

## Consolidation of estuarine marine clays for coastal reclamation using vacuum and surcharge loading

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**ABSTRACT:** Soft clays in coastal areas have low shear strength and high compressibility. Consequently, certain construction activities for infrastructure developments in these deposits often pose geotechnical problems due to large time dependent settlements and lateral movements. Ground improvement techniques are adopted in such terrains to reduce the water content of soft clays by preloading with surcharge fill over vertical drains. Depending on the magnitude of the surcharge load used substantial immediate settlement with lateral movements can take place during preloading, leading to undrained stability problems in various parts of the clay foundation. Therefore, the use of vacuum assisted preloading has now become a popular method in ground improvement works where substantial loads need to be carried out to meet a desired rate of settlement and mitigate undrained failure by controlling lateral displacements. To assist the vacuum propagation to significant depths, vertical drains are used in tandem. At the Port of Brisbane, Australia, vacuum assisted surcharge preloading and conventional surcharge preloading schemes were adopted to reduce the consolidation time and long term settlement in soft Holocene clays in 2009. It is shown that a combined vacuum surcharge loading system with a standard surcharge fill highlights the obvious benefits of vacuum consolidation in reducing long term settlement and enhanced stability.

## INTRODUCTION

The Port of Brisbane is recognized as Australia's third largest container port located between the mouth of the Brisbane River and Fisherman Islands (Indraratna et al. 2011). With rapid demand growth in trading activities, a new outer area (235ha) adjacent to the current port facilities is being reclaimed to provide the additional berths suitable for cargos and containers. In this area, soil profile comprises a highly compressible dredged mud and clay layer over 20m in thickness with an undrained shear strength of less than 15 kPa near the surface. The shear strength of the dredged mud for reclamation has much lower shear strength depending on the time of placement and the duration the capping material (surcharge) placement. Without any appropriate ground improvement scheme (Indraratna et al. 2001), it is expected that the consolidation period will be more than 50 years with vertical deformations of 2.5-4.0m under the actual service loadings (60 kPa). Therefore, vacuum consolidation with prefabricated vertical drains (PVDs) was recommended to accelerate the consolidation process and to limit horizontal deformation for the site located immediately adjacent to the Moreton Bay Marine Park.

Chu et al. (2000), Indraratna and Chu (2000) and Chai et al. (2005) also showed that using a system vacuum preloading combined with PVDs, suction pressure can be transmitted to a significant depth in the soft subsoil. Also, prolonged consolidation time due to staged

embankment construction can be significantly reduced (Indraratna et al. 2005). The surcharge fill height may be lowered by several meters, if a vacuum pressure of at least 70% the atmospheric pressure is maintained (Rujikiatkamjorn et al. 2008). In addition, the embankment construction rate can be increased with the reduction in the number of construction stages. Once the soil shear strength increases due to consolidation, the post-construction settlement can be significantly less, thereby reducing risk of long term differential settlement (Shang et al. 1998; Yan and Chu 2003). The ground improvement provided by PVDs combined with vacuum pressure may be an economically attractive alternative in deep soft clay sites. Olson (1977), Olson et al. (1974) and Geng et al. (2012) introduced a solution for a single ramped load, for both vertical and radial drainage. To date, there is no comprehensively reported case history in which both the conventional surcharge preloading and vacuum technique are applied in the same area. In this paper, the performance comparison between the vacuum and non-vacuum methods has been made on the basis of measured vertical deformations, excess pore pressures and horizontal displacements. The effects of improvement techniques on the long term settlement and excess pore pressure are also elucidated.

## VACUUM PRELOADING SYSTEMS

Currently, there are two main types of vacuum preloading systems adopted in the field (Geng et al. 2011):

**A. Membrane system:** After PVDs are installed and the sand blanket is placed with horizontal perforated pipes, the membrane is laid on the top and its borders are flooded under a bentonite slurry channel (Fig. 1a). The vacuum pumps are then connected to the discharge system. A major advantage here is that the vacuum can propagate within the sand platform, along the soil surface and down the PVDs. An obvious disadvantage is that the efficiency relies mainly on the ability of the airtight system to prevent any air leaks over a significant period of time.

**B. Membraneless system:** When an area has to be subdivided and progressed individually, the vacuum preloading can only be conducted one section after another and therefore the membrane system may not be a reasonable solution. In order to avoid this problem, the vacuum pipes are joined directly to each individual PVD using a tubing system (Fig. 1b). In contrast to the membrane system where any air leak can affect the entire system, each drain acts independently. However, the requirement of significant tubing for hundreds of drains can affect the installation time and cost.

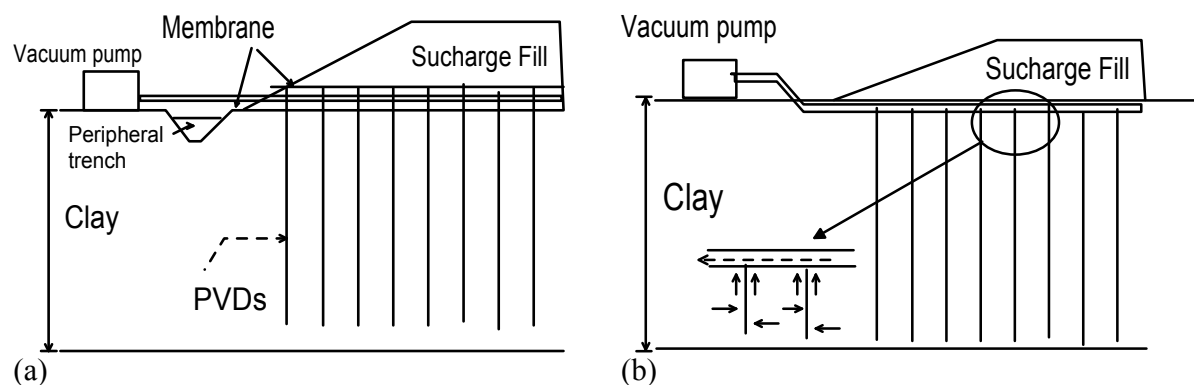


Figure 1. Types of vacuum preloading systems (a) Membrane system and (b) Membraneless system

## GENERAL DESCRIPTION OF EMBANKMENT CHARACTERISTICS AND SITE CONDITIONS

In 2003, the Port of Brisbane Corporation started to recover a sub-tidal land area of 235ha at Fisherman Islands near the mouth of the Brisbane River (Fig. 2). The aim is to provide additional berths and associated infrastructure to accommodate the future demand of the Port. To compare the performance of the vacuum system with the non-vacuum system (PVD and surcharge load), there were 3 contractors selected to carry out this trial. Each contractor was allocated a trial area of about 3000m<sup>2</sup>. The aim was to compare performance based on their design and construction work.

**Contractor A:** Involved in 8 trial zones in Area S3a, designated as WD1, WD2, WD3, WD4, WD5a, WD5b, VC 1 and VC 2. Areas WD1 to WD5a and WD5b had surcharge only, while VC1 and VC2 had surcharge and vacuum consolidation with membrane system.

**Contractor B:** The trial area T11 consisted of seven zones, of which 5 had surcharge and different drain types. Two sub-areas had surcharge in conjunction with the membraneless system.

**Contractor C:** This site T11 was subdivided into trial Areas 4, 5 and 6. Areas 4 and 5 had a surcharge period of a year, whereas Area 6 had a surcharge period of 0.5 years. Vertical drains with 1.4m spacing were adopted in Areas 4 and 5 while Area 6 used vertical drains with a spacing of 1m.

The upper Holocene sand underneath the dredged mud was about few meters thick, and overlaid the Holocene clay layer having a thickness from 5m to 24m. The highly soft and compressible Holocene clay layer had relatively low shear strength (Ameratunga et al. 2010). The Holocene layer overlies a Pleistocene deposit comprising of highly over-consolidated clay. Site investigations e.g. cone penetration/piezcone tests, dissipation tests, boreholes, field vane shear tests and oedometer tests were carried out to quantify the consolidation and stability design parameters. The soil parameter variations are shown in Fig. 3. Groundwater level was at +3.5m RL. The water contents of the soil layers were at or beyond their liquid limits. The field vane tests indicate that the undrained shear strength of the dredged mud and the Holocene clays varied from 5 to 60 kPa. The compression index ( $C_c$ ) varied from 0.1-1.0. The coefficient of consolidation in vertical direction ( $c_v$ ) was about the same as that in horizontal direction ( $c_h$ ) for the remoulded dredged mud layer, while the ratio  $c_v/c_h$  was about 2 for the Holocene clay layer. This is based on laboratory testing on samples obtained in vertical and horizontal directions to the vertical drains. The coefficient of consolidation of remoulded samples was very similar to  $c_v$  of the undisturbed sample obtained in Holocene layer.



Figure 2. Map of the proposed extension area at the Port of Brisbane (adopted from Indraratna et al. 2011)

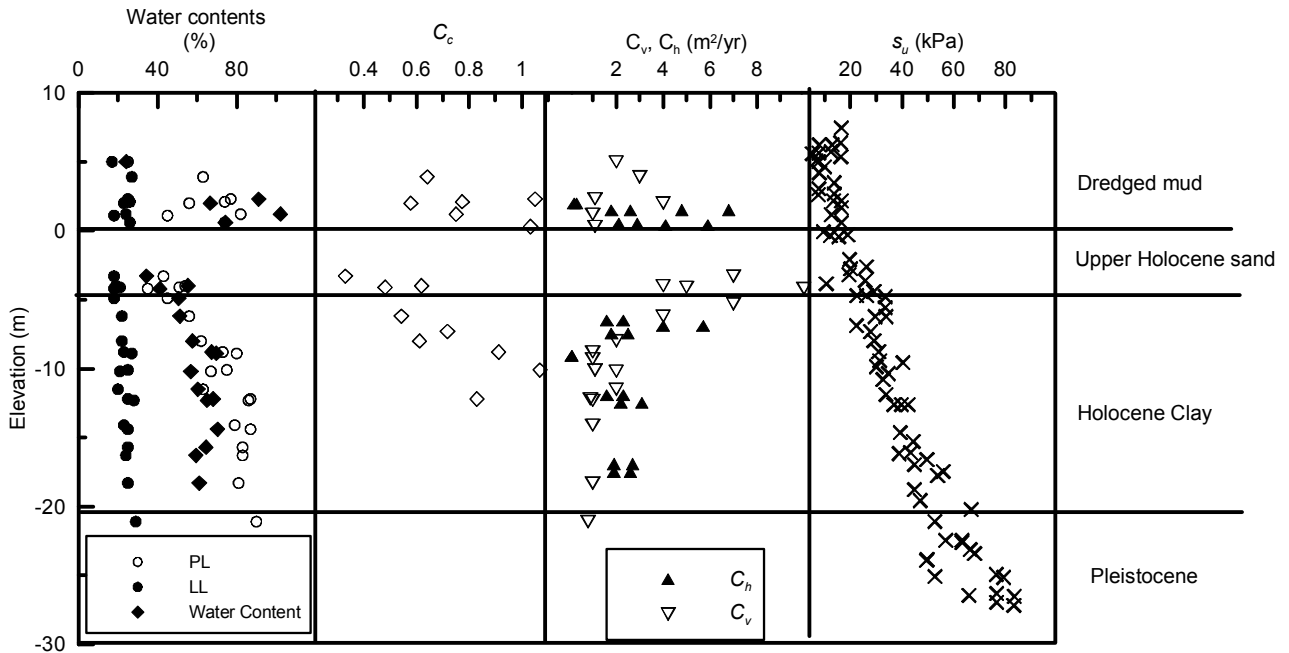


Figure 3. Soil properties and profile at S3A, Port of Brisbane (Indraratna et al. 2011)

As the Holocene clay layer is rather thick (15m or more), two preloading approaches were used to reduce the long term settlement including conventional surcharge preloading system and the vacuum consolidation system both applied in conjunction with PVDs. Rigorous design specifications were considered for the design and construction of fill embankments and vacuum application over the soft Holocene deposits: (a) Service load of 15-25 kPa, (b) maximum residual settlement of not more than 250 mm over 20 years after the application of service load.

## ASSESSMENT OF RELATIVE EFFECTIVENESS OF THE TRIAL SCHEMES

### Degree of Consolidation (DOC) with Time

The numerically determined DOC using measured settlements via Asaoka's method with time plots via spreadsheet software are shown in Fig. 4 for an array of locations, and they all show a comparable behaviour, irrespective of the treatment technique (S3A and T11) and the type of applied loading (i.e. vacuum vs. surcharge). A relatively high DOC has been achieved after 12 months, and all plots provide  $DOC > 80\%$ . In order to separate the 'clustering' especially after one year, the DOC is normalized by the dimensionless factor,  $\beta$  (Indraratna et al. 2012).

The  $\beta$  factor is independent of the soil properties and is designed to capture the drain and site loading conditions, and comprises the favorable effects of: (i) the drain length ( $l_d$ ), (ii) the drain spacing ( $s_d$ ) and its pattern ( $\alpha = 1.05$  for triangular and 1.13 for square spacing), and (iii) the surcharge load height ( $H$ ) to consolidate the given clay thickness ( $h_c$ ), represented by the ratio ( $H/h_c$ ).

In this respect,  $\beta$  can be defined as:

$$\beta = (l_d / \alpha s_d) \times (H / h_c) \quad (1)$$

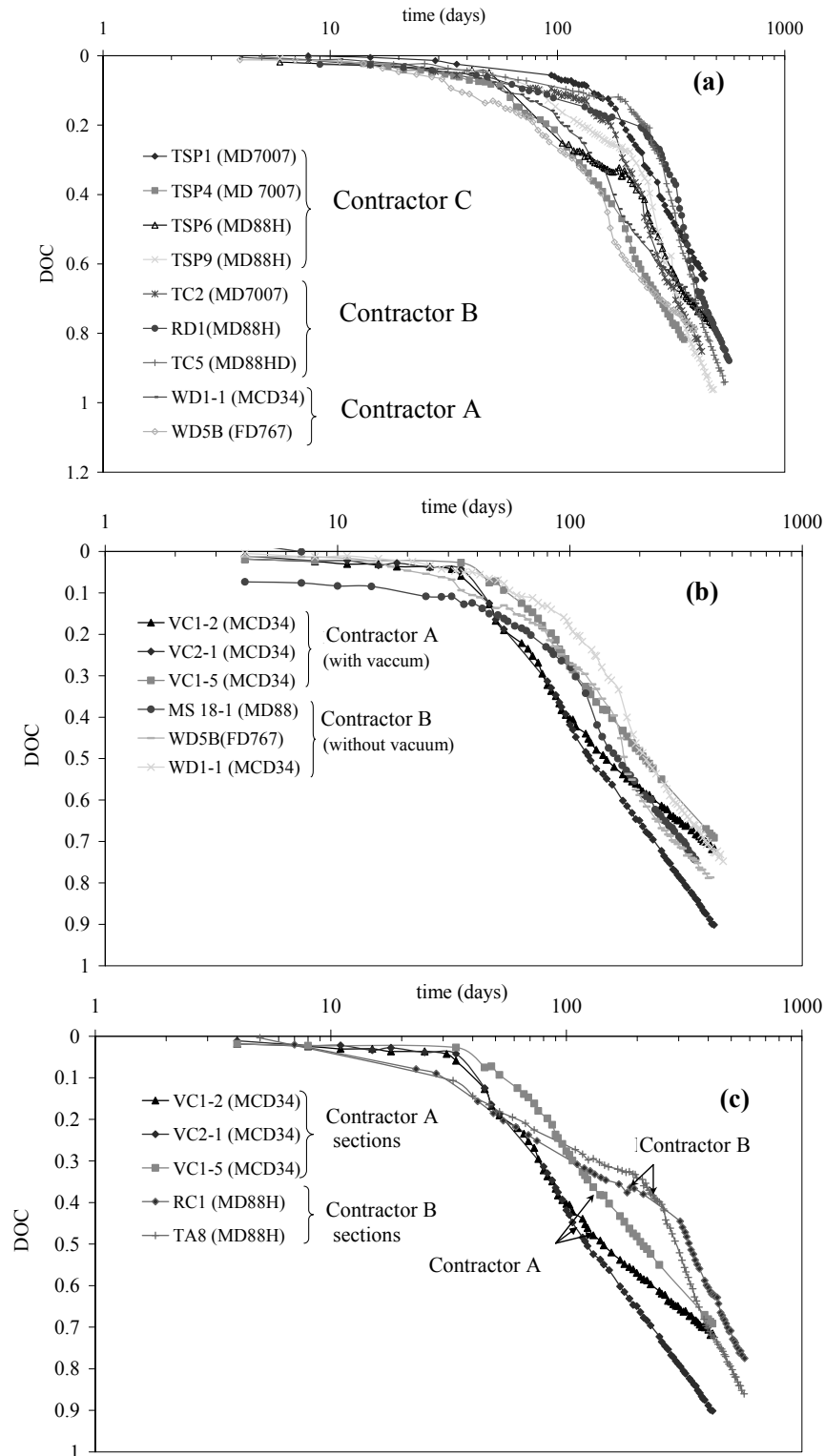


Figure 4. Analytically computed DOC with time for (a) non-vacuum in S3A and T11, (b) treatment in S3A only and (c) vacuum areas in S3A and T11

Based on the magnitude of  $\beta$  determined at each settlement plate location for S3A and T11, the drain and site conditions at the 3 trial areas can be differentiated as:

(i) Low  $\beta$  impact: 2-6 (for S3A area under Contractor A),

- (ii) Moderate  $\beta$  impact: 8-12 (for T11 area under Contractor B), and
- (iii) High  $\beta$  impact: 12 -18 (for T11 area under Contractor C).

Although the value of  $\beta$  has no specific relationship to the converging target of DOC intended to be attained at the date of fill removal by all contractors, it can act as a 'filter' in distinguishing the relative performance in S3A and T11, by dividing the DOC by  $\beta$ . Figure 5 shows the variation of DOC divided by  $\beta$  plotted against time. This results in a separation between vacuum and non-vacuum areas, and also separates the vacuum consolidation effects of Contractors A and B. When considering all 3 sets of plots (Figs. 4a-c), the relative consolidation performance seems more superior in the case of Contractor A treatment areas when using vacuum consolidation, in comparison with all other locations in S3A and T11.

### Excess Pore Water Pressure Dissipation

Figure 6 shows the reduction in measured pore water pressure with time, and it is shown that VC2 in S3A shows the largest reduction closely followed by Section IV in T11 (Contractor C). However, due to the varying fill heights and clay thickness in S3A and T11 paddocks these plots cannot be directly compared and most of them are clustered together during the first 3 months showing little differences. Figure 7a indicates the rate of change of excess pore water pressure for the same locations, and it is observed that VC2, VC1 and WD1 indicate the highest rate of change of excess pore pressure at the start, with VC1 maintaining a steady state over a long period of time. The membraneless systems by Contractor B do not seem to indicate a high rate of excess pore pressure dissipation in comparison with VC1 and VC2 areas. When these plots are normalized by  $\beta$  (Figure 7b), it is shown that VC1 and VC2 provide greater benefit in view of excess pore pressure dissipation, compared to all other areas. While the fill height is reduced in VC areas of S3A thereby involving less mucking operations, the applied suction (-70 kPa) more than compensates for accelerated excess pore pressure dissipation rates, confirming the effective performance of membrane-type vacuum consolidation technique.

### Long Term Settlements

All contractors have proposed measures that are anticipated to control the long term settlements within 25 years, either to be less than 150mm or 250mm depending on the clay thickness and anticipated service loads in the respective areas. In Figure 8, the values of long term settlements for both S3A and T11 areas are calculated based on methods provided by Terzaghi et al. (1996); and then plotted with the  $\beta$ -factor; the observations suggest that the critical long term settlement occurs in the range  $4 < \beta < 16$ . In this critical zone, that includes locations from all 3 contractors from both S3A and T11 paddocks, the long term settlements are close to the permissible limits. At low values of  $\beta < 4$ , the residual settlements are much smaller mainly because of vacuum consolidation. In relation to the clay thickness, at very high values of  $\beta > 16$  (T11), the long term settlements tend to decrease, mainly because of the high fill surcharge levels (i.e. relatively high  $H/h_c$  ratio).

Figure 9 provides approximately linear relationships between the long term settlement and clay thickness for a range of OCR from 1.1 to 1.4 for  $\text{DOC} > 80\%$ . As expected, it is observed that when the OCR increases the residual settlement (RS) decreases substantially. In general, as the total Holocene clay thickness increases, the RS also increases, and the corresponding regression lines and best-fit equations are also provided on Figure 9. In particular, the vacuum consolidation locations of S3A (VC1-2, VC2-2 and VC2-3) show considerably reduced long term settlements at OCR approaching 1.4, well below the permissible limit. At an OCR of approximately 1.3, the long term settlements associated with membraneless consolidation (TA8,) and VC1-5 (S3A) are also small. Based on Figure 9, a lower bound and upper bound for long term settlement in terms of clay thickness ( $h_c$ ) can be obtained as follows for the entire range of over-consolidation upon fill removal:

Lower Bound: Long term settlement =  $3.8 h_c - 27$  (vacuum consolidation in S3A at OCR = 1.4)

Upper Bound: Long term settlement =  $14.3 h_c + 34$  (surcharge only sites at OCR = 1.1)

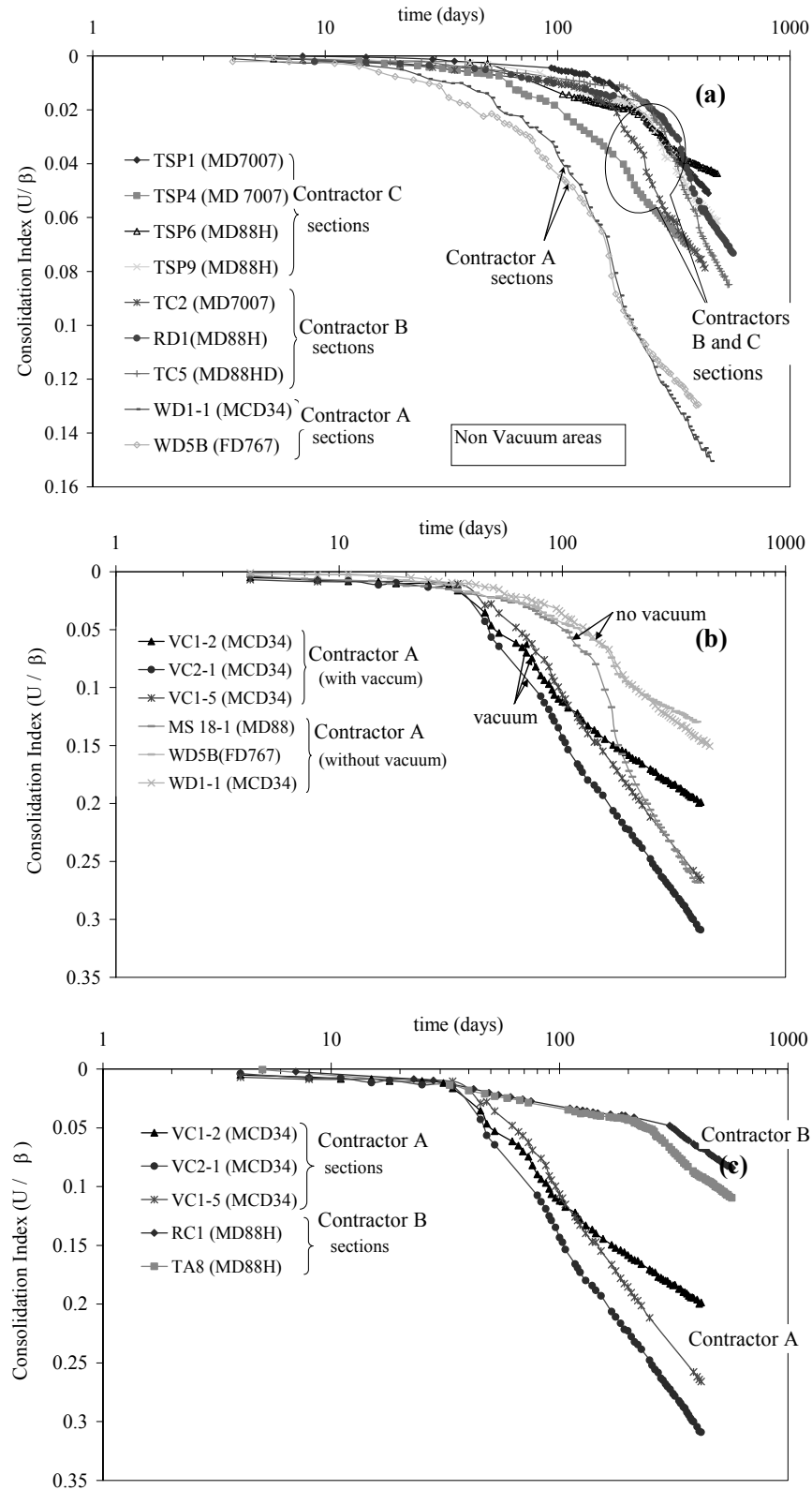


Figure 5. Computed DOC/β with time for (a) non-vacuum in S3A and T11, (b) treatment in S3A only and (c) vacuum areas in S3A and T11

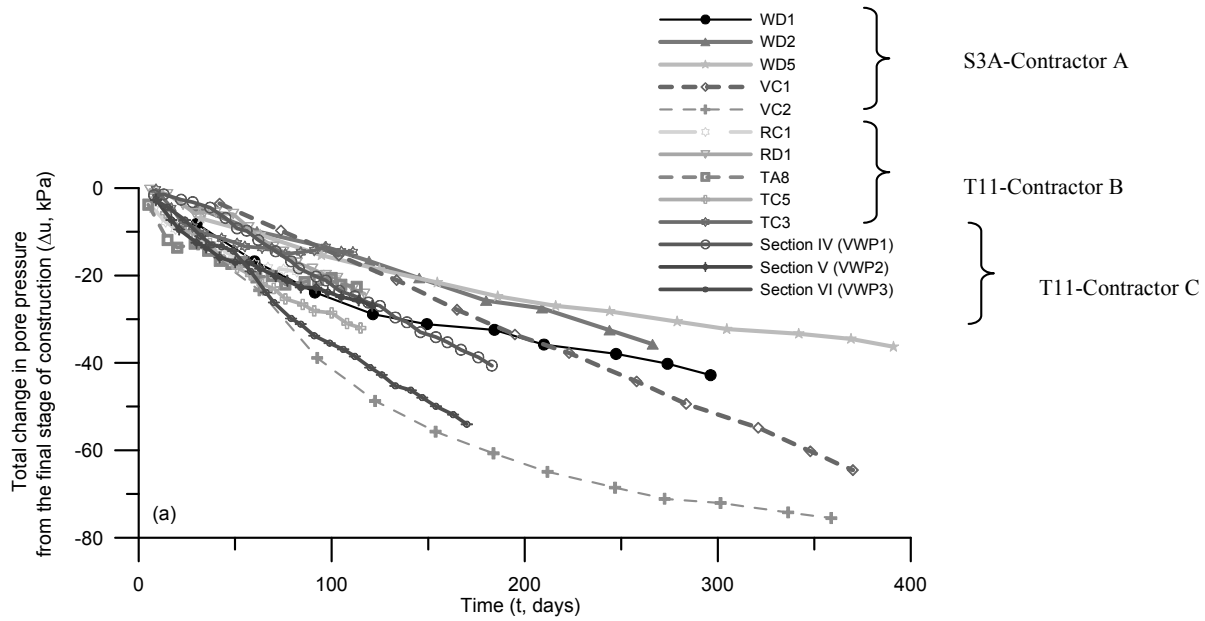


Figure 6. Reduction in Excess Pore Water Pressure with Time in S3A and T11 areas

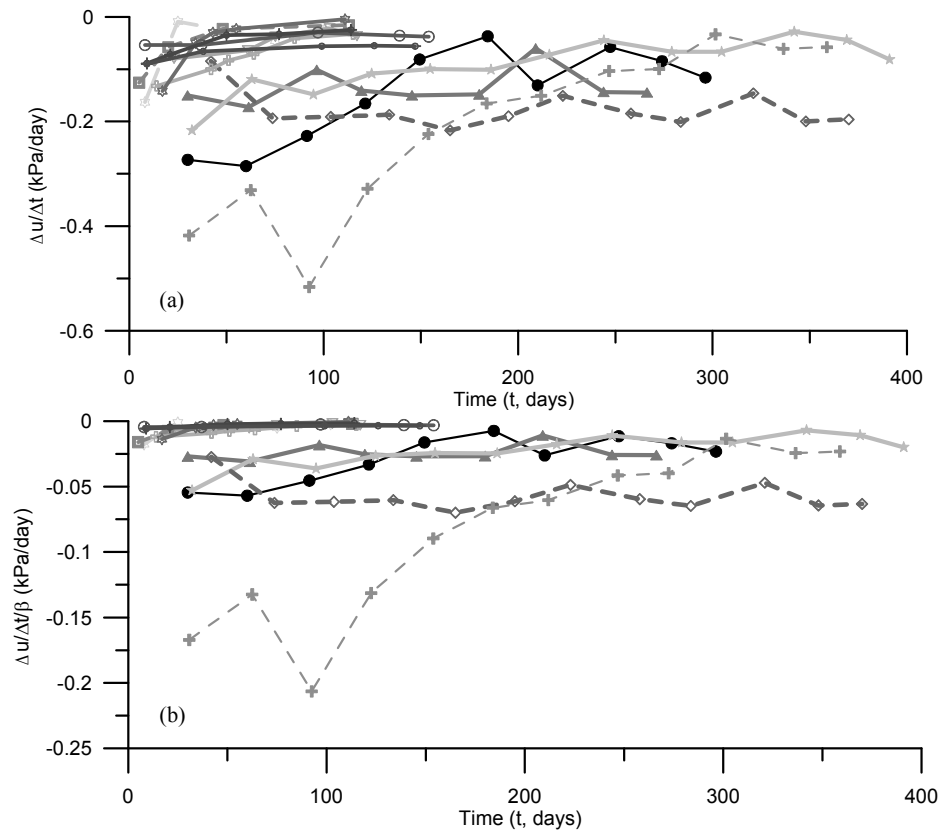


Figure 7. Comparison of excess pore pressure dissipation between S3A and T11 (a) Rate of dissipation of Excess pore pressure, (b) Excess pore pressure dissipation rate normalised by  $\beta$



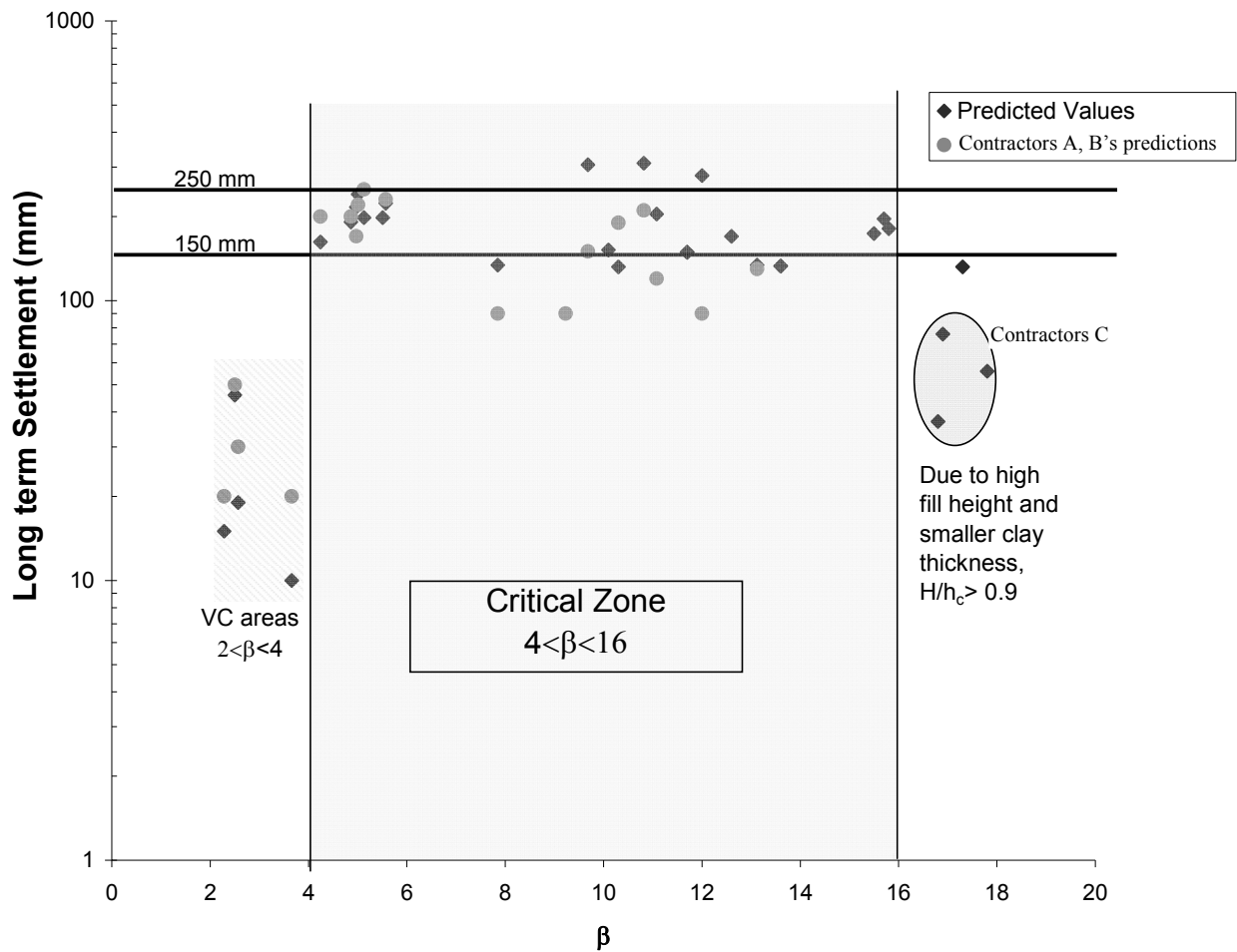
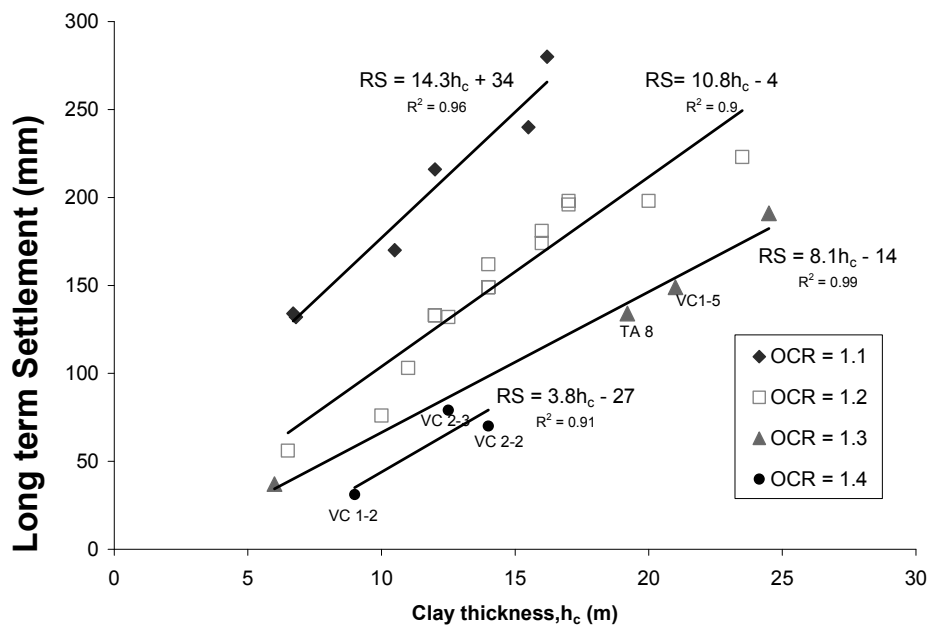
Figure 8. Critical  $\beta$  values for permissible Residual Settlement in S3A and T11

Figure 9. Effect of OCR and Clay Thickness on Residual Settlement

## Controlling the Lateral Displacements

It is well-known that the vertical drains provide the advantage of reducing the lateral yield in soil and that the application of vacuum pressure further curtails the lateral movement, and in some cases may even make the lateral movements go inwards rather than outwards from the centerline of the embankment (Indraratna et al. 2005). The use of vacuum pressure to control of lateral displacements is very important in sensitive areas such as in the vicinity of marine parks. At this site, only very limited field data has been available from a few inclinometers. Nevertheless, in order to compare the lateral movements of selected vacuum and non-vacuum areas that have very different soil profile and surcharge load conditions, the lateral displacement can be divided by the applied effective stress at the same depth.

The normalized lateral displacement profiles with depth for the limited data sections are shown in Figure 10. These plots clearly indicate that while vacuum consolidation is definitely beneficial for controlling the lateral movement, the membrane system with 70 kPa suction further demonstrates the most significant reduction in the normalized lateral displacement (i.e. compare VC1-MS28 with WD3-MS27). In the Membraneless vacuum system with 50 kPa suction, while a reduction in the lateral movement is definitely achieved (i.e. compare MS24 with MS34), the amount of this reduction is not as significant as that of Membrane system. The shape of the lateral displacement curves suggest that in all vacuum areas the suction head propagates significantly with depth such that both the LHC and UHC layers are favorably influenced.

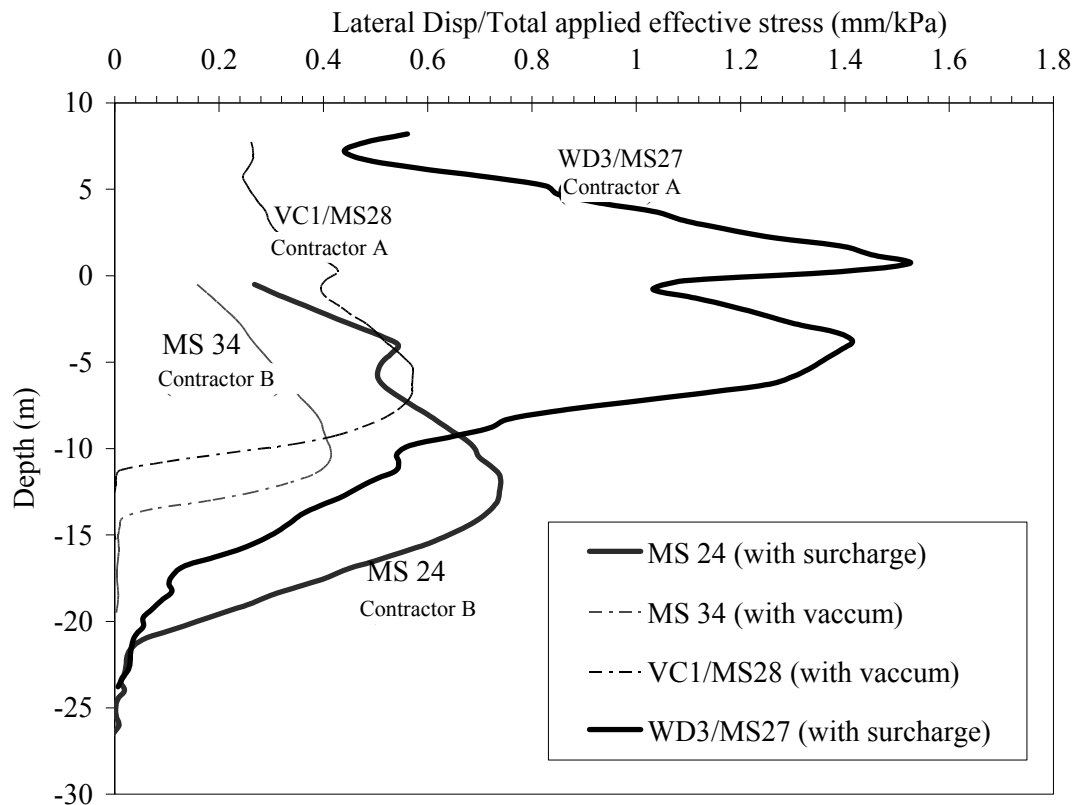


Figure 10. Role of Vacuum Consolidation on Lateral Displacement

## CONCLUSIONS

The performance of soil consolidation at the Port of Brisbane was analyzed and discussed. The technical contents reported in this study are not intended to compare the capabilities of any contractors, but solely focused on the relative efficiency of different methods applied at the Port

of Brisbane reclamation sites. The land was reclaimed using mud dredged from the seabed of shipping channels and berths. A total of 3 trial areas were selected to investigate the behavior of surcharge and vacuum consolidation. In general, a system of vertical drains with vacuum preloading is an effective method for accelerating soil consolidation, however, purely on the basis of Degree of Consolidation (DOC), it was not possible to compare the benefits of relative treatments applied in the trial areas. This is because, in all cases, albeit different time scales, the desired or target DOC could be attained irrespective of the type of drains and their installation pattern, nature of surcharge loading (with or without vacuum) and clay thickness. In order to distinguish the differences between the trial locations, a drain and site representation factor totally independent of soil consolidation properties was defined as the  $\beta$ -factor, designed to capture the drain and site loading conditions. It comprises the effects of: (i) drain length ( $l_d$ ), (ii) drain spacing ( $s_d$ ) and its pattern ( $\alpha = 1.05$  for triangular and 1.13 for square spacing), and (iii) the surcharge load height ( $H$ ) in relation to a given clay thickness ( $h_c$ ).

Normalizing the DOC, settlement and lateral displacement/settlement ratio by proposed  $\beta$ -factor, provides a performance indicator that represents the returns per unit value of  $\beta$ . In such a comparison, the vacuum consolidation applied in S3A seems to be the most beneficial. The membraneless vacuum system application is also effective in terms of controlling lateral displacements, however, the field inclinometer data is very limited to formulate overall conclusions. Control of lateral displacement effectively in sensitive areas such as marine parks would benefit immensely by the application of vacuum pressure and thereby decreasing the required fill heights on the surface.

While a distinct relationship between the DOC and long term settlement is difficult to determine for the given conditions, there is no doubt that the long term settlement decreases almost linearly with the increase in the over-consolidation ratio, and also the long term settlement tends to become closer to the prescribed 150mm limit for the critical range  $4 < \beta < 16$ . The minimum long term settlement is attained in the vacuum consolidation sites in S3A when the OCR exceeds 1.3. The long term settlement tends to become critical when the OCR is close to or less than 1.1, and this situation mainly occurs for surcharge only sites with large clay thickness, where the treatment is not as effective as when vacuum pressure is applied. It verifies that a large surcharge fill height becomes necessary in the absence of vacuum pressure in order to keep the long term settlement less than the prescribed limit, and the need to remove a large amount of fill in order to achieve a significant OCR can be a cumbersome process in the field. Higher the service load, the greater will be the advantage of vacuum application as a means of reducing the need for excessive fill heights as well as lateral displacement control. In view of stringent residual settlement and lateral displacement control plan, the application of sufficiently high vacuum pressure in tandem with some surcharge fill to achieve a relatively high DOC (i.e.  $> 85\%$ ) and subsequent unloading for attaining an  $OCR > 1.3$  would be the optimum choice for the site characteristics and loading conditions encountered here.

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