# Performance and Prediction of Vacuum Consolidation Behavior at Port of Brisbane

## Avantages et prédictions de comportement due a la consolidation sous vide au port de Brisbane

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ABSTRACT: Due to a projected increase in trade activities at the Port of Brisbane, new berths on Fisherman Islands at the mouth of the Brisbane River will be constructed in the outer area (235ha) close to the existing port facilities via land reclamation. A vacuum assisted surcharge load in conjunction with prefabricated vertical drains was choosen to reduce the required consolidation time. The features of the combined vacuum and surcharge fill system and the construction of the embankment are described in this paper. A comparison of the performance of the vacuum combined surcharge loading system with a standard surcharge fill emphasizes the obvious advantages of vacuum consolidation. Field data is presented to show how the embankment performed during construction. An analytical solution for radial consolidation incorporating both time-dependent surcharge loading and vacuum pressure is employed to calculate the settlements and associated excess pore pressures of the soft Holocene clay deposits.

RÉSUMÉ : L'augmentation des activités de commerce au port de Brisbane nécessite la construction, à proximité des terminaux existants, de nouveaux postes de quais dans les iles Fisherman a l'embouchure de la rivière de Brisbane sur une superficie de 235 Ha gagnée sur la mer. Un chargement sous vide contrôle, associe a des drains préfabriqués, a été appliqué pour réduire le temps de consolidation. L'article décrit les caractéristiques de la technique de consolidation sous vide associe au chargement par remblaiement et la construction du remblai. Une comparaison entre la consolidation sous vide associée au remblaiement et le pré chargement classique montre clairement les avantages en faveur de la consolidation sous vide. Les données enregistrées sur le site illustrent le comportement du remblai durant la consolidation. Une solution de consolidation horizontale tenant compte du chargement et de la pression sous vide est présentée en vue de prédire le tassement et l'excès de la surpression interstitielle du dépôt d'argile molle de l'Holocène.

KEYWORDS: consolidation, soil improvement, vertical drains, vacuum.

## 1 INTRODUCTION

The Port of Brisbane is one of the Australia's largest commercial ports located at the entrance of the Brisbane River at Fisherman Islands. With demand in commercial activities, a new outer area (235ha) is being reclaimed for major expansion to maximise the available land, and to provide the maximum number of berths suitable for container handling for servicing regional importers and exporters. In this area, the soil profile mainly consists of compressible clay deposits over 30m in thickness with very low undrained shear strength (<15 kPa at shallow depth). The strength of dredged mud had a much lower strength depending on the placement time and the thickness of capping material. Without surcharge preloading, it is estimated that the consolidation time could be more than 50 years with overall settlements of 2.5-4.0m. Therefore, vacuum consolidation with prefabricated vertical drains (PVDs) was suggested to accelerate the consolidation process and to minimise lateral deformation adjacent to the Moreton Bay Marine Park (Indraratna et al. 2011).

The effectiveness of the vacuum preloading assisted by PVDs has been illustrated by Chu et al. (2000) and Chai et al. (2005). In this technique, vacuum pressure can propagate to a greater depth of the subsoil via PVD length. Also, extended consolidation time due to stage construction can be minimized (Indraratna et al. 2005). The surcharge fill height can be reduced by several metres, if a vacuum pressure (at least 70 kPa) is applied and sustained (Rujikiatkamjorn et al. 2008). The embankment construction rate can be increased and the number of construction stages can be reduced (Yan and Chu 2003). Once the soil has increased its stiffness and shear strength due to consolidation, the post-construction settlement will be significantly less, thereby eliminating any risk of differential settlement of the overlying infrastructure (Shang et al. 1998). To the authors' knowledge, there is no comprehensively reported case history where both the conventional surcharge preloading and vacuum technique have been applied in the same area with distinct variation of drain types and spacing.

In this paper, the performance between the vacuum and non-vacuum areas has been compared based on the measured settlements, excess pore pressures and lateral displacements. The influences of drain spacing, drain types and type of soil improvement are discussed based on the observed degree of consolidation. The analytical solutions for radial consolidation considering both time dependent surcharge loading and vacuum pressure are proposed to predict the settlement and associated excess pore pressure.

## 2 GENERAL DESCRIPTION OF EMBANKMENT CHARACTERISTICS AND SITE CONDITIONS

At the Port of Brisbane, to evaluate the performance of the vacuum consolidation system with the non-vacuum system (PVD and surcharge load), a trial area (S3A) shown in Fig. 1 was partitioned into WD1-WD5 (Non-vacuum areas) and VC1-VC2 (Vacuum areas). After placing the dredged fill, the mud was capped off with a 2-3m layer of dredged sand, which acted as a working platform for PVD installation machine, whilst serving as a drainage layer.

The upper Holocene sand beneath the reclaimed dredged mud was about 2m thick, followed by the Holocene clay layer with different in thickness from 6m to 25m. A Pleistocene deposit containing highly over-consolidated clay underlies the softer Holocene clay layer. Site investigation techniques including cone penetration/piezocone tests, dissipation tests, boreholes, field vane shear tests and oedometer tests were carried out to assess the relevant consolidation and stability design parameters. The water contents of the soil layers were similar to or exceed their liquid limits. The vane tests show that the undrained shear strength of the reclaimed dredged mud and the Holocene clays were from 5 to 60 kPa. The compression index changed from 0.1 to 1.0. The coefficient of consolidation in vertical direction is similar to that in horizontal direction ($c_h$) for the remoulded dredged mud layer, while $c_v/c_h$ is about 2 for the Holocene clay layer.

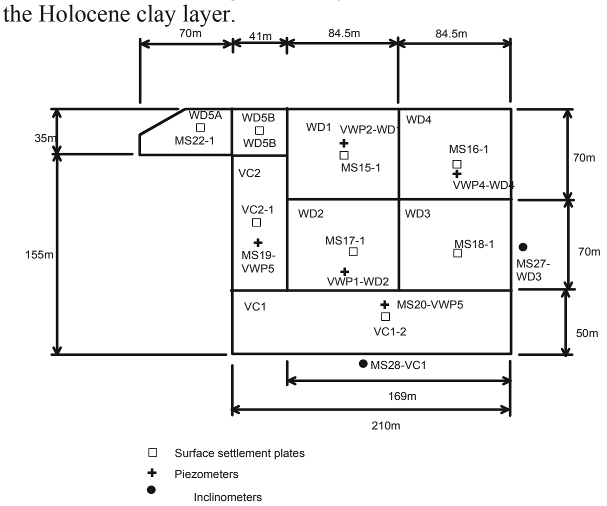


Figure 1. Site layout for S3A with instrumentation plan

The surcharge preloading system was adopted for the inner areas (WD1-WD5) while, in the outer area (VC1 and VC2) close to the Marine Park, the technique of vacuum combined preloading was selected to control lateral displacement in order to minimise disturbance of the nearby marine habitats. Stringent design criteria were adopted for the design and construction of emabankment over the soft Holocene deposits: (a) Service load of 15-25 kPa, (b) maximum residual settlement less than 250 mm over 20 years after treatment. The surcharge embankment heights varied from 3.0m to 9.0m. Based on the design criteria, Table 1 presents the PVD characteristics and treatment types applied to each section. In the non-vacuum areas, both circular and band shape drains were established in a square pattern at a spacing in the range of 1.1-1.3m. The length of PVDs changed from 6m to 27.5m across the site as shown in the Table 1.

Table 1. PVD characteristics and improvement scheme

| | Drain type | Drain spacing | Fill height (m) | Treatment scheme |
|---|---|---|---|---|
| WD1 | Circular drains | 1.1 | 5.2 | Surcharge |
| WD2 | Circular drains | 1.3 | 7-7.2 | Surcharge |
| WD3 | Band drain Type -A | 1.1 | 4.3-4.6 | Surcharge |
| WD4 | Band drains Type -A | 1.3 | 6.1 | Surcharge |
| WD5A | Band drains Type -B | 1.2 | 3.3 | Surcharge |
| WD5B | Band drains Type -B | 1.1 | 5.5 | Surcharge |
| VC1 | Circular drains | 1.2 | 3.2 | Surcharge+ vacuum |
| VC2 | Circular drains | 1.2 | 2.8 | Surcharge+ vacuum |

The inevitable variation in drain lengths was attributed to the non-uniform clay thickness. Wick drains (Band Drain Type-A and Band Drain Type-B) had dimensions of 100mm x 4mm, and the circular drains had an internal diameter of 34mm. The Authors have deliberately omitted the commercial brand names of all PVDs used. To monitor the ground behaviour, comprehensive instruments were installed e.g. settlement plates, vibrating wire piezometers, magnetic extensometers, and inclinometers. In the vacuum area, only circular drains were employed at a spacing of 1.2m in conjunction with a High Density Polyethylene (HDP) membrane, horizontal perforated pipes and the pumps that represent the vacuum system. The horizontally pipes offered the desired uniform distribution of suction beneath the membrane. The measured suction varied from 60 kPa to 75 kPa, and no air leaks were observed during vacuum application that ensured the intact seal provided by the membrane. A vacuum pressure of 70kPa was applied after 40 days.

## 3 INTERPRETATION OF FIELD RESULTS

The embankment performances including settlements and excess pore pressures together with the staged construction of the embankments are depicted in Fig. 2. It would be observed that the trends are very comparable where the settlement occured more quickly at the early stage of consolidation. The amount of final settlement depends on the clay thickness and embankment height. The highest settlement was measured in the WD4 area having the greatest clay thickness (19-26m), whereas the lowest settlement was in the WD5A area in which the clay layer was relatively thin (8-12m).

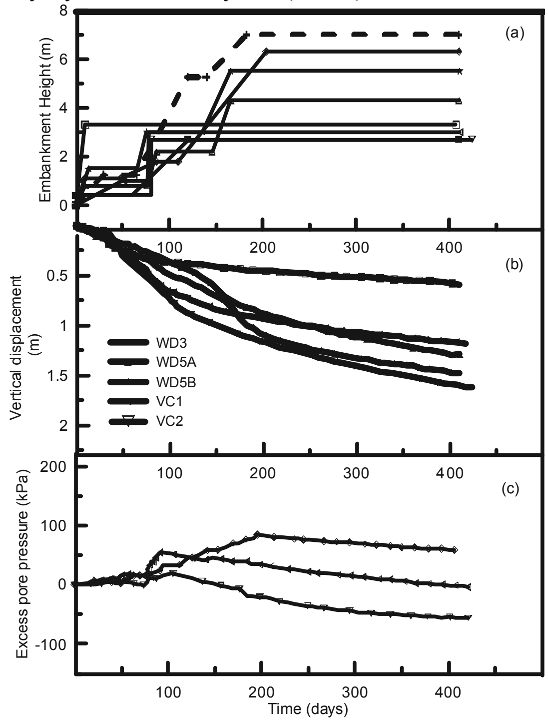


Figure 2. Embankment responses (a) staged construction, (b) settlements and (c) excess pore pressures

The measured lateral displacement normalized to total change in applied stress (vacuum plus surcharge load) for two inclinometer locations is shown in Fig. 3. For WD3 area, the total surcharge height was 90 kPa, whereas for VC1 area the reduced surcharge pressure of 40 kPa was complemented with a vacuum pressure of 65 kPa. The lateral displacements clearly lessen in the Holocene sand due to its greater stiffness. Fig. 3 indicates that the lateral movements are effectively controlled to minimise the disturbance in the adjacent Moreton Bay Marine Park, due to the isotropic consolidation by vacuum pressure.

## 4 SETTLEMENT AND EXCESS PORE PRESSURE PREDICTIONS

In order to analyse the radial consolidation caused by vertical drains, the unit cell theory has been employed to predict the settlement and excess pore pressure. A unit cell theory was introduced by Barron (1948) and Richart (1957) for surcharge preloading alone. Lekha et al. (1998) further extended the radial consolidation by including time-dependent surcharge loading. Indraratna et al. (2005) introduced the unit cell analysis for vacuum preloading under instantaneous loading while Geng et al. (2012) proposed analytical solutions under time-dependent surcharge preloading. During embankment construction, the surcharge fill is increased at a prescribed rate to reach the desired height. Therefore, the time-dependent loading due to the filling would be more realistic than an instantaneous loading, especially during the stages of embankment construction. In this section, the embankment load is assumed to be a ramp loading: i.e., the embankment load ($\sigma_l$) increases linearly with time up to a maximum value ($\sigma_1$) within time $t_0$ and is constant thereafter (Fig. 4a). The vacuum is applied at $t=t_{vac}$. Figure 4b shows the unit cell adopted for analytical solutions with boundary conditions (Fig. 4c).

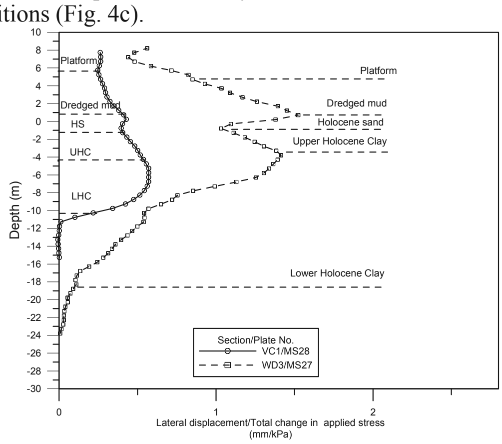


Figure 3. Comparison of lateral displacements at the embankment toe in vacuum and non-vacuum area after 400 days (Indraratna et al. 2011)

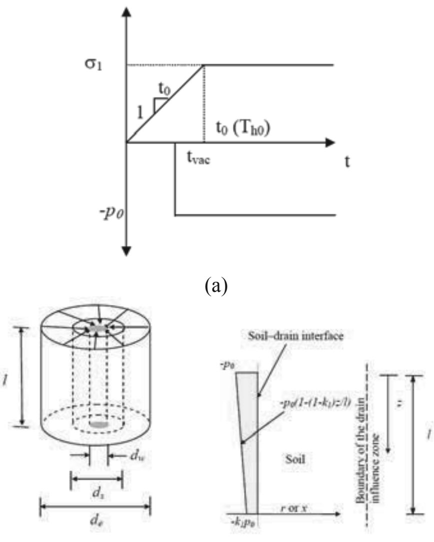


Figure 4. (a) time-dependent surcharge loading, (b) unit cell including smear zone, and (c) boundary conditions with vacuum distribution (after Indraratna et al. 2011)

The excess pore pressure due to radial consolidation considering smear effect under time-dependent surcharge can be expressed by (Indraratna et al. 2011):

$$\overline{u}_L = \frac{\mu d_e^2}{8c_h t_0}\left(1-\exp\left(\frac{-8c_h t}{\mu d_e^2}\right)\right)\sigma_1 \quad for \qquad 0 \le t \le t_0 \tag{1}$$

$$\overline{u}_L = \frac{\mu d_e^2}{8c_h t_0}\left(1-\exp\left(\frac{-8c_h t_0}{\mu d_e^2}\right)\exp\left(\frac{-8c_h(t-t_0)}{\mu d_e^2}\right)\right)\sigma_1 \quad for \quad t > t_0 \tag{2}$$

Recently, Indraratna et al. (2005) proposed that the excess pore pressure dissipation due to vacuum pressure alone could be determined from:

$$u_{vac} = 0, \qquad t < t_{vac} \tag{3}$$

$$u_{vac} = p_0 \exp\left(-\frac{-8c_h(t-t_{vac})}{\mu d_e^2}\right) - p_0\,, \qquad t \ge t_{vac} \tag{4}$$

$$\mu = \left[\ln\left(\frac{n}{s}\right) + \frac{k_h}{k_s}\ln(s) - \frac{3}{4} + \pi\frac{2k_h}{3q_w}l^2\right] \tag{5}$$

$$n = d_e / d_w \tag{6}$$

$$s = d_s / d_w \tag{7}$$

where, $d_e$ = the diameter of soil cylinder dewatered by a drain, $d_s$= the diameter of the smear zone, $d_w$ = the equivalent diameter of the drain, $k_s$= horizontal soil permeability in the smear zone and $q_w$ = drain discharge capacity.

The excess pore pressure at a given time *t* can calculated based on the Equations (2) to (7). For normally consolidated clay, the settlement ($\rho$) can now be determined by the following equation:

$$\rho = \frac{HC_c}{1+e_0}\log\left(\frac{\sigma'}{\sigma'_i}\right) \tag{8}$$

where, $\rho$ = settlement at a given time, $C_c$ = compression index, and $H$ = compressible soil thickness.

In order to calculate excess pore pressures and associated settlements, Equations (1)-(8) are employed using parameters in Table 2. For the completely remoulded dredged mud that was reclaimed from the seabed and the Upper Holocene Sand the ratio $k_h/k_s$ was assumed to be unity. For the upper and lower Holocene clay, the ratios of $k_h/k_s$ and $d_s/d_w$ were 2 and 3, respectively, in accordance with the laboratory obsevrvation decribed by Indraratna and Redana (1998).

The embankment load was applied according to a staged construction (unit weight of 20 kN/m$^3$). Settlement and associated excess pore pressure predictions were calculated at the embankment centreline using Eqs. 1-8. It is noted that, at the beginning of each subsequent stage, the initial in-situ effective stress was calculated based on the final degree of consolidation of the previous stage. In vacuum areas, a suction pressure of 65 kPa was employed.

Figures 5 and 6 present the predicted settlement and associated excess pore pressure with the measured data in Areas WD1 and VC1, where the total applied load (vacuum and surcharge =120-130kPa) and clay thickness (20-23m) are comparable. Overall, the comparisons between prediction and field observation show that the settlement and associated pore water pressure can be predicted very well. In vacuum areas, the degree of consolidation was more than 90% after 13 months, whereas that in the non-vacuum area was less than 85%. This confirms that, at a given time, the vacuum combined preloading would speed up consolidation compared to a surcharge preloading alone. This is because in non-vacuum areas, a staged embankment construction had to be adopted to avoid any undrained failure in the remoulded dredged layer.

Table 2. Soil properties for each layer

| **Soil layer** | **Soil type** | **$C_c/(1+e_0)$** | **$c_h$ (m$^2$/yr)** | **$k_h/k_s$** | **$s=d_s/d_w$** |
|---|---|---|---|---|---|
| 1 | Dredged Mud | 0.235 | 1 | 1 | 1 |
| 2 | Upper Holocene Sand | 0.01 | 5 | 1 | 1 |
| 3 | Upper Holocene Clay | 0.18 | 2 | 2 | 3 |
| 4 | Lower Holocene Clay | 0.2 | 1.9 | 2 | 3 |

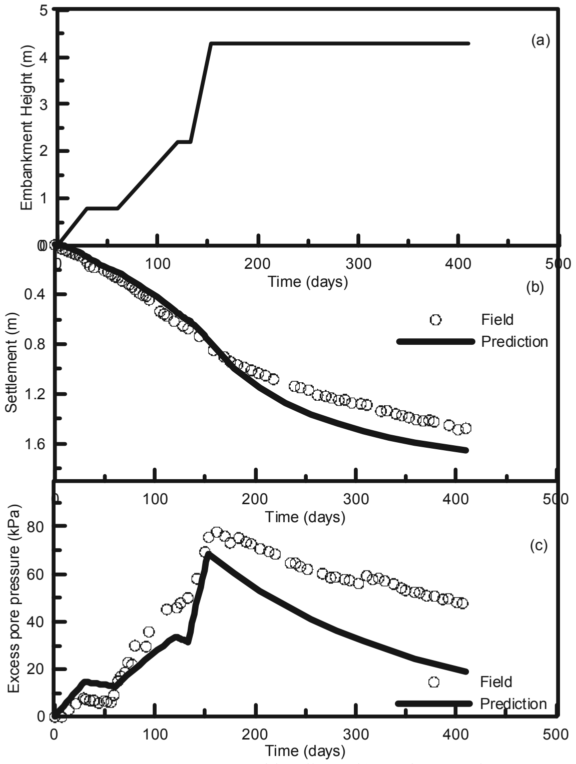


Figure 5. WD1 area: (a) stages of loading, (b) surface settlements at the embankment centreline and (c) excess pore pressures at 9.2m deep

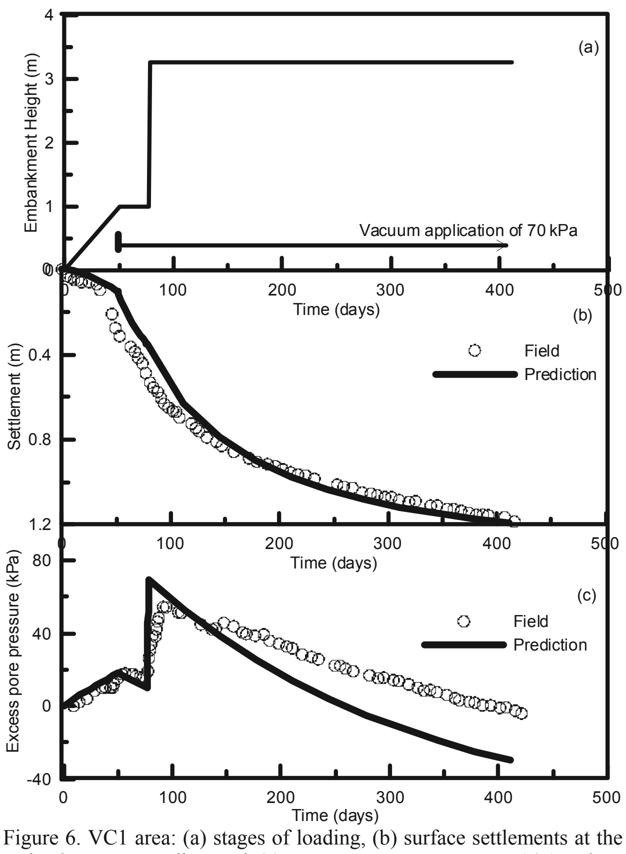


Figure 6. VC1 area: (a) stages of loading, (b) surface settlements at the embankment centreline and (c) excess pore pressures at 14.1m deep (Indraratna et al. 2011)

## 5 CONCLUSIONS

A system of vertical drains with vacuum preloading is an effective method for speeding up soil consolidation. The performance of 2 treatment schemes at the Port of Brisbane was analysed and discussed. The dredged materials from the seabed were placed in the reclaimed area. A total of 8 areas were selected to examine the performance of vacuum consolidation, and the vertical drain spacing varied from 1-1.3m for 3 different drain types. The vacuum application induces an inward lateral movement, whereas the conventional surcharge fill creates outward movement. When the vacuum pressure combined with surcharge fill is employed, the overall lateral movement is decreased due to the isotropic consolidation induced by vacuum pressure. From a stability point of view, vacuum pressure reduces the ratio of lateral displacement to surcharge fill height at any given time.

The unit cell theory considering time-dependent surcharge load and vacuum application was employed to predict the settlement and associated excess pore pressure, which provided a good agreement with the field measurements. After 1 year, the degree of consolidation in the vacuum areas was much higher than the non-vacuum areas for the same total stress.

## 6 ACKNOWLEDGEMENTS

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