacuum pump. The selection and use of these systems are often based on empirical assessments that are invariably influenced by various aspects of the tender and/or the experience of the contractors, rather than detailed numerical studies. In this section, the analytical solutions to vertical drains incorporating the vacuum preloading of both systems (membrane and membrane-less) under time-dependent surcharge loading will be described.

The analytical modelling principles for both systems of the applied vacuum are shown in Figure. The smear zone and well resistance are also considered in both models. The general solutions for excess pore water pressure, settlement, and degree of consolidation were derived through the Laplace transform technique. In addition, a time dependent surcharge preloading can be considered in lieu of an instantaneously applied constant load that can neither simulate the construction history of the embankment nor the variation of the applied vacuum pressure. The results elicited the need for correctly determining the permeability of the sand blanket in the membrane system, and the role of any variation in vacuum in the membrane-less system. The permeability of the sand blanket can significantly affect overall consolidation in the membrane system.

Figure 3. Vacuum-assisted preloading system: (a) membrane system; (b) membrane-less system; and (c) vacuum at Port of Brisbane (Indraratna et al. 2005c)
With the Second Bangkok International Airport, various ground improvement schemes via PVDs with vacuum preloading and conventional surcharge preloading were studied by Indraratna and Redana (2000) and Indraratna et al. (2004). Consolidation with only surcharge preloading would take much longer than using vacuum preloading (Figure 5). The corresponding settlements, excess pore water pressure, and lateral displacement, are presented in Figure 5 and Figure 6, respectively. As expected, the use of a vacuum pressure increased the rate of excess pore pressure dissipation. This is a direct result of an increased pore pressure gradient towards the drains due to negative pressure (suction) along the length of the drain. The use of sufficient vacuum pressure with properly sealed surface membranes accelerates the preconstruction settlement faster and better than the conventional surcharge preloading method. Moreover, a combination of embankment load with vacuum pressure can reduce the outward lateral displacement (Chai et al. 2005; Indraratna and Redana 2000).

![Figure 5. Second Bangkok International Airport (without vacuum pressure):](image)

(a) Construction loading history;
(b) Vacuum pressure history;
(c) Surface settlement at the centreline of embankment;
(d) Variation of excess pore-water pressure at 8m depth below ground level at the centreline for embankments (for surcharge only) and at 3m depth below ground level, 0.5 m away from the centreline for embankments (with surcharge and vacuum preloading together) (Indraratna et al. 2000, 2004)

![Figure 6. Lateral-displacement profiles 20m from the centreline of embankments](image)

(Indraratna et al. 2000, 2004)
VACUUM CONSOLIDATION THEORY

Mohamedelhassan and Shang (2002) developed a combined vacuum and surcharge load system and adopted the one-dimensional Terzaghi’s consolidation theory (Figure 7). The mechanism for the combined vacuum and surcharge loading (Figure 7a) may be determined by the law of superposition (Figure 7b and Figure 7c). The average of degree of consolidation for combined vacuum and surcharge preloading can then be expressed by:

\[ U_w = 1 - \sum_{m=0}^{2} \frac{2}{M} \exp \left( - \frac{w}{w_e} \right) \]

\[ T_w = c_v t / H^2 \]

where \( T_w \) is a time factor for combined vacuum and surcharge preloading, and \( c_v \) is the coefficient of consolidation for combined vacuum and surcharge preloading.

Indraratna et al. (2004) showed that when a vacuum is applied in the field through PVDs, the suction head along the length of the drain may decrease with depth, thereby reducing its efficiency. Laboratory measurements taken at a few points along PVDs installed in a large-scale consolidometer at the University of Wollongong clearly indicated that the vacuum propagates immediately, but a gradual reduction in suction may occur along the length of the drain. The rate at which the suction develops in a PVD depends mainly on the length and type of PVD (core and filter properties). However, some field studies suggest that the suction may develop rapidly even if the PVDs are up to 30 m long (Bo et al. 2003; Indraratna et al. 2005a).

Indraratna et al. (2004, 2005a) proposed a modified radial consolidation theory inspired by laboratory observations to include different distribution patterns of vacuum pressure (Figure 8). These results indicated that the efficiency of the PVD depended on the magnitude and distribution of the vacuum. In order to quantify the loss of vacuum, a trapezoidal distribution of vacuum pressure along the length of the PVD was assumed.

Based on these assumptions, the average excess pore pressure ratio \( R_u = \Delta p / \bar{u}_0 \) of a soil cylinder for radial drainage that incorporates vacuum preloading can be given by:

\[ R_u = \left( 1 + \frac{p_0}{u_0} \left( 1 + k_1 \right) \right) \exp \left( - \frac{8T_w}{u_0} \right) - \frac{p_0}{u_0} \left( 1 + k_1 \right) \]

and

\[ \mu = \ln \left( \frac{n}{s} \right) + \left( \frac{k_e}{k_s} \right) \ln(s) - 0.75 \pi \left( 2l - z \right) k_e^2 \left( 1 - \frac{k_s / k_e - 1}{q_u} \right) \left( \frac{k_s / k_e}{(k_s / k_e - 1)} \right) \]

where \( p_0 \) is the vacuum applied at the top of the drain, \( k_1 = \) ratio between the vacuum at the top and bottom of the drain, \( u_0 \) is the initial excess pore water pressure, \( k_s = \) the horizontal permeability coefficient of soil in the undisturbed zone, \( k_e = \) the horizontal permeability coefficient of soil in the smear zone, \( T_w = \) the time factor, \( n = \) the ratio \( d_e / d_w \), \( d_e = \) the diameter of the equivalent soil cylinder = 2\( r_e \), and \( d_w = \) the diameter of the drain = 2\( r_w \), \( s = \) ratio \( d_e / d_w \) (\( d_e = \) the diameter of the smear zone = 2\( r_e \)), \( z = \) depth, \( l = \) the equivalent length of drain, \( q_u = \) the well discharge capacity.
FACTORS INFLUENCING THE PERFORMANCE OF A VACUUM OR SURCHARGE PRELOADING WITH CONSOLIDATED PVDS

Smear zone

Installing vertical drains with a steel mandrel significantly remoulds the subsoil, especially in its immediate vicinity. This disturbed annulus in the smear zone has a reduced lateral permeability and increased compressibility. In varved clays, the finer and more impervious layers are dragged down and smeared over the more pervious layers which in turn decrease the permeability of the soil near the periphery of the drain. Barron (1948) suggested the concept of reduced permeability by arbitrarily lowering the apparent value of the coefficient of consolidation. Hansbo (1979) included a further explicit smear zone with a reduced permeability near the drain, surrounded by an outer undisturbed zone.

Based on constant but reduced permeability in the smear zone, Jamiolkowski et al. (1983) proposed that the diameter of the smear zone ($d_s$) and the cross section of the mandrel can be related by:

$$d_s = (2.5 \text{ to } 3) \times d_m$$

(5)

In the above, $d_m$ is the diameter of the circle with an area equal to the cross section of the mandrel. Based on the results of Akagi (1979) and Hansbo (1987), the smear zone is often evaluated by the simple expression:

$$d_s = 2d_m$$

(6)

Onoue et al. (1991) introduced a three zone hypothesis defined by (a) a plastic smear zone close to the drain where the soil is highly remoulded during installation, (b) a plastic zone where the permeability is reduced moderately, and (c) an outer undisturbed zone where the soil is unaffected by installation. For practical purposes a two-zone approach is generally sufficient.

On the basis of their experimental work, Indraratna and Redana (1998) proposed that the estimated smear zone is at least 3-4 times larger than the cross section of the drain. This proposed relationship was verified using a specially designed large scale consolidometer (the schematic section is shown in Figure 9). Figure 10 shows the variation of the ratio of horizontal to vertical permeability ($k_h/k_v$), and the water content along a radial distance from the central drain in the large scale consolidation apparatus (Indraratna and Redana 1998; Sathananthan and Indraratna 2006a; Walker and Indraratna 2006). The radius of the smear zone is about 2.5 times the equivalent radius of the mandrel. The lateral permeability (within the smear zone) is 61%-92% of the outer undisturbed zone, which is similar to Hansbo (1987) and Bergado et al. (1991) recommendations. Only recently, Sathananthan et al. (2008) used the cavity expansion theory (CET), obeying the modified Cam-clay model, to analyse the extent of the smear zone caused by mandrel driven vertical drains. Their predictions were verified by large scale laboratory tests where the extent of the smear zone was quantified based on (a) response of excess pore pressure generated while driving the steel mandrel, (b) change in lateral permeability, and (c) obvious reduction in the water content towards the central drain.

Figure 9. Schematic section of the test equipment showing the central drain and associated smear (Indraratna and Redana 1998, with permission from ASCE)
As inspired by field observations, a lower boundary for drain spacing seems to exist, below which there is no discernible increase in the rate of consolidation. Walker and Indraratna (2007) investigated the effect of overlapping smear zones by incorporating a more realistic linear permeability distribution. As shown in Figure 11, two smear zones will interact when the spacing parameter \( n \) is less than the parameter \( s \) of the smear zone. With reference to the undisturbed soil properties, a newly modified expression \( \mu_X \) representing the effect of interacting smear zones can be defined. Figure 12 shows the time required to reach 90% consolidation (\( t_{90} \)) for various interacting smear zone configurations. As Figure 12 suggests, a range of drain spacing values exist, across which the time required to reach a certain degree of consolidation does not change. These results are also in agreement with some observations reported by Saye (2001). This new analytical model for overlapping smear zones provides the basis for selecting the minimum drain spacing, below which the rate of consolidation may decrease. It appears that this radius of minimum influence is 0.6 times the value of the radius of the linear smear zone assumed for non-overlapping smear zones.

Figure 11. Schematic of overlapping smear zones (Walker and Indraratna 2007, with permission from ASCE)

Effect of removing and re-applying a vacuum

A large scale consolidometer can be utilised to examine the effect of vacuum preloading in conjunction with the surcharge load (Indraratna et al. 2004). A large scale consolidation test was conducted by applying a vacuum pressure close to the theoretical maximum of 100kPa to the PVD and
the soil surface through the centre hole in the rigid piston. A surcharge pressure was then applied in two stages, 50kPa, and 100kPa. The vacuum pressure was released for a short time in two stages over a 28 day period, to investigate the effect of unloading and reloading (Figure 13a).

The laboratory results indicated that the suction head decreased with the depth of the drain because a maximum suction of 100kPa could not be maintained along the entire length of the drain. The settlement associated with a combined vacuum and surcharge load is shown in Fig. 13b, which clearly reflects the effect of removing and re-applying the vacuum by the corresponding gradient settlement plot. The above experimental procedure also showed that it is very difficult to sustain a vacuum pressure greater than 90 kPa (the theoretical maximum is 100 kPa).

![Figure 13. a) Suction in the drain (240mm from bottom); b) surface settlement surface settlement associated with simulated vacuum loading and removal (Indraratna et al. 2004)](image)

Soil disturbance during mandrel installation and removal

When a mandrel is removed quickly, the soil near the drain can become unsaturated, i.e. an air gap. Indraratna et al. (2004) attempted to describe the apparent retardation of excess pore pressure dissipation using a series of models in large scale laboratory tests, whilst considering the effects of unsaturation at the drain-soil interface. The consolidation of soft clay in the large scale consolidometer under a combined vacuum and surcharge preloading was analysed using the FEM programme ABAQUS employing the modified Cam-clay theory (Roscoe and Burland 1968). Figure 14 illustrates the plane strain finite element mesh using 8-noded linear strain quadrilateral elements (CPE8RP) with 8 displacement nodes and 4 pore pressure nodes. The associate shape functions for displacements and pore pressure are quadratic and linear respectively.

![Figure 14. FEM discretisation for plane strain analysis in large-scale consolidometer (Indraratna et al. 2004)](image)

The soil moisture characteristic curve (SMCC), including the effect of drain unsaturation could be captured by a thin layer of elements governed by elastic properties. The permeability coefficients converted to the 2D plane strain condition were based on the technique introduced by Indraratna and Redana (2000). Three distinct models were analysed, as summarised below:

Model 1 – fully saturated soil with a linear vacuum pressure distributed along the drain, (suction could be reduced to zero at the pressure bottom of drain).

Model 2 – The soil was fully saturated initially. When a linearly varying vacuum was applied a layer of unsaturated elements was created at the PVD boundary. For convenience, the thin unsaturated layer was modelled elastically ($E = 1000$ kPa, $\nu = 0.25$).

Model 3 – Conditions were similar to Model 2, but included a time-dependent variation in the vacuum pressure (i.e. vacuum removal and reloading) to represent typical field conditions

Figure 15 shows the surface settlement predicted by the models described above. These predictions confirmed that the assumption of an unsaturated layer of soil at the drain-soil boundary with a time dependent variation in vacuum pressure (Model 3) was justified. Not surprisingly, the
condition of full saturation Model 1 over-predicted the settlement.

The predicted and measured values of excess pore water pressure (mid layer) are presented in Fig. 16. Clearly, the Models 2 and 3 are in acceptable agreement with the laboratory observations. As expected, Model 1 (fully saturated) gives the lowest pore pressure suggesting that the unsaturated soil-drain boundary certainly retards the dissipation of excess pore water pressure. In view of both settlement and excess pore water pressure, Model 3 provides the most accurate prediction compared to the laboratory data. Applying a vacuum head accelerates consolidation by increasing the lateral hydraulic gradient. Never the less, any soil unsaturation at the PVD boundary caused by mandrel driving would retard the excess pore pressure dissipation during the early stages of consolidation. To simulate how a mandrel disturbs the soil near the drain, Ghandeharioon et al. (2010) postulated that installing PVDs with a rectangular (conventional) steel mandrel would cause an elliptical cavity expansion with a concentric progression in the horizontal plane (Figure 17).

The elliptical cavity expansion theory (CET) was formulated using modified Cam-clay parameters to address the undrained analysis of PVDs installed in soft clay deposits. Mathematically, this process based on polar coordinates accounts for the rate of mandrel penetration and the time factor for predicting the internal pressure in the cavity, and the corresponding stresses and excess pore water pressure in the soil while driving the mandrel. The trend of excess pore pressure was verified by the laboratory results obtained from a fully instrumented large scale consolidometer (Figure 18).
An elliptical smear zone based on the CET was introduced while the disturbed soil surrounding the mandrel was characterised by plastic shear strain normalised by the rigidity index. As shown in Fig. 19, the analysis of three different cases mentioned above revealed that this term \( \frac{\gamma_p q_f}{\sqrt{3G}} \) was 0.86%-1.05% of the boundary of the failed soil. (\( \gamma_p \) was the plastic shear strain, \( q_f = M p_0 \left( \frac{n_p}{2} \right)^\Lambda \), \( M \) is the slope of critical state line in the \( p \) and \( q \) plane; \( p_0 \) is the initial effective mean stress, \( n_p \) is the isotropic over-consolidation ratio, \( \Lambda \) is the plastic volumetric strain ratio, \( G \) is the shear modulus). The smear zone propagates outward where the normalised plastic shear strain within the smear zone was from 0.10%-0.17%, and at the boundary of the marginally disturbed zone, the magnitude of \( \frac{\gamma_p q_f}{\sqrt{3G}} \) was about 0.01%-0.05% (Figure 19). The region where \( \gamma_p \) was greater than zero constituted the plastic zone, while the outer elastic zone (zero plastic shear strain) was not affected by any change in the excess pore water pressure before or after driving the mandrel. The dimensionless ratio of plastic shear strain to the rigidity index was useful for estimating the extent of the smear zone, because, it facilitated the use of basic soil parameters in purchase simulation without sophisticated large scale testing. The results also confirmed that the radius of the smear zone was at least 3 times the equivalent radius of the mandrel, a value close to the extent of smear zones suggested by previous studies. (Bergado et al. 1991; Indraratna and Redana 1997).

The effect of vacuum consolidation on the lateral yield of soft clays.
any tension zones where the vacuum pressure may be excessive.

As expected, the vacuum pressure alone can create inward lateral movement, whereas preloading without any vacuum may contribute to an unacceptable outward lateral movement. The particular situations for most clays is generally a combination of 40% surcharge preloading stress with a 60% vacuum, which seems to maintain a lateral displacement close to zero. Figure 20b presents the various profiles of surface settlement with an increasing surcharge loading. A vacuum alone may generate settlement up to 10m away from PVD treated boundary while the application of VP can minimise the value of soil heave beyond the embankment toe.

Partially penetrating drains

In some situations, the soft clay is too deep for PVDs to fully penetrate, or the vertically propagated load will not be high enough to justify the full penetration of PVD into the entire clay layer. Therefore, consolidating the clay with partially penetrating vertical drains will be adequate. Indraratna et al. (2008) have numerically analysed the effects of partially penetrating vertical drains and vacuum pressure on the corresponding settlement and lateral displacement.

Figure 21 illustrates the effect of partially installed vertical drains (i.e. different \( l_1/H \) ratios) on the overall degree of consolidation (Figure 21a) and lateral displacement (Figure 21b). The degree of consolidation was calculated on settlement at the centre line and lateral displacement at the embankment toe. The drain may be reduced in length by up to 90% of the entire thickness of clay without significantly affecting the degree of consolidation. The lateral displacements are rather insensitive to the PVD level, as shown in Figure 21b. As shown in Figure 22a, vertical drains are assumed to be installed to a depth \( l_2 \), while the drains in between these are installed to the entire depth of clay \((H)\). It can be seen that \( l_2 \) can be reduced by up to 0.6\( H \) without any significant increase in the time for 90% primary consolidation to occur. In Figure 22a, the primary PVD can be shortened by up to 80-90% of the thickness of the soil without seriously affecting the time for a given degree of consolidation, whereas alternating shorter drains can be reduced in length by up to 40% of the entire clay thickness.
\begin{align*}
\text{Non-Darcian flow} \\
\text{Hansbo (1997) stated that at small hydraulic} \\
\text{gradients, conventional (linear) Darcy’s law may} \\
\text{be replaced by a non-Darcian flow condition defined} \\
\text{by an exponential relationship. Based on non-} \\
\text{Darcian flow, Hansbo (1997) modified the classical} \\
\text{axi-symmetric solutions. The pore water flow} \\
\text{velocity } v, \text{ caused by a hydraulic gradient } \iota, \text{ might} \\
\text{deviate from the original Darcy’s law } v = k \iota, \text{ where} \\
\text{under a certain gradient } \iota, \text{ below which no flow} \\
\text{occurs. Then the rate of flow is given by } v = k (\iota - \iota), \text{ hence the following mathematical relations have} \\
\text{been proposed:} \\
\begin{align*}
v &= k \iota \text{ for } \iota \leq \iota \tag{7} \\
v &= k (\iota - \iota, \iota) \text{ for } \iota \geq \iota \tag{8} \\
\text{where } &\iota = \frac{i_n}{(n-1)} \text{ and } \kappa = (n^{-}\iota^{-}) k \tag{9} \\
\text{In order to study the effects of non-Darcian flow,} \\
\text{Hansbo (1979, 1997) proposed an alternative} \\
\text{consolidation equation. The time required to reach a} \\
\text{certain average degree of consolidation including} \\
\text{smear effect is given by:} \\
t &= \frac{\alpha D^2}{\lambda} \left( \frac{\bar{D} u}{u_0} \right)^{n-1} \left( \frac{1}{1-\bar{U}} \right)^{n-1} \tag{10} \\
\text{where the coefficient of consolidation } \lambda &= \frac{\kappa M}{\gamma_w} , \\
M &= \frac{1}{m^c} , \text{ the oedometer modulus, } \alpha \text{ is the} \\
\text{diameter of the drain influence zone, } d_i \text{ is the} \\
\text{diameter of smear zone, } n = \frac{d_d}{d_u} \text{ in which } d_d \text{ is the} \\
\text{drain diameter, } u_0 \text{ is the initial average excess pore} \\
\text{water pressure, and } \alpha \text{ is determined explicitly as a} \\
\text{high non-linear function of } n, \alpha, \frac{d_d}{d_u} \text{ and } \kappa_0 / \kappa_1 \text{ (Hansbo 1997).} \\
\text{When } n \rightarrow 1 \text{ Eq. (10) gives the same result as the} \\
\text{average degree of consolidation represented as} \\
\bar{T}_b = \frac{c_b t}{d_i^2} , \text{ provided the well resistance is} \\
\text{neglected.} \\
\text{Sathananthan et al. (2006b) developed a new} \\
\text{plane strain lateral consolidation equation which can} \\
\text{be applied to the exponential and linear} \\
\text{correlation between the hydraulic gradient and flow} \\
\text{velocity, while neglecting the well resistance of} \\
\text{vertical drains. A comparison was made between} \\
\text{the results obtained by a Darcian (linear) flow} \text{solution} \\
\text{and the new solution based on a non-} \\
\text{Darcian (exponential) flow.} \\
\text{The parameters described by Sathananthan and} \\
\text{Indraratna (2006b) under plane strain condition are:} \\
\bar{D} = 1 - \frac{1}{4} \frac{\lambda_{hp}}{\alpha_p (2B)^{1/2}} \left( \frac{u_0}{B u_w} \right)^{n-1} , \tag{11} \\
\text{where subscript } p \text{ stands for plane strain,} \\
\lambda_{hp} = \frac{\kappa_{hp}}{m u_w}, \text{ B is the half width of plane strain} \\
\text{unit cell (m), } u_0 \text{ is the initial average excess pore} \\
\text{water pressure (kN/m^2) and} \\
\alpha_p = \frac{\beta_p^2}{4(n-1)} , \tag{12a} \\
\beta_p = \left( \frac{\kappa_{hp}}{\kappa_p} \right)^{1/2} \left[ f_p (n_b - \frac{n_b}{B}) + f_p (n_b B) \right] , \tag{12b} \\
f_p (n, y) = \left[ \frac{1}{2} \frac{1}{n-1} \left( \frac{y}{n} \right)^{2} - \frac{1}{n-1} \left( \frac{y}{n} \right)^{2} \right] \\
\text{It is noted that } k_{hp} / k_b = \frac{\lambda_{hp}}{\lambda} , \text{ because, the} \\
\text{coefficient of permeability is proportional to the} \\
\text{coefficient of consolidation for a particular soil of} \\
given compressibility. Figure 23 shows the} \\
\text{variation in the equivalent parameters ( } \alpha_p , \beta_p , \\
\kappa_{hp} / k_b = \frac{\lambda_{hp}}{\lambda} \text{ and } k_{hp} / k_b \text{) with spacing ratio} \\
\text{ ( } B / B_c, \text{ smear ratio ( } b / b_w , \text{ and permeability} \\
\text{ratio ( } k_b / k_i ) \text{ of the axi-symmetric cell for } n = 1.5. \\
\text{Figure 24 shows a comparison between Darcian} \\
\text{and non-Darcian analysis. The field data agree with} \\
\text{the non-Darcian analysis.} \\
\text{The advantage of the above equivalent plane} \\
\text{strain procedure is that it not only matches the} \\
\text{average degree of radial consolidation (axi-} \\
\text{symmetric), but it also yields a more realistic} \\
\text{distribution of excess pore pressure in the lateral} \\
\text{direction compared to the Darcian condition. It was} \\
\text{verified that the conventional solution based on} \\
\text{conventional Darcian flow ( } v = k \iota \text{) was better when} \\
\text{it was replaced with an exponential equation} \\
\text{ ( } v = \kappa M t^{n-1} \text{). It was also demonstrated that for} \\
\text{ } n \rightarrow 1 \text{, the current non-Darcian solution} \\
\text{approached the Darcian solution proposed earlier} \\
\text{by Indraratna and Redana (1997), with a deviation} \\
\text{of less than 0.01%. This analysis showed that the} \\
\text{consolidation process was clearly influenced by the} \\
\text{exponent factor } n. \text{ The graphical representations of} \\
\text{equivalent plane strain parameters as a function of} \\
\text{the spacing ratio, smear ratio and the permeability} \\
\text{ratio of the axi-symmetric cell (e.g. Figure 23),} \\
\text{would facilitate the practical use of this theory.}
Performance of PVD subjected to cyclic loading

Low lying areas with high volumes of plastic clays can sustain high excess pore water pressure during static and repeated cyclic loading. The effectiveness of PVDs for dissipating cyclic pore water pressures has been discussed by Indraratna et al. (2009a).

A large scale tri-axial test was used to examine the effects of cyclic load on radial drainage and consolidation by PVDs (Fig. 25a). This test chamber can accommodate specimens 300 mm diameter and 600 mm high (Fig. 25b). The excess pore water pressure was monitored via miniature pore pressure transducers. These instruments were saturated under distilled water with vacuum pressure, and then fitted through the base of the cell to the desired locations on the samples.

The tests could be conducted at frequencies of 5-10 Hz, typically simulating train speeds of say 60-100 km/h with 25-30 tonnes/axle train loads. Figure 26 shows an example of the excess pore pressure recorded. This indicates that the maximum
excess pore water pressure closer to the PVD (T2) during cyclic load was significantly less than that near the cell boundary (T1), and the dissipation rate of excess pore pressure at T2 is faster than that of T1.

Figure 27. Excess pore pressure generated with and without PVD under cyclic loading (Indraratna et al. 2009a, with permission from ASCE)

Figure 28. Axial strains during cyclic loading with and without PVD versus number of loading cycles (N): (a) arithmetic; (b) semi logarithmic scales (Indraratna et al. 2009a, with permission from ASCE)

Figure 27 shows the excess pore pressures and corresponding excess pore water pressure ratio $R_u$ versus the number of loading cycles $N$ under the three separate series of tests. Without PVD, the excess pore pressure increased rapidly $R_u \approx 0.9$, and undrained failure occurred very quickly. The corresponding axial strains are shown in Figure 28a. Without a PVD, large cyclic axial strains developed and failure occurred rapidly after about 200 cycles in the cyclic CK$\sigma$U test, and after about 100 cycles in the cyclic UC (cyclic confined compression) test. As seen from Fig. 28b, failure was detected when $e_{uv} - \log N$ curves began to concave rapidly downwards. With a PVD, the axial strain gradually increased to a constant level and no failure was evident even after 3,000 cycles, as shown in Figure 28a and Figure 28b.

The test results revealed that PVDs effectively decreased the maximum excess pore pressure, even under cyclic loading, and they also decreased the build up of excess pore pressure and helped to accelerate its dissipation during any rest periods. In reality, dissipating pore water pressure during a rest period stabilises the track for the next loading stage (i.e. subsequent passage of train). This cyclic-induced excess pore pressure tends to rise substantially as the shear strain exceeds 1.5–2%. Soft clays provided with radial drainage via PVD can be subjected to cyclic stress levels higher than the critical cyclic stress ratio without causing undrained failure.

In practice, railway tracks and airport runways are constantly subjected to relatively high cyclic loads that build up pore water pressures in the underlying subsoil unless sufficient drainage is provided. Laboratory experiments indicate that cyclic pore pressures build up rapidly at high frequencies and the rate of pore pressure dissipation is less than its rate of build up under cyclic loading. The Author worked as a consultant in the monitoring of the Sandgate rail track near Newcastle where relatively short drains were installed to stabilise the track that was constructed on at least 30m of soft estuarine clays in some areas of the track (Indraratna et al. 2010). As the vertical load from 25 tonne axle trains is mainly taken by the shallow subgrade, relatively short PVD were adequate to dissipate the cyclic excess pore water pressure (Figure 29). Moreover, the short PVD also contributed to the control of laterals displacements on the shallow soft estuarine clay having effectively consolidated the very soft clay beneath the track within a period of a few months upon the initial passage of trains. In this case, no external surcharge fill was used as preloading and no vacuum application was required as only the shallow clay layer immediately beneath the ballast and sub-ballast warranted stabilisation. A FEM model based on PLAXIS was used to simulate the track behaviour, and the Class A prediction of excess pore pressure, settlement and lateral movement was in very good agreement with the field data (Figure 30 and Figure 31). The field measurements were only made available to the Author one year after the FEM results had been submitted to the client.
Constitutive model of soft soils under cyclic loading

A constitutive model for soft soils under cyclic loading was presented by Ni et al. (2014).

Compared to the static behaviour, the cyclic behaviour of soft subgrade soils is more complex as the excess pore pressure and strain continue to develop with increasing number of cycles. Based on the Modified Cam-clay theory (Roscoe and Burland 1968), Carter et al. (1980, 1982) proposed a model for the cyclic behaviour of soft soils, in which only one additional parameter characterizing the cyclic behaviour is added. In order to consider the dependence of the generation rate of excess pore pressures on the number of cycles, a new cyclic model extending that of Carter et al. (1980, 1982) was presented by Ni et al. (2014). In this model, only two additional parameters are included in the parameters of Modified Cam Clay model.

It is assumed that during elastic unloading, the yield surface remains unchanged, but reduces the size in an isotropic manner (Carter et al. 1980, 1982) as follows,

$$\frac{d\bar{p}}{p} = \theta^* \frac{dp_y}{p_y}$$

(13)

where, $p_x$ is a hardening parameter and $p_y$ is defined as (Roscoe and Burland 1968):

$$p_y = p + \left( \frac{q}{M} \right)^{\frac{1}{2}}$$

(14)

In the above, $M$ is the slope of the critical state line in $p - q$ space and $p$ and $q$ are the effective mean stress and deviator stress, respectively.

The parameter $\theta^*$ is assumed to be (Ni et al., 2014):

$$\theta^* = \frac{1}{N\xi_1 + \xi_2}$$

(15)

where, $\xi_1$ and $\xi_2$ are experimental constants, and $N$ is the number of cycles.

The stress path for normally and isotropically consolidated soils under cyclic loading is shown in Figure 32. When the stress path moves from point $A$ to point $A'$ during the first loading period, the
soil behaves elastically. During the first unloading period, while the stress path travels from point $A$ to $A^*$, the effective mean stress remains constant. The yield stress for the second cycle (i.e. yield stress after unloading) can be calculated through Eqn. (13). During the first part of the second cycle, the stress path travels from point $A^*$ to point $B$ and the soil behaves elastically. Subsequently, the stress path moves from point $B$ to $B$ and the soil behaves plastically.

Figure 32. The stress path for cyclic loading. (Ni et al. 2014, with permission from ASCE)

Undrained cyclic triaxial loading tests were conducted on reconstituted kaolinite specimens. The experimental results in terms of the axial strain and excess pore pressure are given in Figure 33. It can be observed that the excess pore pressure shows a sharp increase at the low cycle range and increases only modestly towards the large number of cycles. The excess pore pressures reached a stable state for the specimens with CSR= 0.4 and 0.6, but for the specimen with CSR= 0.8, a critical value of normalized excess pore pressure is reached after only a few cycles. It is also observed that the failure cannot be assessed only on the basis of the normalized excess pore pressures. In fact, the failure of the two samples U03 and U12 is indicated by a sharp rise in axial strains at a critical number of cycles. In contrast, for samples U01, U02, U10 and U11, the final axial strains are still very small in the end.

The simulation results are also plotted together with the experimental data in Figure 33. It can be observed that the model proposed accurately predicts the experimental behaviour both in terms of excess pore pressures and axial strains.

NUMERICAL ANALYSIS

Two-dimensional plane strain conversion

For multi-drain simulation, plane strain finite element analysis can be readily adapted to most field situations (Indraratna and Redana 2000;
Indraratna et al. (2005a). Nevertheless, realistic field predictions require that the axi-symmetric properties to be converted to an equivalent 2D plane strain condition, especially the permeability coefficients and drain geometry. Plane strain analysis can also accommodate vacuum preloading in conjunction with vertical drains (e.g. Gabr and Szabo 1997). Indraratna et al. (2005b) proposed an equivalent plane strain approach to simulate vacuum pressure for a vertical drain system with modification to the original theory introduced by Indraratna and Redana (1997), as shown in Figure 34.

Equivalent plane strain conditions can be fulfilled in three ways:

1. Geometric approach where the PVD spacing varies, but the soil permeability remains constant;
2. Permeability approach where the equivalent permeability coefficient is determined while the drain spacing remains unchanged;
3. Combined permeability and geometric approach where plane strain permeability is calculated based on a convenient space between the drains.

Indraratna et al. (2005b) proposed an average degree of consolidation for plane strain by assuming that the plane strain cell (width of $2B$), the half width of the drain $b_w$ and the half width of the smear zone $b_s$ may be kept the same as their axi-symmetric radii $r_w$ and $r_s$, respectively. This implies that $b_w = r_w$ and $b_s = r_s$ (Figure 34). To excess pore pressure can be determined from:

$$\frac{p_{ex}}{u_0} = \left(1 + \frac{p_{ex}}{u_0} (1 + k_1) \right) \exp \left(-\frac{8f_{np}}{\mu_p} \right) - \frac{p_{ex}}{u_0} \left(1 + k_1 \right)$$

and

$$\mu_p = \left[\alpha + \beta \frac{k_{wp}}{k_{wp}^*} \right]$$

where $p_{ex}$ = the initial excess pore pressure, $\mu$ = the pore pressure at time $t$ (average values) and $T_{np}$ = the time factor in plane strain, and $k_{wp}$ and $k_{wp}^*$ are the equivalent undisturbed horizontal and corresponding smear zone permeability, respectively. The geometric parameters $\alpha$ and $\beta$ are given by:

$$\alpha = \frac{2}{3} \frac{2h_s}{B} \left(1 - \frac{b_w}{B} + \frac{b^2}{3B^2} \right)$$

and

$$\beta = \frac{1}{B^2} \left(b_w - b_s \right)^2 + \frac{b_s}{3B^2} \left(3b^2 - b_s \right)^2$$

At a given level of effective stress, and at each time step, the average degree of consolidation for the axi-symmetric ($U_{axi}$) and equivalent plane strain ($U_{pl}$, $pl$) conditions are made equal.

By making the magnitudes of $R$ and $B$ the same, Indraratna et al. (2005a) presented a relationship between $k_{wp}$ and $k_{wp}^*$. The smear effect can be captured by the ratio between the smear zone permeability and the undisturbed permeability, hence:

$$\frac{k_{wp}}{k_{wp}^*} = \frac{k_{wp}}{k} \left[ \ln \left(\frac{n}{s} \right) + \frac{\beta}{k} \ln \left(s - 0.75 \right) \right] - \alpha$$

Ignoring the effects of smear and well resistance in the above expression would lead to the simplified solution proposed earlier by Hird et al. (1992):

$$k_{wp} = \frac{0.67}{k} \left[ \ln \left(\frac{n}{s} \right) - 0.75 \right]$$
Indraratna et al. (2005b) compared two different distributions of vacuum along a single drain for the equivalent plane strain (2D) and axi-symmetric conditions (3D). Varying the vacuum pressure in PVDs installed in soft clay would be more realistic for long drains, but a constant vacuum with depth is justified for relatively short drains.

CASE HISTORIES

**Port of Brisbane**

The Port of Brisbane is located at the mouth of the Brisbane River at Fisherman Islands. An expansion of the Port includes a 235ha area to be progressively reclaimed and developed over the next 20 years using dredged materials from the Brisbane River and Moreton Bay shipping channels. The site contains compressible clays of over 30 m in thickness. At least 7 m of dredged mud capped with 2 m of sand was used to reclaim the sub-tidal area. Generally, the complete consolidation of the soft deep clay deposits may well take in excess of 50 years, if surcharging was the only treatment, with associated settlements of probably 2.5-4 m likely. To reduce the consolidation period, the method of PVDS and surcharge or PVD combined with vacuum pressure (at sites where stability is of a concern) was chosen to be trialled (Indraratna et al., 2011). Three contractors undertook the trial works being Austress Menard, Van Oord and Cofra/Boskalis. All three trialled prefabricated drains and surcharge with Austress Menard and Cofra/Boskalis also trialling their respective proprietary membrane and membrane-less vacuum systems. Figure 35 shows the final layout of a typical trial area with the PVD design results for each area.

Table 1. Typical Soil Properties (Indraratna, 2010)

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Soil type</th>
<th>$\gamma_i$ (kN/m$^3$)</th>
<th>$C_d/(1+e_0)$</th>
<th>$C_v$ (m$^2$/yr)</th>
<th>$C_h$ (m$^2$/yr)</th>
<th>$k_v/k_s$</th>
<th>$s=d_i/d_w$</th>
<th>$C/(1+e_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dredged Mud</td>
<td>14</td>
<td>0.3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.005</td>
</tr>
<tr>
<td>2</td>
<td>Upper Holocene Sand</td>
<td>19</td>
<td>0.01</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0.001</td>
</tr>
<tr>
<td>3</td>
<td>Upper Holocene Clay</td>
<td>16</td>
<td>0.18</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.008</td>
</tr>
<tr>
<td>4</td>
<td>Lower Holocene Clay</td>
<td>16</td>
<td>0.235</td>
<td>0.8</td>
<td>1.9</td>
<td>2</td>
<td>3</td>
<td>0.0076</td>
</tr>
</tbody>
</table>

![Figure 35. S3A Trial Area – Layout and detail design specifications (Indraratna et al., 2011, with permission from ASCE)](image)

To compare two locations with a different loading history, the lateral displacement normalised by the applied effective stress at two inclinometer positions (MS24 and MS34) are plotted in Fig. 36. It was clear that the lateral displacements were largest in the upper Holocene shallow clay depths and were insignificant below 10m. From this limited inclinometer data, the membrane-less BeauDrain system (MS34) had controlled the lateral displacement more effectively than the surcharge only section (MS24). Settlement and excess pore water pressure predictions and field...
This rate of change of $\mu$ continuously increasing gradient of with respect to lateral movement, while a decreasing gradient can be considered to be stable relatively small time increments where a small and decreasing gradient can be considered to be stable with respect to lateral movement, while a continuously increasing gradient of $\mu$ reflects potential lateral instability. In Figure 38, the gradient in the non-vacuum area WD3 increased initially, which could be attributed to the final surcharge loading placed quickly, while the clay was still at early stages of consolidation. However, as the PVDs become fully active and settlement increased at a healthy rate, the gradient of $\mu$ decreased, as expected. In general, Figure 38 illustrates that the vacuum pressure provides a relatively unchanging gradient of $\mu$ with time.

Figure 39 provides approximately linear relationships between the long term residual settlement (RS) and the clay thickness of clay for an over-consolidation ratio (OCR) from 1.1 to 1.4, and for a degree of consolidation (DOC) that exceeding 80%. The reduced settlement (RS) was determined based on the theory secondary consolidation employing the secondary compression index $C_{os}$ (Table 1). More detail on the computation of RS are given by Mesri and Castro (1987), Bjerrum (1972) and Yin and Clark (1994). As expected, when the OCR increased, the RS decreased substantially. In general, as the thickness of Holocene clay increased, the RS also increased. The corresponding regression lines and best–fit equations are also shown in Figure 39. In particular, the vacuum consolidation locations (VC1-2, VC2-2 and VC2-3) show a considerably reduced RS at an OCR approaching 1.4, which is well below the permissible limit of 250mm. At an OCR of approximately 1.3, the residual settlement associated with membrane-less BeauDrain consolidation (TA8) and membrane type (VC1-5) were also small.
Ballina Bypass

The Pacific Highway linking Sydney and Brisbane is constructed to reduce the high traffic congestion in Ballina. This bypass route has to cross a floodplain consisting of highly compressible and saturated marine clays up to 40 m thick. A system of vacuum assisted surcharge load in conjunction with PVDs was selected to shorten the consolidation time and stabilise the deeper clay layers. To investigate the effectiveness of this approach, a trial embankment was built north of Ballina, 34mm diameter circular PVD at 1.0m spacing were installed in a square pattern. The vacuum system consisted of PVDs with an air and water tight membrane, horizontal transmission pipes, and a heavy duty vacuum pump. Transmission pipes were laid horizontally beneath the membrane to provide uniform distribution of suction. The boundaries of the membrane were embedded in a peripheral trench filled with soil-bentonite to ensure absolute air tightness. Figure 40 presents the instrument locations, including surface settlement plates, inclinometers and piezometers. The piezometers were placed 1m, 4.5m, and 8m below the ground level, and eight inclinometers were installed at the edges of each embankment. The embankment area was then divided into Section A (no vacuum pressure), and Section B, subject to vacuum pressure and surcharge fill. As the layers of soft clay fluctuated between 7m to 25m (Table 2), the embankment varied from 4.3m to 9.0m high, to limit the post-construction settlement. A vacuum pressure of 70 kPa was applied at the drain interface and removed after 400 days. The geotechnical parameter of the three subsoil layers obtained from standard odometer tests are given in Table 3.

Figure 39. Effect of OCR and clay thickness on residual settlement. (Indraratna, 2010)

Figure 40. Instrumentation layout for the test embankments at Ballina Bypass (Indraratna et al. 2009b)
Table 2. Bottom level of soft clay layer at each settlement plate (Indraratna et al. 2009b)

<table>
<thead>
<tr>
<th>Settlement plate</th>
<th>SP1, SP2</th>
<th>SP3,SP4</th>
<th>SP5,SP6</th>
<th>SP7, SP8</th>
<th>SP9, SP10</th>
<th>SP11, SP12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom level of soft clay layer (m-RL)</td>
<td>2.7-6.7</td>
<td>6.7-9.7</td>
<td>9.7-11.7</td>
<td>11.7-14.7</td>
<td>14.7-17.7</td>
<td>20.7-24.7</td>
</tr>
</tbody>
</table>

Table 3. Soil parameters at SP12 (Indraratna et al. 2009b)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil Type</th>
<th>( \lambda )</th>
<th>( \kappa )</th>
<th>( \gamma ) (kN/m³)</th>
<th>( e_0 )</th>
<th>( k_{0,10} ) (10⁻⁴ m/s)</th>
<th>OCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.5</td>
<td>Clayey silt</td>
<td>0.57</td>
<td>0.06</td>
<td>14.5</td>
<td>2.9</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>0.5-15.0</td>
<td>Silty Clay</td>
<td>0.57</td>
<td>0.06</td>
<td>14.5</td>
<td>2.9</td>
<td>10</td>
<td>1.7</td>
</tr>
<tr>
<td>15.0-24.0</td>
<td>Stiffer Silty Clay</td>
<td>0.48</td>
<td>0.048</td>
<td>15.0</td>
<td>2.6</td>
<td>3.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The soil profile with its relevant properties is shown in Figure 41. A soft silty layer of clay approximately 10m thick was underlain by moderately stiff and silty layer clay located 10-30m deep, which was in turn underlain by firm clay. The groundwater was almost at the ground surface. The water content of the soft and medium silty clay varied from 80 to 120%, which was generally at or exceeded the liquid limit, ensuring that the soils were fully saturated. The field vane shear tests indicated that the shear strength was from 5-40 kPa. The compression index \( \left( \frac{C_U}{1+e_0} \right) \) determined by standard oedometer testing was between 0.30-0.50.

Settlement and associated pore pressure recorded by the settlement plates and piezometers are shown in Figure 42, with the embankment construction schedule. The actual suction varied from -70 kPa to -80 kPa, and no air leaks were encountered. Suction was measured by miniature piezometers embedded inside the drains.
Lateral displacement at the border of the embankments needed to be examined carefully, particularly the vacuum area where the surcharge loading was raised faster than that at the non-vacuum area. The soil properties and lateral displacement plots before and after vacuum are shown in Figure 43. Inclinometer I1 was installed at the border of the vacuum area, whereas inclinometers I2-I4 were located at the edge of the vacuum area. Here the lateral displacement subjected to vacuum was smaller even though the embankments were higher. In Figure 43b the plot of lateral displacement normalised to embankment height showed that the vacuum pressure undoubtedly reduced lateral displacement.

![Figure 43](image1)

Figure 43. (a) Soil properties before and after vacuum application; and (b) Measured lateral displacement and lateral displacement normalised with embankment height (Indraratna et al. 2009b)

2D and 3D single drain analyses were used to compute the settlement at location SP-12. Typical 2D finite element mesh is shown in Figure 44a. The construction history and measured settlement at the settlement plate SP-12 are shown in Fig. 44b. Here the clay was assumed to 24m thick, based on the CPT data. The analytical pattern was similar to Indraratna et al. (2005a). The predictions from 2D and 3D analyses agreed with the measured data, where the rate of settlement increased significantly after a vacuum was applied (Figure 44c).

![Figure 44](image2)

Figure 44. (a) 2D Finite element mesh; (b) loading history; and (c) consolidation settlements for settlement plate SP-12 (Indraratna et al. 2009b)

**Second airport Bangkok international airport**

The location of the Second Bangkok International Airport is about 30 km east of Bangkok. The subsoil consists of a relatively uniform, top weathered crust with thickness of approximately 1.5 m. At a depth of 20-24 m below the ground surface, a stiff clay layer underlies the soft clay. Due to the frequent flood recurrence during the wet seasons, the soil generally has very high moisture content. The sub-soil profile and pattern of the vertical drain adopted are shown in Figure 45. Table 4 gives the geometric drain parameters whereas the plane strain permeability coefficients for Bangkok clay are shown in Table 5.
Figure 45. Cross section of an embankment with the subsoil profile, Second Bangkok International Airport, Thailand (Indraratna et al. 2000)

### Table 4. Geometric parameters of the drains for embankments TS1, TS2 and TS3 at Second Bangkok International Airport (Indraratna et al. 2000)

<table>
<thead>
<tr>
<th>Embankment</th>
<th>Spacing (m)</th>
<th>B (m)</th>
<th>b_s (m)</th>
<th>b_w (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td>1.5</td>
<td>0.75</td>
<td>0.03</td>
<td>0.27</td>
</tr>
<tr>
<td>TS2</td>
<td>1.2</td>
<td>0.60</td>
<td>0.03</td>
<td>0.27</td>
</tr>
<tr>
<td>TS3</td>
<td>1.0</td>
<td>0.50</td>
<td>0.03</td>
<td>0.27</td>
</tr>
</tbody>
</table>

### Table 5. Undisturbed and smear zone hydraulic conductivities for Bangkok clay and Muar clay (Indraratna et al. 2000)

<table>
<thead>
<tr>
<th>Embankment</th>
<th>Dept h (m)</th>
<th>k_h (m/s)</th>
<th>k_v (m/s)</th>
<th>k hp (m/s) (no smear)</th>
<th>k hp (m/s) (with smear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1 (S=1.5 m)</td>
<td>0-2</td>
<td>5.23 ×10^{-8}</td>
<td>2.99 ×10^{-8}</td>
<td>1.47 ×10^{-8}</td>
<td>1.18 ×10^{-9}</td>
</tr>
<tr>
<td></td>
<td>2-7</td>
<td>1.2 ×10^{-8}</td>
<td>6.83 ×10^{-9}</td>
<td>3.36 ×10^{-9}</td>
<td>2.7 ×10^{-10}</td>
</tr>
<tr>
<td></td>
<td>7-12</td>
<td>5.25 ×10^{-9}</td>
<td>3.0 ×10^{-9}</td>
<td>1.48 ×10^{-9}</td>
<td>1.19 ×10^{-10}</td>
</tr>
<tr>
<td>TS2 (S=1.2 m)</td>
<td>0-2</td>
<td>5.23 ×10^{-8}</td>
<td>2.99 ×10^{-8}</td>
<td>1.62 ×10^{-8}</td>
<td>2.04 ×10^{-9}</td>
</tr>
<tr>
<td></td>
<td>7-12</td>
<td>5.25 ×10^{-9}</td>
<td>3.0 ×10^{-9}</td>
<td>1.63 ×10^{-9}</td>
<td>2.05 ×10^{-10}</td>
</tr>
<tr>
<td>TS3 (S=1 m)</td>
<td>0-2</td>
<td>5.23 ×10^{-8}</td>
<td>2.99 ×10^{-8}</td>
<td>1.78 ×10^{-8}</td>
<td>2.91 ×10^{-9}</td>
</tr>
<tr>
<td></td>
<td>7-12</td>
<td>5.25 ×10^{-9}</td>
<td>3.0 ×10^{-9}</td>
<td>1.78 ×10^{-9}</td>
<td>2.92 ×10^{-10}</td>
</tr>
</tbody>
</table>
The surcharge load of the embankment was applied in stages, whereby Stage 1 was equivalent to 18 kPa including a sand blanket and clay sand 1.0 m high. The construction of Stage 2 (45 kPa), Stage 3 (54 kPa) and Stage 4 (75 kPa) followed and it resulted in an equivalent total fill height of 4.2 m. In order to maintain the stability requirements, a berm of 5 m width and 1.5 m height was added after the surcharge was increased from 45 to 54 kPa. The berm was further extended to 7 m wide when the surcharge load exceeded 54 kPa. The settlement and excess pore water pressure development in the sub-soil were measured for over 1 year, and the behaviour of embankment was monitored by settlement plates, slope inclinometers, and piezometers such as closed hydraulic piezometers and open standpipes.

The finite element mesh used in the embankment is shown in Figure 46. The clay foundation was discretised into linear strain quadrilateral (LSQ) elements. A finer mesh was used for the PVD zone where each drain element represents a PVD containing the smear zone on either side of it (see insert, Figure 46). The properties of the soil inside and outside the smear zone were assumed to be similar to those used in the single drain analysis. The instrumentation was placed in the mesh in such a way that so the measuring points coincided with the mesh nodes. The piezometers were placed 0.75 m from the centreline of the embankment between 2 drains, to measure the excess pore water pressure.

Ground settlement for the three embankments is shown in Figure 47, and the predictions were made from the centreline of each embankment up to 100 m away. As shown, the predicted and measured settlement was very similar. Heave or swelling was predicted to take place past the toe of the embankment, i.e. about 27 m away from the centreline. Surface settlement was measured on either side of the centreline and proved to be acceptable with the calculated settlement profiles.

In Figure 48 the lateral deformation measured by an inclinometer 7.5 m away from the centreline of embankments TS1, TS2 and TS3 were plotted respectively. The finite element predictions (smear and well resistance) were also plotted for comparison purposes. Given the limitations of the 2-D plane strain model, the predictions are acceptable. Undoubtedly, the inclusion of both smear and well resistance in the plane strain, FEM model helped to predict the lateral yield of the soft clay foundation. In comparison with a no drain situation, vertical drains definitely reduce lateral displacement, thereby directly contribution to the stability of the embankment.

Tianjin Port

Tianjin port is approximately 100km from Beijing, China. The top 15m of soil at this site was soft to very soft and needed to be improved using a preloading surcharge of more than 140kPa (Rujikiatkamjorn et al. 2008). To avoid any
stability problems (high lateral yield) associated with a high surcharge embankment, a fill height of 50 kPa plus a vacuum pressure of 80kPa were applied on top of the 20m thick soft soil layer in construction with PVDs installed at 1.2 m spacing. The conversion method proposed by Indraratna et al (2005b) was used for the 2D plane strain FEM analysis (Fig. 49), and the finite element program (ABAQUS) was used to simulate the 3D multi-drain analysis (Figure 50), employing the Biot coupled consolidation theory.

Figure 47. Surface settlement profile for embankments: a) TS1; b) TS2; and c) TS3, Second Bangkok International Airport (Indraratna et al. 2000)

Figure 48. : Lateral displacement profiles at 7.5 m away from centreline of embankments TS1, TS2 and TS3, Second Bangkok International Airport (Indraratna et al. 2000)
Figure 49. 2D finite-element mesh: (a) x=0 plane; (b) y=0 plane
(Rujikiatkamjorn et al. 2008, with permission from ASCE)

Figure 50. 3D finite-element mesh: (a) Isometric view; (b) top view
(Rujikiatkamjorn et al. 2008, with permission from ASCE)
In terms of settlement, excess pore pressure, and lateral displacement, the numerical results from the equivalent 2D and true 3D analyses were quite similar (Figure 51 and Figure 52). This proves that, the equivalent plane strain (i.e. 2D) analysis was sufficient from a computational point of view, especially for multi-drain analysis of large projects where a 3D model would be more time consuming. From a practical point of view, the height of surcharge fill can be reduced by applying a vacuum preloading to achieve the same rate and degree of consolidation. Applying a surcharge pressure after the initial vacuum preloading could also reduce excessive inward lateral movement near the toe of the embankment (Rujikiatkamjorn et al. 2008; Rujikiatkamjorn et al. 2007).

**DESIGN CHARTS OF PVDS WITH VACUUM PRELOADING**

*Design steps*

Rujikiatkamjorn and Indraratna (2008) proposed design charts eliminating cumbersome iteration procedures using the equivalent drain diameter as an independent variable to obtain the relevant drain spacing. The design steps are summarised below:

1. Use the available soil profiles, in-situ test measurements and laboratory data to obtain the relevant soil properties, hence, determine the appropriate installation depth \(l\), and the desired consolidation time \(t\);

2. Assume the required degree of consolidation \(U_t\) for surcharge fill alone;

3. For vacuum pressure application, specify the mean suction, \(p_o\), required total design stress \(\Delta \sigma\), and the surcharge fill pressure, \(\Delta p\) and then determine the required degree of consolidation from

\[
U_{vac} = \left(\Delta \sigma / (p_o + \Delta p)\right) U,
\]

4. Use \(c_v\), \(t\) and \(l\), to determine \(u^*\) using Figure 53 or from,

\[
u^* = \sum_{m=1}^{\infty} \frac{8}{(2m+1)^2 \pi^2} \exp\left(-\frac{(2m+1)^2}{2}\right) T_m\]

5. Determine the available size of the PVD (circular or wick shape) and then compute the equivalent drain diameter (for wick drains), \(d_w\) from \(d_w = 2(a+b)/\pi\);

6. Find \(T_m\) from:

\[
T_m = c_s l / d_w^2
\]
7. Calculate \( \gamma = -\frac{8T_{u}'}{\ln \left( \frac{1-U_{\text{vac}}}{U_{\text{vac}}^*} \right)} \) for surcharge fill only (no vacuum),

or \( \gamma = -\frac{8T_{u}'}{\ln \left( \frac{1-U_{\text{vac}}}{U_{\text{vac}}^*} \right)} \) for vacuum pressure plus surcharge fill.

8. Establish the diameter and permeability of the smear zone.

9. Determine \( \xi \) using Fig. 54 or from the equation:

\[
\xi = \left( \frac{k_{a}}{k_{r}} - 1 \right) \ln (s) \tag{24}
\]

10. Calculate \( n \) from \( n = \exp(\alpha \ln \gamma + \beta) \).

where, \( \alpha = 0.3938 - 9.505 \times 10^{-4} \xi^{1.5} + 0.03714 \xi^{0.5} \)

\( \beta = 0.4203 + 1.456 \times 10^{-3} \xi^{2} - 0.5233 \xi^{6.5} \); \( \tag{26a} \)

11. Calculate the influence zone \( (d_{r} = n d_{o}) \).

12. Choose the drain pattern and determine the spacing of drain \( (d) \) from either \( d = d_{r}/1.05 \) (triangular grid) or \( d = d_{r}/1.128 \) (square grid).

---

**Worked-out Example**

The required soil parameters for the project are assumed to be: \( U_{r} = 90 \%, \ t = 24\text{m}, \ d_{w} = 34\text{ mm} \) (circular drain: Mebra-MCD34), \( c_{h} = 2.5 \text{ m}^{2}/\text{year} \), \( c_{v} = 1.0 \text{m}^{2}/\text{year} \), \( k_{d}/k_{r} = 5 \), \( s = 3 \), Maximum Design Surcharge, \( \Delta \sigma = 120 \text{ kPa} \), surcharge fill pressure, \( \Delta p = 60 \text{ kPa} \), vacuum pressure, \( p_{0} = -60\text{kPa} \) (suction). Well resistance is neglected. Calculate the drain spacing \( (d) \), for (a) \( t = 1 \text{ year} \); (b) \( t = 9 \text{ months} \); and (c) how the drain spacing can be altered with an increased vacuum pressure up to 90 kPa over 9 months.

**Solution:**

**Part (a) \( t = 1.0 \text{ year} \)**

1. \( T_{v} = 1.0 \times 1/24^{2} = 0.002; \)

\( U_{\text{vac}} = (120/(60+60)) \ast 0.9 = 0.9 \)

2. Calculate \( U_{\text{vac}}^* \) using Equation (20) or from Figure 53; hence, \( U_{\text{vac}}^* = 0.95 \)

3. \( T_{h}' = c_{h} t / d_{w}^2 = 2.5 \times 0.75 / 0.034^2 = 2163 \)

4. \( \gamma = -8T_{u}' / \ln \left( \frac{1-U_{\text{vac}}}{U_{\text{vac}}^*} \right) = -8 \times 2163 / \ln \left( \frac{1-0.9}{0.95} \right) = 7686 \)

5. From Figure 54 or using Equation (24), \( \xi = 4.39 \)

6. Using Equations (26a and 26b), determine \( \alpha = 0.463 \) and \( \beta = -0.649 \).

7. From Equation (25),

\( n = \exp(\alpha \ln \gamma + \beta) = \exp(0.463 \times \ln 7686 - 0.649) = 33 \)

8. Calculate \( d_{r} \) from, \( d_{r} = n d_{o} = 33 \times 0.34 = 1.122 \text{ m} \)

9. Drain spacing = 1.1 m for triangular (1.122/1.05) or 1.0 m for square grid (1.122/1.128), respectively.

The above calculations confirm that the design spacing of 1m×1m used at Ballina Bypass can be justified for similar soil properties.

**Part (b) \( t = 0.75 \text{ years} \ (9 \text{ months}) \)**

1. \( T_{v} = 1.0 \times 0.75/24^{2} = 0.001; \)

\( U_{\text{vac}} = (120/(60+60)) \ast 0.9 = 0.9 \)

2. Calculate \( U_{\text{vac}}^* \) using Equation (20) or from Fig. 53; hence, \( U_{\text{vac}}^* = 0.96 \)

3. \( T_{h}' = c_{h} t / d_{w}^2 = 2.5 \times 0.75 / 0.034^2 = 1622 \)

4. \( \gamma = -8T_{u}' / \ln \left( \frac{1-U_{\text{vac}}}{U_{\text{vac}}^*} \right) = -8 \times 1622 / \ln \left( \frac{1-0.9}{0.96} \right) = 5737 \)

5. Using Figure 54 or from Equation (28), \( \xi = 4.39 \)
6. From Equations (26a and 26b), find 
   \( \alpha = 0.463 \) and \( \beta = -0.649 \).

7. From Equation (25),
   \[ n = \text{exp}(\alpha \ln \gamma + \beta) = \text{exp}(0.463 \times \ln 5737 - 0.649) = 29 \]

8. Calculate \( d_e \) from \( d_e = n \cdot d_u = 29 \times 0.034 = 0.986 \) m.

9. Drain spacing = 0.95 m for triangular grid (i.e. 0.986/1.05) or 0.90 m for square grid (i.e. 0.986/1.128).

**Part (c): Vacuum pressure increased up to 90 kPa over 9 months. Revised Drain Spacing?**

1. \( T_v = 1 \times 0.75/24^2 = 0.001 \);
   \( U_{w,vac} = (120/(90 + 60))^* 0.9 = 0.72 \)

2. C Calculate \( u^* \) using Equation (20) or Fig. 53, Hence, \( u^* = 0.96 \)

3. \( T'_v = c_t / d^2_v = 2.5 \times 0.75 / 0.034^2 = 1622 \)

4. \( \gamma = -8T'_v \ln \left( \frac{1 - U_{v, vac}}{u^*} \right) = -8 \times 1622 = 10531 \)

5. Use Fig. 542 or Equation (28), \( \xi = 4.39 \)

6. Using Equations (26a and 26b), find \( \alpha = 0.463 \) and \( \beta = -0.649 \).

7. From Equation (25),
   \[ n = \text{exp}(\alpha \ln \gamma + \beta) = \text{exp}(0.463 \times \ln 10531 - 0.649) = 38 \]

8. Calculate \( d_e \) from \( d_e = n \cdot d_u = 38 \times 0.034 = 1.29 \) m.

9. Drain spacing = 1.23 m for triangular pattern (i.e. 1.29/1.05) or 1.14 m for square grid (i.e. 1.29/1.128).

This demonstrates that increased vacuum pressure allows the drain spacing to be increased. This should also reduce the risk smear overlapping and reduced drain costs.

**NUMERICAL SOLUTION OF STONE COLUMNS WITH CONSIDERATION OF ARCHING, CLOGGING AND SMEAR EFFECTS**

Indraratna et al. (2013) presented a numerical model based on finite difference technique to analyse the response of stone column− reinforced soft soil considering arching, clogging effects as well as smear effects, adopting free strain hypothesis. In contrast with the conventional vertical drains, the stone columns have a reinforcement effect as well as allow radial drainage at a much faster rate that enables the quick dissipation of excess pore water pressure caused by surcharge loading.
Upon installation, alike the vertical drains, the stone columns develop a smear zone in the interface between the soil and the stones. In addition, a clogged zone can be formed by the movement of soil particles into the voids of the stone column. This is better illustrated in Figure 55 and the four distinct zones of the cross section are given in Figure 55 (c).

Vertical stress distribution \( w(r) \) on the soil is governed by (Low et al., 1994):

\[
w(r) = w(r_e) + (N - r/r_e)^2 F(N, n_s)
\]

(27)

where \( N = r_e/r_c \), and \( n_s \) is the stress concentration factor.

The dissipation of the excess pore pressure is governed by (Indraratna et al., 2013):

\[
\frac{\partial e_v}{\partial t} = -\frac{k_h}{\gamma_s} \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right)
\]

(28)

where \( e_v \) is the volumetric strain in the element and \( u \) is the excess pore water pressure.

The clogging effect can have an adverse impact on the performance of stone columns. The effective radius of the clogging zone can be written as (Indraratna et al., 2013):

\[ r_c' = \alpha r_c \]

(29)

and the coefficient of horizontal permeability in it can be expressed as (Indraratna et al., 2013):

\[ k_h = \alpha k_s \]

(30)

An example case is calculated with the parameters as \( N=2, \ k_s/k_h=10, \ r_e/r_c=1.1, \ H/r_c=20, \ n_s=3, \) and \( \alpha = \alpha_1 = 1 \), and the results are compared against the existing models of Han and Ye (2000, 2002) and Wang (2009). The average degree of consolidation variation with the time factor is shown in Figure 57. It is observed that proposed model agree well with the existing models. Oh et al. (2007) have carried out some field tests in the soft estuarine clay site in Queensland, Australia. Figure 58 shows the ground settlement data together with the predictions of the model of Indraratna et al. (2013). A reasonable agreement was reached, although the computed settlements were slightly over-predicted.

CONCLUSION

It is clear that the application of PVDs combined with vacuum and surcharge preloading has become common practice, and is now considered to be one of the most effective ground improvement techniques. Analytical and numerical modelling of vacuum preloading is still a developing research area. There has always been a discrepancy between the predictions and observed performance of embankments stabilised with vertical drains and vacuum pressure. This discrepancy can be attributed to numerous factors such as the uncertainty of soil properties, the effect of smear, inaccurate assumptions of soil behaviour and vacuum pressure distribution, and an improper conversion of axi-symmetric condition to plane strain (2D) analysis of multiply drains.

Vacuum assisted consolidation is an innovative method which has recently, and successfully, been used for large scale projects on very soft soils in reclamation areas. The extent of surcharge fill can be decreased to achieve the same amount of settlement and the lateral yield of the soft soil can
be controlled by PVDs used in conjunction with vacuum pressure. The effectiveness of this system depends on (a) the air tightness of the membrane, (b) the seal between the edges of the membrane and the ground surface, and (c) the soil conditions and location of the ground water level. The exact role of membrane type and membrane-less systems for vacuum preloading requires detailed evaluation. In the absence of a comprehensive and quantitative analysis, the study of suitable methods to apply vacuum preloading becomes imperative, experimentally, numerically and in the field.

To study the performance of vacuum assisted consolidation, a process simulation test using a large-scale consolidometer was conducted to obtain more realistic parameters, including the correct smear zone characteristics, the distribution of vacuum along the length of the drain, as well as soil and drain properties. Conventional small equipment (e.g. Rowe cell) cannot capture these parameters. The equivalent radius of the smear zone is generally 2-3 times larger than the equivalent radius of the mandrel and the soil permeability in the smear zone is lower than the undisturbed zone by a factor of 1.5-2. The presence of even a thin unsaturated layer of soil at the boundary of the PVD would retard the pore pressure dissipation at the initial stage of consolidation.

Analytical modelling of vertical drains that include vacuum preloading under axi-symmetric and plane strain conditions that simulate the consolidation of a unit cell surrounding a single vertical drain has been developed. The effects of vacuum propagation along the length of a drain and the occurrence of non-Darcian flow conditions have been incorporated in the proposed solutions to obtain a more realistic prediction. The elliptical cavity expansion theory provided further insight to evaluate the role that smear zone characteristics play on consolidation.

In large construction sites where many PVDs are installed, a 2D plane strain analysis is usually sufficient. The proposed conversion from axi-symmetric to a plane strain condition agreed with the data available from case histories, including Ballina Bypass and Port of Brisbane (Australia), the Second Bangkok International Airport (Thailand) and Tianjin Port (China). These simplified plane strain methods can be readily incorporated in numerical (FEM) analysis. The conversion procedure from 3D to 2D based on the correct transformation of permeability and vacuum pressure, ensure that the time-settlement curves are the same as the true 3D analysis. Field behaviour and model predictions indicate that the efficiency of vertical drains depends on the magnitude and distribution of vacuum pressure as well as the degree of drain saturation during installation, and the extent of smear caused by the vertically penetrating mandrel.

From a practical point of view, the surcharge fill can be reduced in height by using vacuum preloading to achieve the same desired rate of consolidation. This system eliminates the need for a high embankment surcharge load, but air leaks must be prevented as much as possible. Suitable design charts for vertical drains that consider both vertical and horizontal drainage have been developed. As a result, the conventional and often cumbersome trial and error methods used to estimate the appropriate parameters and spacing of drains be avoided. Once the equivalent drain diameter and other relevant parameters are known, the diameter of the influence zone can be readily obtained without any further iterations or interpolations. These preliminary design charts have now been extended to represent a larger array of soil properties and drain patterns, on the basis of the same governing equations presented here.

Apart from road embankments, PVDs will also help stabilise rail tracks in coastal areas containing a high percentage of clayey subgrades. It has been shown that short PVDs can be used under rail tracks to improve stability by dissipating excess cyclic pore pressure and curtailing lateral displacement. Much of this research is still ongoing at the University of Wollongong, particularly in view of future high speed rail. Current laboratory observations prove without doubt that high speed trains cannot operate efficiently on tracks built on soft subgrade clays unless it is consolidated before construction, or alternative improvements such as chemical treatment or stone columns are considered.

For stone column application, arching, clogging, and smear effects can affect the performance of the stone column. A numerical solution based on Finite Difference Method was developed with a comprehensive consideration of these effects. The results showed that this solution had a good agreement with other existing models and field tests. In future, the laboratory studies on these factors are expected to be conducted so that more models for them could be developed for determining the parameters.
ACKNOWLEDGEMENTS

A number of research projects on the application of vertical drains and vacuum preloading have been supported in the past and present by the Australian Research Council (ARC). Keen collaborations with industry through numerous projects have facilitated the application of theory to practice. In this respect, I sincerely thank Queensland Department of Main Roads, Port of Brisbane Corporation, Roads and Traffic Authority, Coffey Geotechnics, Polyfabrics, Geofabrics, ARUP, Douglas Partners, Sydney Trains, ARTC, Chemstab and Austress Menard. At least a dozen PhD students and half a dozen research fellows have contributed to the soft soil engineering research over the past 12-15 years.

This invited Keynote lecture can be considered as a significant extension of the 1st Author’s 2009 EH Davis Memorial Lecture of Australian Geomechanics Society. Much of the contents have also been elaborated in past issues of the Canadian Geotechnical Journal, ASCE Journal of Geotechnical & Geoenvironmental Engineering, Geotechnique, Int. J. of Geomechanics, and J. of Ground Improvement, among others. Salient contents from these past articles have been reproduced here with kind permission from the original sources.

REFERENCES


