A successful trial of vacuum consolidation at the Port of Brisbane

Daniel Berthier¹, Peter Boyle², J Ameratunga³, Cynthia De Bok³ and Philippe Vincent¹
¹Austress-Menard, Macquarie Park, NSW, Australia
²Port of Brisbane Corporation, Fisherman Islands, QLD, Australia
³Coffey Geotechnics Pty Ltd, Newstead, QLD, Australia

Abstract

As part of the plan to increase the capacity of the Port of Brisbane, a 235 ha land reclamation is in progress, using dredged materials from the Brisbane River and Moreton Bay shipping channels. Austress-Menard was selected by Port of Brisbane Corporation to conduct a deep soft ground consolidation trial using the vacuum method along the site boundary where any instability will significantly impact the adjacent Marine Park.

Ground conditions were challenging, with dredged mud reclamation up to 7m thick overlying paleochannels of soft clay up to 25m in thickness. A unique feature in the vacuum system adopted was the 15m deep soil-bentonite cut-off wall, which was required to isolate the vacuum area because of the deep permeable layers in the subsurface profile. An extensive instrumentation program was installed and monitored by Coffey Geotechnics. Results were back-analysed by Austress-Menard, to confirm the conformance of the actual consolidation process against the predictions of the design. The performance of the trial was independently assessed by a panel of external reviewers.

The vacuum trial with a deep cut-off wall, a first in Australia, has been successful. Depressurisation under the vacuum membrane was constantly maintained, in the range of -0.80 bars. The enhanced stability against slip failure along the environmentally sensitive Moreton Bay Marine Park, the saving of 4m of fill surcharge and the overall time saving on the consolidation process, were the designed objectives being achieved.

1. Introduction

The Port of Brisbane is located at the mouth of the Brisbane River in South-East Queensland, Australia. In recent years, the modern purpose built Fisherman Island’s Port, has seen rapid development due to increased trade growth. The expansion and development of future Port land is critical to ensure that the Port’s facilities can expand at a rate to meet this growth.

Reclamation is in progress, over the 235 hectares of sub-tidal lands contained within the perimeter Seawall, built in 2005 for the Future Port Expansion (FPE). In late 2005, the Port of Brisbane Corporation (PBC) engaged Coffey Geotechnics (Coffey) as its geotechnical advisor for development of the FPE reclamation areas.

The subsurface conditions in the recent reclamation and FPE areas are significantly different from the previously developed areas at Fisherman Islands. The in-situ compressible clay is much deeper, up to 30m thickness. The reclamation is carried out using channel maintenance and berth dredging materials resulting in 7~9m metres of mud being deposited on the original seabed and being capped off with sand.

Generally, consolidation timings for these undeveloped areas were predicted to be well in excess of 50 years if surcharging was the only treatment employed, as has been past practice at the Port. Settlements in the range of 2m to 3m were also forecasted.

Given the pressures of creating additional usable Port land in time frames approximately half of those achieved in the past, it was decided that new techniques to speed up the consolidation process needed to be employed to meet the land development timings.

To identify suitable ground improvement techniques to suit local conditions, PBC in 2006 selected Austress-Menard (Menard) to conduct a design and construct trial using vacuum consolidation on a 15,000m² area along the site boundary of the existing reclamation area where any instability will significantly impact the adjacent Moreton Bay Marine Park and purpose built Migratory Wader Bird Roost (Boyle et al 2007).
2. Geotechnical Conditions

Using the information from borehole drilling and laboratory testing, the main geological formations across the project site can be summarised as Holocene deposits overlying Pleistocene deposits which in turn overlie the Petrie Formation consisting of basalt bedrock.

The Pleistocene is an older alluvial deposit and comprises mainly over consolidated, very stiff to hard clays and medium dense to dense sands of low compressibility.

The Holocene alluvial deposit consists of two sub-layers, with the upper layer comprising mainly sand with inter-layered soft clays and silts and therefore highly permeable. The lower layer, comprising very soft to firm clay, is generally normally consolidated and therefore highly compressible. The thickness of the Holocene deposits varies significantly over short distances due to the existence of several paleo-channels which underlie the Port of Brisbane reclamation area.

Recent fill found above the natural soils, comprise dredged materials which has been capped by white sand, the latter traditionally 2m in thickness. The dredged materials are highly compressible and weak in strength. During placement of the sand capping in March 2006, the dredged mud in the paddocks displaced significantly (mud waving), giving rise to a variable distribution of the mud and sand cap across the site.

Table 1 presents the geological profile, including the recent fill, in a summarised form.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>Thickness Range (m) across the Trial Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent – Sand capping</td>
<td>White sand, generally uniform with an average size of about 300 µm</td>
<td>0.9m–5.0m</td>
</tr>
<tr>
<td>Recent – Dredged materials</td>
<td>Dredged mud, marine and dune sands with layers of silt and clay.</td>
<td>2.5m–7.6m</td>
</tr>
<tr>
<td>Holocene</td>
<td>Normally consolidated marine clay, silt and sand.</td>
<td>8.8m–24.4m</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Generally over-consolidated clay, sand and gravel.</td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>Weathered basalt bedrock of the Petrie Formation</td>
<td></td>
</tr>
</tbody>
</table>

In addition to the geotechnical information available from previous testing in the wider area of the reclamation, Coffey carried out site specific investigations required to provide assistance to Menard’s design.
3. Vacuum consolidation method
The Menard Vacuum Consolidation method is designed for preloading/surcharging and consolidating very soft and soft saturated soils of low permeability. The method consists of installing vertical and horizontal vacuum transmission pipes under an airtight membrane and sucking the air below the membrane thus imposing a partial atmospheric pressure on the soil. This loading process creates an accelerated isotropic consolidation in the soil mass. The vacuum method can be combined with a conventional surcharge placed on top of the membrane, in order to achieve the required degree of consolidation under a given design load and within the allowed time frame.

The main advantages of the vacuum method are as follows: the risks of slip failure at boundaries under the vacuum load are nil and drastically reduced if an additional surcharge is placed; saving in preloading surcharge, the vacuum being equivalent to ~ 4m of fill; significant overall time saving over other consolidation methods.

![Figure 2: Principle of Menard Vacuum Method](image)

4. Trial Design and Construction

4.1 Design Criteria
The initial design criteria, specified a residual settlement of less than 250mm, over a period of 20 years, and under a design service load of 15 KPa applied at a final surface level.

The sand capping forming the working platform, was at approximate level, PD +8.5m (PD=0m Lowest Astronomical Tide). Due to the hydraulic fill placement, the ground water level raised to PD+7.0m. However, the ground water level in developed reclamation areas was +3.5m, therefore this level was adopted in the final design and PD+7.0m during construction.

4.2 Concepts
The Menard vacuum proposal included the main concept to create a ‘dam’ against potential slip failure under high fill surcharge of the adjacent wick drain trial areas. The 40m ~ 50m wide vacuum strip along the sensitive southern and western bunds, was providing this stability enhancement, thanks to the inward isotropic vacuum load and the limited amount of additional fill surcharge required (4m saving). The trial was also undertaken to demonstrate that significant overall time saving could be achieved using the vacuum consolidation process.
4.3 Design Analyses
A comprehensive analysis of the available soils investigation was undertaken by Menard and the soil parameters summarised in Table 2 were adopted.

Table 2. Design soil parameters and profiles

<table>
<thead>
<tr>
<th>Soil Parameters/Profiles</th>
<th>Symbol</th>
<th>Unit</th>
<th>Dredged Mud Deposit</th>
<th>Upper Holocene Clay</th>
<th>Lower Holocene Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio</td>
<td>C&lt;sub&gt;c&lt;/sub&gt;/(1+&lt;e&gt;_o&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>-</td>
<td>0.235</td>
<td>0.18</td>
<td>0.235</td>
</tr>
<tr>
<td>Coeff. of secondary consolidation in terms of strain</td>
<td>C&lt;sub&gt;c&lt;/sub&gt;/(1+&lt;e&gt;_o&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>-</td>
<td>0.0059</td>
<td>0.008</td>
<td>0.0076</td>
</tr>
<tr>
<td>Bulk unit weight</td>
<td>γ</td>
<td>kN/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>14.0</td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Coefficient of vertical consolidation</td>
<td>c&lt;sub&gt;v&lt;/sub&gt;</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;/yr</td>
<td>1.0</td>
<td>10.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Coefficient of horizontal consolidation</td>
<td>c&lt;sub&gt;h&lt;/sub&gt;</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;/yr</td>
<td>1.0</td>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Undrained cohesion</td>
<td>s&lt;sub&gt;u&lt;/sub&gt;</td>
<td>kPa</td>
<td>10.0</td>
<td>20.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Cohesion increase with depth</td>
<td>Δs&lt;sub&gt;u&lt;/sub&gt;/m</td>
<td>kPa/m</td>
<td>0.0</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Coefficient of cohesion gain with effective stress</td>
<td>λs&lt;sub&gt;u&lt;/sub&gt;</td>
<td></td>
<td>0.25</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>Compressible soil thickness</td>
<td>m</td>
<td></td>
<td>1.0~5.0</td>
<td>3.0~5.0</td>
<td>6.0~18.0</td>
</tr>
</tbody>
</table>

A large variability of the compressible soils thicknesses, as shown in Table 2, was encountered in the trial area, the deepest being in the south-west corner where the base of the lower Holocene was found some 33m below platform level.

Time dependent analysis of the primary consolidation was undertaken using the Hansbo theory and considering the filling history of the paddock, as well as the timing of the vacuum system and additional surcharge installation. Vacuum depressurisation of the ground mass was simply represented, in the model, by an equivalent 70 kPa load applied on top. Secondary consolidation and effect of pre-aging the soil, by over surcharging, were appraised by the conventional Bjerrum method.

Stability analyses of the southern and western boundaries have been undertaken, using a limit equilibrium model (Talren IV). The “apparent cohesion” in the top sand mattress provided by the vacuum and the strength gain of the clay material under rapid vacuum consolidation were the contributing factors opposing the destabilising effect of the surcharge being erected on the adjacent wick drain areas. Safety factors, well above the minimum 1.3 were shown at various steps. This would not have been achieved if high surcharge had been placed up to the bunds.

The optimised design included vertical transmission pipes (Menard MCD34, diameter 34mm ) at a square grid of 1.2m, a sand surcharge of only 2.2m above the vacuum membrane, a 9 month consolidation period from the start of the vacuum operation, and a resultant 77% degree of consolidation under the preload including vacuum.

4.4 Construction
A unique feature of the Vacuum Trial was the design and installation of a deep cut-off wall along the whole perimeter of the area. This was necessitated by the specific soil conditions encountered at the site. The original seabed consisted of 4m-5m of Upper Holocene permeable marine deposits; in addition some deep sand capping layers (up to 8m) were clearly present at a number of locations resulting from the uneven hydraulic fill process. To prevent water and air leakages from these permeable horizons, which would have compromised the vacuum efficiency, an impermeable ground barrier was designed to be anchored 1.5m into the Lower Holocene Clay.

Thanks to its extensive experience in Australia, Menard implemented the soil-bentonite technique to realise the 15m deep wall, with a permeability of less than 1e-9m/s.
A trench was created under bentonite slurry using a long arm excavator; the excavated materials were mixed on the side with bentonite slurry and then backfilled into the trench.

The use of vacuum consolidation with a deep cut-off wall in Brisbane was a first for Australia.

The preliminary activities carried out on the site included the proof-testing and rectification of the working platform to allow movements of the heavy machinery, dewatering of the excessively wet areas and trial of the soil-bentonite wall.

The construction of the trial itself was performed in less than 4 months including installation of vertical transmission pipes up to 35 m depth, cut-off wall, horizontal transmission pipes, instrumentation, protection fill, peripheral trenches, vacuum membrane and vacuum modules.

The vacuum operation was switched on starting on 9 June 2007.

Two weeks later, after fully checking the membrane was airtight, the required 2.2m of additional sand fill surcharge was placed in a very short timeframe without any stability concerns.

5. Instrumentation
It was accepted by Menard, PBC and Coffey that appropriate instrumentation be installed and monitored to assess the performance of the trial. The typical Menard procedure to control the vacuum efficiency, uses pressure gauges (CPVs) evenly spread under the membrane; they were installed and monitored daily during the initial three months and bi-weekly thereafter.

Three instrument stations, comprising piezometers in the ground and in selected, vertical transmission pipes, extensometers and deep settlement plates were installed in the vacuum area. Further, two inclinometers were installed on the outside boundary of the vacuum area to assess the lateral movement when the additional surcharge was being placed. Settlement plates were placed at regular intervals across the site to monitor surface settlements. While intensive monitoring was carried out during construction, after construction was complete, the instruments were generally monitored once a week. The results were saved into a database which could be accessed by various parties via the web. The monitoring results provided useful information about settlement at various soft clay depths as well as pore pressures, including vacuum pressures achieved at various depths.

Figure 3, graphically compares the vacuum effect as measured under the membrane (average of all CPVs) and at depths of 14.20m and 21.20m in the vibrating wire piezometers of one measuring station.

6. Results.
Within less than one week from vacuum operations starting, the vacuum gauges indicated an excellent average depressurization of -80 kPa under the membrane.

The piezometers installed, at different depths, in the vertical drains showed a rate of decrease of the pore pressure in the same range.
The graph highlights the very effective transmission of the depressurisation, through the vertical transmission pipes to the soil mass. This confirms that the vacuum is propagated at depth, with limited head-losses.

Figure 3 shows the vacuum pressure versus time; only a minor decrease is recorded over an 18 month period. This demonstrates the excellent performance of the air/water tight seal provided by the membrane and the impermeable wall enveloping the soil mass under vacuum pressure.

The in ground piezometers did not show a noticeable or immediate response to the vacuum effect. In fact, as the surcharge was placed soon after vacuum start, an increase of the pore pressure was observed. The pore pressure then started to decrease gently, conforming to the consolidation theory. The interpretation of pore water pressure measurements in vertical drain projects is difficult. It was found more reliable to base the verification analyses on settlement measurements.

The two inclinometers installed on the south bund and west bund did not show significant movement, during the surcharge placement on the wick drain area.

The records of the measured surface settlements have been used to verify that the consolidation process was very effective and conformed to the design assumptions adopted.

In May 2008, an interim review found that the initial soil parameters adopted were reasonable, except for the coefficient of horizontal consolidation in the lower clay, which was found, by the Asaoka method, marginally lower than initially assumed.

The back-analyses performed during this interim review showed that the degree of consolidation, required by the initial design, had been reached well in advance of the targeted 9 month vacuum period. This result was also well ahead of the consolidation recorded in the adjacent trial areas which adopted wick drains plus surcharge, all of which had commenced at the same time as the vacuum consolidation trial.

Given the good performance of the vacuum and the sustainability of the depressurisation, it was then decided to continue the vacuum trial with the view to upgrade the initial design specifications nominated by the Port.

The residual settlement criteria (20 years) was reduced from 250mm to 150mm and the required design live load adopted increased from 15 kPa to 25 kPa; these were the new targets set.

The new analyses with these revised criteria showed that upgraded results was possible by November 2008, the vacuum being continued up to that date and an extra 0.5m of surcharge being placed on a limited area where the clays were thickest.

Menard finally turned-off the pumps on 18 November 2008. The final back analyses showed that the degree of consolidation achieved by that date varied between 92% and 97% which were satisfactory to meet the upgraded design criteria.

Fig 4 shows the recorded settlements at VC1-4 marker, one of the deepest clay profile, versus
the predicted settlements. These curves show that the actual settlements were in good harmony with the predictions and illustrate the high degree of consolidation being achieved.

![Figure 4. Actual vs Predicted settlements](image)

7. Independent review by Experts

PBC and Coffey assessed the trial and Menard's performance during the design, installation and consolidation phases. During the consolidation period PBC commissioned a specialist review of the Vacuum Consolidation trial by three Professors, considered experts in soft soils. The scope of the Professors’ review was to assist with assessing the Trial in relation to criteria set at the commencement of the Trial in November 2006. Of particular note for the Professors was the assessment of the design, the construction and performance of the trial and the innovation and use of new technologies used by Menard. To achieve this, the Professors were asked to review all pre and post installation design reports and provide assessment of same.

The Professors concluded that Menard's proprietary Vacuum Consolidation system provided excellent results and confirmed the advantages of using vacuum consolidation at a site where edge stability under surcharge loading is critical. In addition they concluded that the vacuum system is clearly very efficient and superior in terms of achieving a rapid consolidation when comparing to the results obtained by wick drains and surcharge. The use of the MCD34 round drain when applied with a vacuum pressure provided enhanced results when compared to the performance of flat PVDs under surcharge.

Consolidation times were verified under this trial which will provide confidence where this system is used at the Port in the future.

8. Conclusions

The trial using vacuum consolidation which incorporated a 15m deep soil bentonite cut-off wall, a first in Australia, has proved to be very successful. Depressurisation under the vacuum membrane was constantly retained, in the range of -0.80 bars throughout the vacuum pumping phase. The adoption of the vacuum consolidation process ensured that from the initial application of the vacuum pressure, enhanced stability against potential edge slip failure was incorporated into the construction process along an environmentally sensitive site bordered on two sides by a Marine Park and on the other a Bird Roost. A saving of 4m of fill
surcharge and also time on the overall consolidation process further benefited PBC.
An independent technical review by a panel of Professors of the overall process and field results obtained, confirmed that all design objectives were met. This panel also concluded that the vacuum consolidation system was very effective and efficient as the rapid consolidation it provided undoubtedly enhances stability of sites where edge stability under surcharge loadings is of significant concern.
Current trends necessitate that asset owners and developers continue to investigate and embrace new construction techniques and the means through which projects can be delivered.

References


F. Masse, C. Spaulding, I. C. Wong, S. Varaksin, Vacuum consolidation - A review of 12 years of successful development, in Geo-Odissey, Blacksburg VA, USA (2001)


The outcome from these trials clearly reinforced the decision by PBC to trial innovative vacuum consolidation technology. The success of the vacuum consolidation trial at the Port of Brisbane resulted in PBC adopting Menard’s vacuum consolidation system for a further 9.3 ha area, which is currently under construction.