Ground Improvement Methods for Port Infrastructure Expansion

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ABSTRACT: The demand for reliable and efficient transport infrastructure is vital to sustain Australia's economic growth and quality of life. Due to the forecasted increase in the freight trade demand, existing Ports will need to undergo major expansion, e.g. for accommodating berths suitable for bulk cargoes and container handling. To maximise the use of available land, typically port expansions projects involve land reclamation which includes the use of dredged materials (e.g. Port of Brisbane) or other granular fill materials locally available (e.g. Port Kembla). In both situations, ground improvement methods need to be implemented to ensure the fills and the foundations for the port infrastructure have sufficient shear strength and bearing capacity to comply with serviceability requirements in terms of settlement and lateral displacements. In this paper, typical ground improvement methods employed in Port infrastructure are described and their application in two different Australian Port Infrastructure projects is discussed.

Keywords: Port infrastructure, Port expansion and reclamation, Prefabricated vertical drains, Granular waste materials.

1. INTRODUCTION

The transport industry is vital to sustain the Australia's economic growth. Recent increases in freight trade have increased the demand for reliable and efficient transport infrastructure. In line with the growing demand for imports and exports from Australia, port infrastructure have become an increasingly critical part of the country's growth as they are the gateways for both international and domestic freight to Australian markets. Port facilities in most Australian cities and major export hubs are already near capacity (Infrastructure Partnership Australia, 2009). Furthermore, the ability of these facilities to expand is severely restricted by access to suitable adjacent land for the establishment of new facilities and transport links, due to their proximity to urban areas.

Owing to the limited availability of usable space and constrains associated with environmental and safety issues, maintenance costs and the longevity of geostructures, port expansion projects often rely on land reclamation. The reclamation schemes involve mainly the use of dredged or borrowed materials that typically require additional improvement in order to achieve the required performance criteria. Furthermore, as many coastal regions of Australia contain very soft clays (estuarine or marine), there are additional challenges when dealing with the undesirable geotechnical properties of those such as, low bearing capacity and high compressibility. In fact, in the absence of appropriate ground improvement (Indraratna & Redana 1998; Bergado et al. 2002; Rujikiatkamjorn and Indraratna 2009; Saowapakpiboon et al. 2010), excessive vertical settlement and lateral movements can adversely affect the stability of built infrastructure (Indraratna and Redana 2000).

This paper focusses on the ground improvement activities undertaken as part of the expansion projects of two Australian Ports, i.e. Port of Brisbane and Port Kembla. In both projects, the required new facilities were constructed adjacent to the existing port facilities via land reclamation. In the Port of Brisbane, a conventional surcharge scheme in conjunction with prefabricated vertical drains as well as vacuum assisted surcharge load was selected as the preferred ground improvement method to reduce the required consolidation time through the deeper subsoil layers. In Port Kembla, the shear strength behaviour and bearing capacity aspects associated with use of compacted granular waste materials locally available (i.e. coal wash and steel furnace slag) is reported. Their individual geomechanical characteristics and the different blend ratios adopted are described and a results obtained in a field trial are discussed.

2. PORT OF BRISBANE

The Port of Brisbane is Australia's third largest container port located at the mouth of the Brisbane River at Fisherman Islands. With rapid growth in trading activities across a range of commodities, a new outer area (235ha) adjacent to the existing port facilities is being reclaimed for major expansion to maximise the available land, and to provide the maximum number of berths suitable for bulk cargoes and container handling for servicing regional importers and exporters. The area also acts as a receptacle for the disposal of dredged mud from maintenance dredging of the approach channel to the Port prior to development (Figure 1).

The soil profile in this area consisted of highly compressible clay with thickness exceeding 30 m which had undrained shear strength less than 15 kPa at shallow depth. The dredged mud used for reclamation exhibited a much lower strength and it depended mainly on the time of placement and the time elapsed since the capping material was in place. If no surcharge preloading is adopted, it was estimated that the consolidation time can go beyond 50 years with associated vertical settlements in the order of 2.5 to 4.0m. To accelerate the consolidation process and minimise lateral deformation adjacent to the Moreton Bay Marine Park, vacuum consolidation through the use of prefabricated vertical drains (PVDs) was recommended (Indraratna et al., 2011).

In this method, the PVD system permits the vacuum pressure to be distributed to a greater depth of the subsoil. In addition, the lengthy consolidation time due to the stage construction can be avoided (Indraratna et al. 2005, Rujikiatkamjorn and Indraratna, 2013). The amount of the surcharge fill may also be decreased by several metres with the accelerated rate of embankment construction (Yan and Chu 2003).

2.1 Site conditions and surcharge characteristics

The site investigation program revealed that underlying the reclaimed soil (dredged mud) is an upper Holocene sand layer of approximately 2-3m thick, followed by the Holocene clay layer varying in thickness from 6m to 25m. This normally to lightly overconsolidated Holocene clay has low shear strength and is highly compressible. A Pleistocene deposit comprising of highly over-consolidated clay underlies the Holocene clay layer.

To assess the consolidation and stability design parameters, a range of different *in situ* and laboratory tests were conducted. These included cone penetration/piezocone tests, dissipation tests, boreholes, field vane shear tests and oedometer tests.

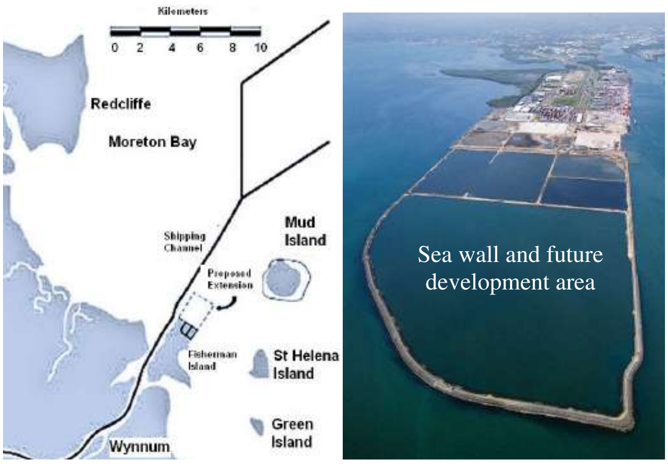

Figure 1 Illustration of the proposed extension area of the Port of Brisbane (modified after Indraratna et al., 2011)

Two consolidation techniques were adopted to reduce the long term settlement of the thick Holocene clay, i.e. conventional fill preloading system and the membrane-type vacuum consolidation system both applied in conjunction with PVD. The surcharge preloading system was applied to the inner areas (WD1-WD5, Figure 2) while, in the outer area (VC1 and VC2, Figure 2) adjacent to the Marine Park, the vacuum combined preloading approach was employed to control the excessive lateral displacement and to minimise disturbance of the marine habitats.

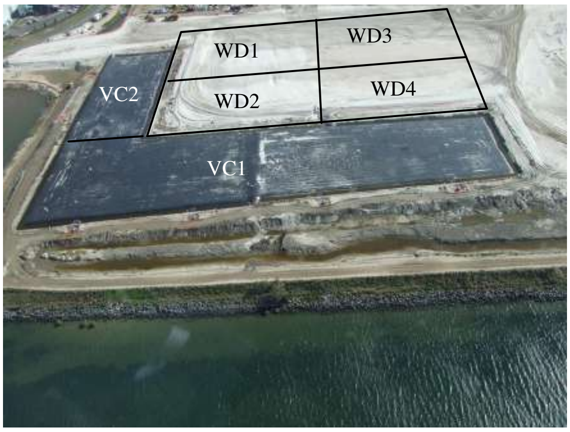

Figure 2 Detail of the of the proposed extension area at the Port of Brisbane

The design specifications considered for the design and construction of the embankments and vacuum application over the soft Holocene deposits, included:

(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.

In non-vacuum areas, both circular and band shape drains were installed in a square pattern @ 1.1-1.3m spacing whereas in the vacuum area, only circular drains were installed at a spacing of 1.2m in a square pattern. In the latter, the drains were installed in conjunction with the vacuum system consisting of membrane, horizontal transmission pipes and the heavy duty vacuum pumps (Figure 3). Further details are reported by Indraratna et al., (2011).

Figure 3 Field trial (a) drain installation, (b) horizontal drain installation, (c) membrane installation and (d) connection between horizontal drainage and vacuum pump
(Courtesy of Austress-Menard)

2.2 Field trial results

To monitor the ground behaviour (e.g. vertical and lateral displacement and pore water pressures) during the application of surcharge and vacuum, an array of different instruments were used, including settlement plates, vibrating wire piezometers, magnetic extensometers, and inclinometers (Figure 2). The staged construction and associated settlements and excess pore pressures responses are shown in Figure 4.

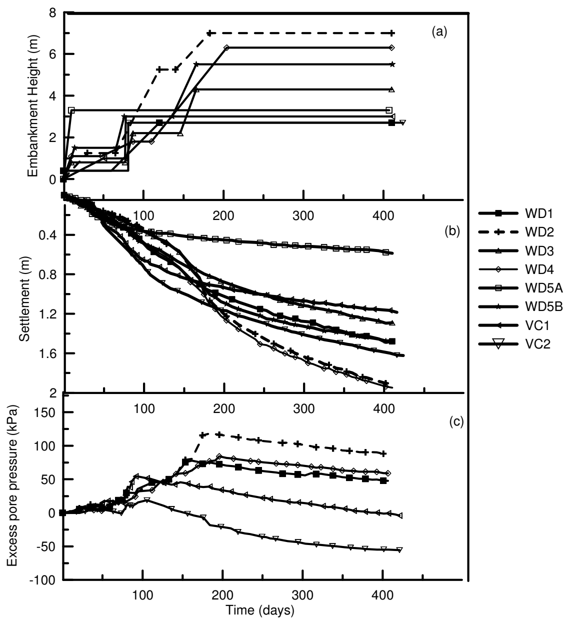

Figure 4 Embankment responses (a) staged construction, (b) settlements and (c) excess pore pressures (Indraratna et al., 2011)

It can be observed that the settlement trends are very similar among the different sub-areas. Typically, the settlement rate is higher at the initial stage of consolidation and the magnitude of ultimate settlement depends largely on the clay thickness and embankment height. The measured pore pressures (Figure 4c), show the effect of surcharge loading on the development of excess pore water pressure with time. The results clearly show the extent of pore pressure rise due to total stress increase (e.g. surcharge load incremental ramps), and the pore pressure dissipation that is expected to follow with time. Furthermore, it was observed that for the same time duration, the pore pressure reduction rate in vacuum areas (VC1 and VC2) is greater than that in the non-vacuum areas, thereby yielding a higher excess pore pressure dissipation, compared to the fill only areas. Although, Indraratna et al. (2005) showed that a small loss of vacuum head along the drain length could occur when the vacuum pressure was applied in conjunction with certain band drains, the circular drains used in the trial did not show any loss of vacuum with depth. This implies that the vacuum area performance at the greater depth is benefited by the use of circular drains as they can propagate vacuum pressure more effectively (without losing suction head) compared to the band drains.

While the fill height was reduced in vacuum areas, thereby involving less filling operations, the applied suction (-70 kPa) compensates for the accelerated excess pore pressure dissipation rates, confirming the effective performance of the vacuum consolidation technique (Indraratna et al., 2011). The measured lateral displacement normalized to total change in applied stress (vacuum plus surcharge load) for two inclinometer locations (VC1/MS28 and WD3/MS27) are shown in Figure 5. In VC1 and WD3 area, the total load on the surface is similar. For WD3 area, the total surcharge height was 4-5m (90 kPa), whereas for VC1 area the reduced surcharge pressure of 40 kPa (2m surcharge height) was supplemented with a vacuum pressure of 65 kPa. The maximum lateral displacements normalised to the total change in total stress are observed within the lower Holocene clay layer. Figure 5 indicates that the lateral movements were well controlled to minimise the disturbance in the adjacent Moreton Bay Marine Park, due to the isotropic consolidation by vacuum pressure.

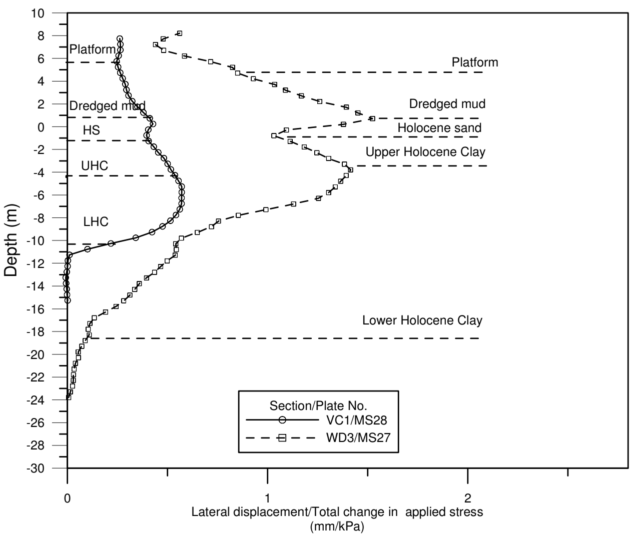

Figure 5 Comparison of lateral displacements at the embankment toe in vacuum and non-vacuum area after 400 days (Indraratna et al., 2011)

3. PORT KEMBLA

The Port Kembla Harbour, situated approximately 90 kilometres south of Sydney, was established in the late 1890's to facilitate the export of coal from the mines of the Wollongong region.

In the last decades the Port has rapidly grown to accommodate the expansion of local industries, e.g. coal and steel export market. Much of the essential port activities has been concentrated in the Inner Harbour area; however, as it is reaching capacity, the port authority has been focusing on the planning of the development of the Outer Harbour (Figure 6). The development of the Port Kembla Outer Harbour will create additional bulk cargo berths, which corresponds to approximately 45 hectares of reclaimed land.

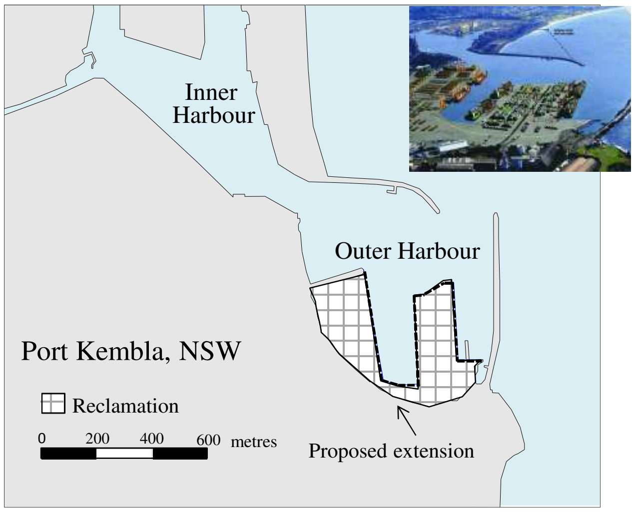

Figure 6 Illustration of the proposed extension area of the Port Kembla

Based on the available field data (Lai et al., 2011), volcanic sandstone bedrock can be found at the bottom of Port Kembla's Outer Harbour area (RL -15 to -20m), while the thickness of soft estuarine clay was relatively small. Unacceptably high consolidation settlement over time was not a critical issue in many parts of the proposed reclamation site. Also, any such settlement under initial preloading and subsequent live loading can be relatively easy to predict and control, as the clay thickness rarely exceeds 10m in most areas. Therefore, compared to certain ports where the clay thickness in some reclamation sites can be very large (e.g. Port of Brisbane), the type of reclamation fills used at Port Kembla would dictate a more important component of the total settlement, apart from the obvious implications on the load bearing capacity. Therefore, for the Outer Harbour development, PKPC selected a reclamation design that eliminated the need for removal of any of the underlying dredged spoil and did not utilise ground treatments other than passive preloading (Lai et al., 2011).

If the foundations for port infrastructure are not properly stabilised, unacceptable settlement and sudden subsidence of these granular fills, significant differential movements and lateral displacements can cause damage to the surface structures, as well as to the adjacent facilities (pipelines, retaining walls etc.). Thus, it is vital to examine the geotechnical properties of the fills used in the reclamation. The use of locally available granular waste materials (i.e. coalwash and steel furnace slag) as potential reclamation fills was considered as an economical alternative to the conventional (quarried) aggregates and dredged sandy fills as well as it represents some benefits from the environmental sustainability viewpoint (Rujikiatkamjorn et al., 2013, Tasalloti et al., 2015a). However, the improvement of heterogeneous waste materials such as slag and coalwash through compaction poses some challenges related to their individual adverse geotechnical properties, i.e. breakage potential for coalwash (Indraratna et al., 1994) and volumetric instability (swelling) for steel furnace slag (Wang, 2010, Heitor et al., 2015). To examine the geomechanical behaviour of these granular waste materials a compaction field trial was undertaken.

3.1 Materials

Coalwash (CW) is a by-product from the washery process conducted for refining run-of-mine (ROM) coal. For every metric tonne of ROM coal that enters the washery plant, approximately 200 kg of the output is made up of granular waste material of which 80% corresponds to coarse-grained coalwash and 20% as fine-grained tailings. Coal mining operations in Australia alone generate a few hundreds of millions of tonnes per year of coal wash (Leventhal and de Ambrosis, 1985). The steel furnace slag (SFS) by-product is a direct result of steelmaking by the implementation of processing iron and steel scrap with lime in high-temperature such as the Basic Oxygen (BOF) and Electric Arc (EAF) furnaces. Approximately 10-15% by weight of the output from the Basic oxygen furnace (BOF) is steel furnace slag or SFS. The source CW and SFS materials selected were a Dendrobium coalwash produced by Illawarra Coal and a SFS produced via the basic oxygen method (BOS) by ASMS (Australia Steel Milling Services), respectively (Figure 7).

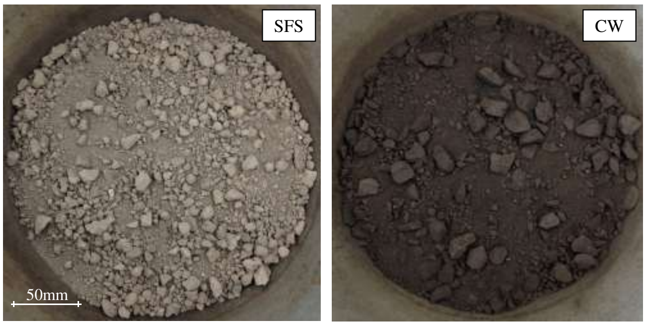

Figure 7 Typical aspect of steel furnace slag (SFS) and coal wash (CW) granular waste by-products

3.2 Field trial results

The field trial was conducted at Port Kembla Outer Harbor reclamation site shown in Figure 8. An area of 55m by 14m was provided by Port Kembla Port Corporation (PKPC) for the field trial, and the depth of layer was 1.4m, corresponding to a total volume of 1078m^3. The area was divided into two sections in which to the performance of two selected mixtures were assessed. The mixture ratios adopted were selected based on a preliminary study (Chiaro et al. 2013), i.e. CW50-SFS50 and CW20-SFS80 by volume percentage which is equivalent to CW43-SFS57 and CW27-SFS73 by weight percentage. It was found to be more efficient the adoption of a volume ratio in the field compared to the conventional weight percentage criterion adopted in laboratory. The mixing and placing of the materials was performed by an excavator and the materials were spread and levelled by a grader in the designated area (Figure 8). For the compaction of coalwash and steel furnace slags blends, a 13-tonnes smooth steel drum roller with a vibration mode at a frequency of 30Hz was selected. For a typical fill thickness of 300mm, after four and eight roller passes the mixtures had attained sufficient dry unit weight to comply with the 90% and 95% specification, respectively. The compaction roller adopted was also instrumented with accelerometers that enabled the measurement of the soil response during compaction. Upon a given number of passes, the in-situ dry unit weight and moisture content were routinely monitored using sand cone replacement (SCR) and nuclear densometer (ND) tests. It was found that the nuclear method was ineffective for determining the in situ moisture content.

To assess the post-compaction shear strength behaviour of the mixtures, Dynamic Cone Penetration Tests (DCPTs) and plate load tests (PLT) were performed. In the DCPT tests the number of blows required to drive the cone penetrometer 100mm into the compacted layers was measured throughout the test. Figure 9 shows the equivalent in-situ California Bearing Ratio (CBR) values obtained via the number of DCPT blows ($CBR = 292/DCP^{1.12}$). Having equivalent CBR values in a range of 25-50, these mixtures may be considered suitable to be used as structural fill in terms of shear strength.

Figure 8 Photos of the field trial (a) arrival of the material on site, (b) stock pile of steel furnace slag and coalwash, (c) mixed materials ready for (d) spreading, (e) sampling prior to compaction, (f) levelling, (g) adding moisture and (h) compaction

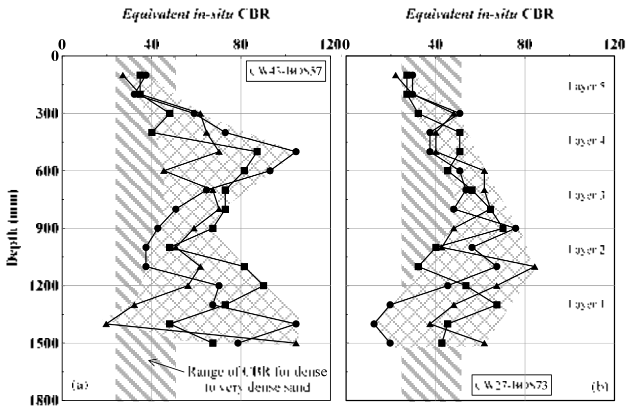

Figure 9 Variation of the equivalent in-situ CBR with depth for (a) CW43-BOS57 and (b) CW27-BOS73 (Tasalloti et al., 2015b)

Two tests for each mixture were performed at two different elapsed periods to investigate the potential effects of hydration reactions taking place due to the presence of free lime (CaO) and free magnesium (MgO) in the SFS. The variation of applied pressure with settlement, for the two stages (i.e. 30 and 170 days after compaction) is plotted in Figure 10. As it was expected the mixture having a higher percentage of steel furnace slag (Figure 10b) exhibited larger difference between the 30 and 170 days tests. A crust layer was formed on the surface, and thus a sitting pressure equal to 400kPa was identified in the results of the second stage. From a post-construction settlement viewpoint, under the expected port service loads ranging from 60-120kPa, the settlement measured would not exceed 1mm which confirms further their suitability as structural fill.

The presence of free lime (CaO) and free magnesium (MgO) in the SFS may cause the mixtures to experience swelling. To investigate the swelling potential (ratio of vertical expansion to the layer thickness), surface markers were monitored with time using surveying equipment. While, the mixture with higher SFS content showed more swelling, it was still modest for a free swelling condition; CW43-SFS57 and CW27-SFS73 were 6.3% and 5%, respectively. Furthermore, provided that the applied surcharge and live loads (e.g. pavement, live loads) exceeds the swell pressure (approximately 50kPa for CW43-SFS57) no vertical expansion would occur. This indicates that if these mixtures are to be used in locations where surcharge loads exceed 50kPa, which is nearly equivalent to typical pavement load (i.e. 30 - 45kPa); the swelling potential is not likely to influence the performance and stability of the built Port Infrastructure.

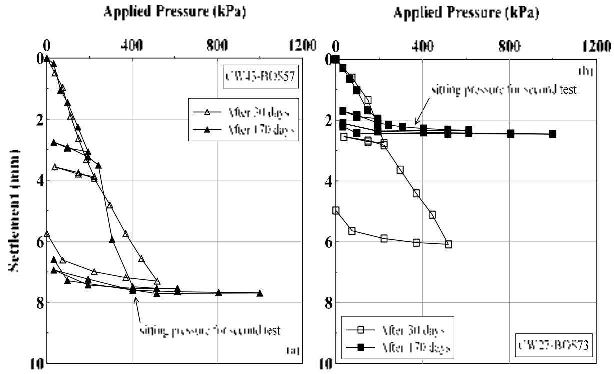

Figure 10 Variation of pressure against settlement on (a) CW43-BOS57 and (b) CW27-BOS73 (Tasalloti et al., 2015b)

4. CONCLUSION

Different ground improvement methods commonly used in Port Infrastructure projects were outlined and particular emphasis was placed on two Australian Port expansion projects, i.e. Port of Brisbane and Port Kembla.

For improving the shear strength and provide adequate stability requirements for the foundation of the Port of Brisbane infrastructure, a system of vertical drains with vacuum preloading and surcharge fill were adopted for accelerating soil consolidation. The performance of different ground improvement approaches tested in the trial area has been analysed and discussed. A number of subdivisions were selected to investigate the performance of vacuum consolidation, and the different vertical drain spacing and drain types. It was observed that the average degree of consolidation achieved was more than 85% after 1 year.

In the non-vacuum areas (i.e., surcharge only), both band drains and circular drains provided a similar performance. However, the circular drain performed better in vacuum areas because the circular drains can propagate vacuum pressure more effectively (less resistance) compared to the band drains. With a similar magnitude of applied preloading, the excess pore pressure dissipation rate at significant depths in the vacuum areas was shown to be generally higher than that in the non-vacuum areas. When the vacuum pressure combined with surcharge fill is used, the overall lateral movement is reduced due to the isotropic consolidation induced by vacuum application. From a stability point of view, vacuum pressure decreases the ratio of lateral displacement to surcharge fill height at any given time. The system of PVD subjected to vacuum combined surcharge preloading is a useful method for accelerating the radial consolidation and for controlling the lateral displacement, as long as the possible air leaks in the field can be prevented.

The potential use of a new synthetic material by blending two granular wastes by-products (i.e. coalwash and steel furnace slag) was evaluated. Upon compaction the material exhibited promising characteristics in terms of shear strength for use as a structural fill. The field performance of two CW and SFS mixtures were evaluated and discussed by conducting DCPTs, PLTs, and swell monitoring. The two selected mixtures were assessed through laboratory studies as suitable reclamation fill. It was observed that a minimum 4 passes of a 13-tonne vibratory smooth roller was adequate to compact the mixtures to the dry unit weight exceeding 90% relative compaction. The results of DCPT on the mixtures showed that the average equivalent in-situ CBR was between 46 and 60, which indicates that the shear and compression strength of the compacted CW-SFS mixtures is adequate to be qualified as a structural fill. The results of the PLT indicated that the settlement-deformation of the compacted mixtures decreased with time due to hydration of SFS component. From a post-construction settlement viewpoint, under the expected Port loads ranging from 60 -120kPa, the settlement measured would not exceed 1mm which confirms further confirming their suitability as structural fill.

Although the two mixtures exhibited promising results in terms of strength and settlement behaviour, the vertical expansion under free swelling conditions was 6.3% and 5% due to the presence of CaO and MgO in the SFS fraction. The field investigation confirmed that the compacted mixtures of CW-SFS had adequate shear strength properties, to be used in reclamation projects provided that a surcharge load exceeding the swelling pressure is applied (e.g. pavement structure).

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