Settlement analysis of eastern reclamation area: Port of Townsville

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ABSTRACT

The Port of Townsville's successive maintenance and capital dredging campaigns for the last two decades have resulted in the deposition of over two million cubic metres of soft dredged material into the port's eastern reclamation area. The dredged mud slurry is hydraulically placed into containment ponds and left to settle and self-weight consolidate, thereby forming 50 hectares of reclaimed land. In addition to challenges of low bearing capacity and high compressibility, land reclaimed with compressible dredged material would take decades to complete the consolidation process by natural means. Ground improvement techniques are usually applied to enhance strength and compressibility characteristics, to expedite the lengthy consolidation duration, and allow early land utilization. To ascertain geotechnical properties of the dredged fill material and subsurface soil of its eastern reclamation area, the Port of Townsville in collaboration with its geotechnical consultants, has conducted a series of field investigations and laboratory testing. Using soil parameters obtained from geotechnical investigations, the Port of Townsville has carried out ground settlement analysis on its eastern reclamation area under a range of applied loadings to evaluate the anticipated ground settlement. The estimated settlement values were utilized to refine the established consolidation lead times guidelines, ground improvement methods selection, and to appreciate likely performance of the treated ground. This paper discusses the Port of Townsville's eastern reclamation area site description, geology, geotechnical investigations, site categorization, assumptions made to allow a rational ground settlement analysis, settlement assessment method used, obtained results and observations.

Keywords: compressibility, consolidation, dredged material, land reclamation, sedimentation, settlement

1 INTRODUCTION

Since early 1940's, the Port of Townsville has reclaimed over 200 hectares of land using material derived from its maintenance and capital dredging campaigns (Port of Townsville 2011). The soft dredged mud slurry is hydraulically placed into containment ponds and left to undergo sedimentation and self-weight consolidation to form a land fill material.

The most eastern part of the port reclaimed land is known as eastern reclamation area. It is located between the existing port infrastructure and the sea channel section of Ross River. It has a trapezoidal shape measuring about 500 to 1000 m long (north to south) by 600 to 700 m wide (east to west). The eastern reclamation area is the port's principal location for land based dredged material disposal. The reclaimed land is created to accommodate future port infrastructure such as warehouses, office blocks, workshops, roads, railway, hardstands, sewage and drainage (Port of Townsville 2013). Land reclaimed with soft dredged material has challenges of low bearing capacity and high compressibility that need to be addressed prior to land utilization. To ascertain properties of the reclaimed land fill material, and the subsurface, the Port of Townsville in collaboration with its geotechnical consultants has conducted series of field investigations and laboratory testings on its eastern reclamation area.

Data gathered from these geotechnical investigations has been analysed to identify values of soil parameters required for the reclaimed land settlement calculations and consolidation modelling. Using the obtained soil parameters, the port has carried out settlement analysis under a range of applied loading conditions. The estimated settlement values were used to refine the established consolidation lead time guidelines, ground improvement selection criteria and predication of likely performance of the treated ground.

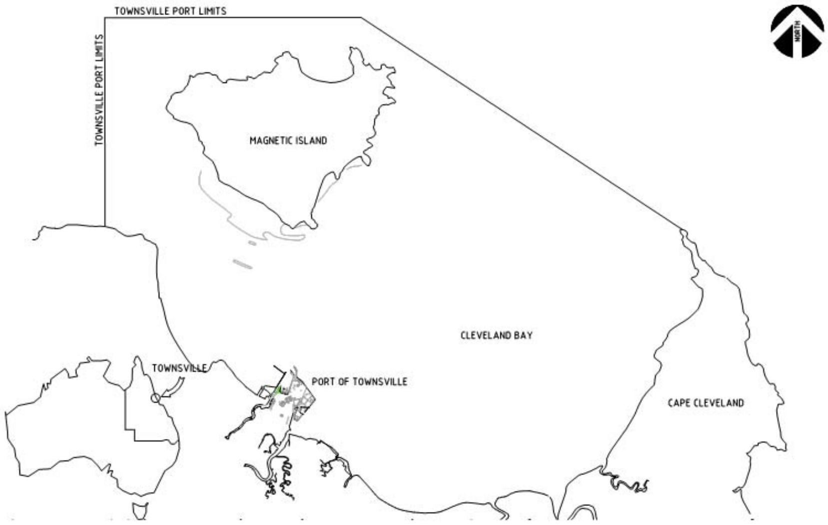

Figure 1. Port of Townsville location plan

2 SITE DESCRIPTION

The Port of Townsville eastern reclamation area is a 50 hectare land that cut off from ocean by a perimeter rock wall (eastern breakwater) with internal partition bunds to enable hydraulic placement of the dredged material. The eastern reclaimed area comprises several containment ponds which have been progressively filled with fine grained maintenance dredging materials from the port's navigation channels, swing basin and berth pockets. The dredge material pipeline is located in the southern ponds with decants and sedimentation progressing from south to north. The material flow within the containment ponds is controlled by box weirs.

Before construction of the perimeter rock revetment, the top soft sediments on the sea floor were dredged to minimize potential settlement due loading induced from rock wall and the dredged fill material (Port of Townsville 2013). The construction of perimeter rock wall was started in 1982 and was completed in 1992. The placement of dredged material commenced early 1993 and it is progressing up to date. The reclamation works are complete for some parts of the eastern reclaim area to reduced level of + 5.2 to +5.6 m, while reclamation operations are still progressing on other parts.

Figure 2. Aerial photo of Port of Townville eastern reclamation area - 2014 (view to the north)

3 SITE GEOLOGY

The geology of Townsville region comprises Quaternary aged alluvium and colluvium sediments underlain by Late-Palaeozoic age granite (Golder Associates 2008A). The Port of Townsville's eastern reclamation area is not included on the Queensland Department of Mines' Townsville 1:100,000 Geological Series Sheet, as the site was submerged at the time of the sheet preparation. Review of the Townsville geological map indicates that the terrain to the south of the eastern reclamation area is to be underlain by Quaternary age estuarine deposits comprising mud, clay, silt and sand, then Permian age granite at depth (Queensland Department of Mines 1986).

4 GEOTECHNICAL INVESTIGATIONS

The geotechnical investigations undertaken on the eastern reclamation area showed that subsurface conditions encountered comprise dredged material filling of low to high plasticity clays/silts, sandy clays, silty sands and sand to approximately top 1 to 5.6 m, underlain by about 1 to 2 m layer of recent seabed sediments of alluvial deposits that generally contain mixture of (very soft to soft clays/silts) and very loose to medium dense sand with shell fragments and organic material (Douglas Partners 2009). The layer below the sea bed have been found to be consolidated older stiff to hard clays, silty clays and sandy clays and medium dense to very dense clayey sands and sands to depth of 14.96 to 16.52m , the consolidated older layer is underlain by deeper residual soils and rock (granite/basalt) .

5 SITE CATERGORIZATION

In order to allow a rational ground movement analysis and ground treatment response, the site is divided into eight areas that are considered likely to have similar settlement performance based on the available geotechnical information. The site reclamation history of each area (pond) was established using dredge logs, reclamation progress reports, aerial photos, and geotechnical reports. The functional requirement of the eastern reclamation area is for industrial use; the Port of Townsville is preparing the reclaimed land to light industrial standards, leaving the site preparation for any heavier load conditions to potential site lessees (Port of Townsville 2008).

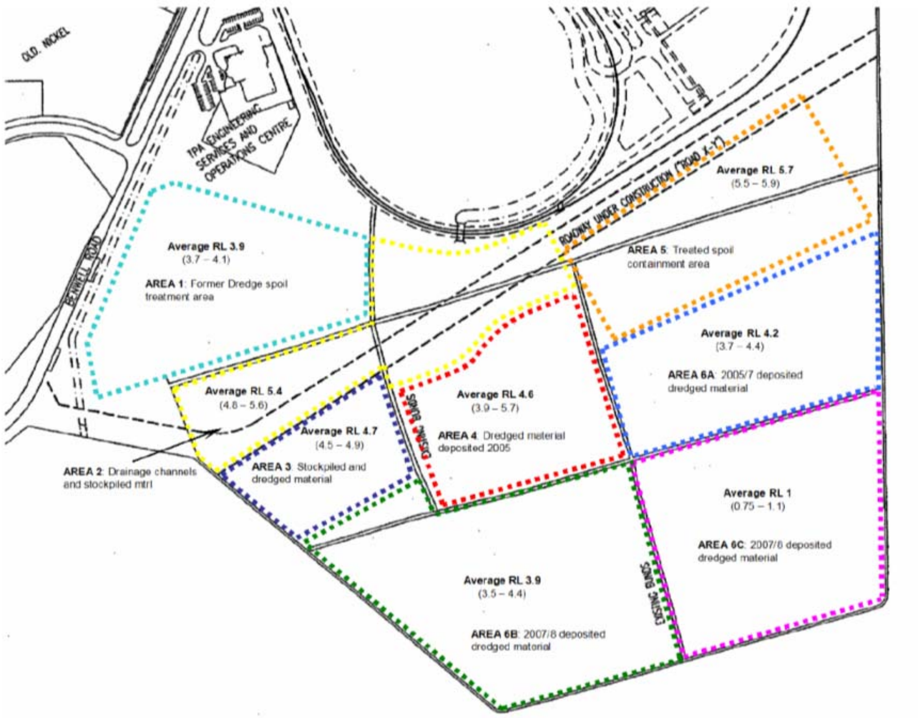

Figure 3. Settlement analysis areas - site plan

Table 1: Characteristics of the eight site categories (Port of Townsville 2008)

Area ID	Area Description	Surface Reduced Level (m)
1	Former dredge spoil treatment area	3.9
2	Drainage channels and stockpiled material	5.4
3	Stockpiled and dredged material	4.7
4	Dredged material deposited 2005	4.6
5	Treated spoil containment area	5.7
6A	2005/2007 deposited dredged material	4.2
6B	2007/2008 deposited dredged material	3.9
6C	2007/2008 deposited dredged material	1.0

6 SETTLEMENT ANALYSIS METHOD

The settlement performance of each of the eight areas, the underlying seabed and the natural stiff clay was calculated using soil parameters obtained from the geotechnical investigations. Statistical assessment has been undertaken on the actual geotechnical data collected for each relevant soil parameter to provide the most likely values. Empirical correlations were used to allow calculation of the soil parameters that have not been directly tested. In order to account for potential of variations in settlement performance within a selected area due to variability in the dredged material, geotechnical data considered to give largest settlement estimate is chosen for settlement calculation. Some adjustments on soil engineering properties were made to account for differences expected between laboratory measured and in-situ soil properties.

Table 2: Soft soil parameters used for settlement analysis (Golder Associates 2008B)

Material Type	$C_c/(1+e_0)$	$C_v(m^2/year)$	$C_\propto$(% per log cycle)
Soft clayey dredged fill	0.25	4	1%
Natural soft/firm clay	0.25	7	1%
Medium dense sands	0.01	50	0%

Terzaghi one-dimensional consolidation theory was used to assess the expected primary and secondary consolidation settlement (Terzaghi 1943). Series of one-dimensional consolidation tests under vertical double drainage to both top and bottom of reconstituted dredged mud specimens and undisturbed samples of deeper in-situ layers were conducted to determine the coefficient of vertical consolidation (C_v). For the horizontal (radial) drainage condition, it is assumed that the marine sediment layers will exhibit relatively isotropic deformation behavior (Lee et al 1999).

Total settlement (S_T) of soils both in the short-term and over a nominal period of 25 years is calculated as the sum of: immediate settlement (S_i), primary consolidation settlement (S_c), and secondary consolidation settlement (S_{sc}).

$$S_T=S_i+S_c+S_{sc} \quad (1)$$

When foundations are constructed on very compressible clays, the consolidation settlement can be several times greater than the immediate (elastic) settlement (Das and Sobhan 2013). The immediate settlement of cohesive soils is relatively small part of the total vertical movement, as such; a detailed immediate settlement study is seldom justified unless the structures are very sensitive to distortion (Patrick 2003). As the functional requirement of the Port of Townsville's eastern reclamation area is to be used for port related infrastructure that tolerate some deformation, the immediate settlement component is assumed to be negligible.

$$S_i \approx 0 \quad (2)$$

Thus, the total settlement comprises the primary and secondary consolidation settlements

$$S_T = S_c+S_{sc} \quad (3)$$

$$S_c = \frac{C_c}{1+e_0} H \log\left(\frac{\sigma_0'+\Delta\sigma'}{\sigma_0'}\right) \quad (4)$$

$$S_{Sc} = \frac{C_{\propto}}{1+e_p} \text{ H} \log\left(\frac{t_2}{t_1}\right) \quad (5)$$

$$C_{\propto} = \frac{\Delta e}{\Delta \log t} \quad (6)$$

$$T_v = \frac{C_v t}{H^2} \quad (7)$$

Degree of over consolidation of various layers of soil within each area was estimated as function of cone resistance values that obtained from the relevant cone penetration test (CPT) for each area using methods outlined by (Lunne et. al 1997).

The loading sequence is assumed to be initial filling with dredged to reduced level + 5.5m of an average bulk density of 20KN/m3, allowed to complete preliminary consolidation, followed by additional loading of 20kPa ,50kPa or 70kPa that is expected to be imposed by future development. The secondary consolidation is assumed to commence after primary consolidation is 90% complete.

7 RESULTS

The Port of Townsville's eastern reclamation area settlement estimates for dredged material filling to surface level of RL 5.5 m, allowing primary consolidation to complete, then followed by application of development project loads of 20kPa or 50kPa are presented in tables 3, 4 and 5 respectively.

Table 3: Settlement estimates (mm) for dredged material filling to RL 5.5m

Property	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6A	Area 6B	Area 6C
S_c	120-160	10-20	110-130	10-30	0*	80-130	120-140	260-300
T_{90}(month)	3-6	<1	3	3-4	0	3-4	3-4	3-4
S_{sc} (25 yrs.)	40-60	40-60	140-160	50-70	0	50-70	50-70	50-70
S_T (25 yrs.)	160-220	50-80	250-290	60-100	0	130-200	170-210	310-370

* Area 5 is at RL 5.7m, comprises stiff partially treated material, therefore settlements due to dredged material filling are negligible.

Table 4: Settlement estimates (mm) for 20kPa loading after filling to RL 5.5m

Property	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6A	Area 6B	Area 6C
S_c	60-80	50-70	120-150	50-70	80-120	50-70	50-70	50-70
T_{90} (months)	3	7	<3	3-4	<3	3-4	3-4	3-4
S_{sc} (25 yrs.)	50-70	60-70	120-140	40-60	100-140	40-60	40-60	40-60
S_T (25 yrs.)	110-150	110-140	240-290	90-130	180-260	90-130	90-130	90-130

Table 5: Settlement estimates (mm) for 50kPa loading after filling to RL 5.5m

Property	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6A	Area 6B	Area 6C
S_c	150-180	150-180	280-320	120-160	210-230	120-160	120-160	100-130
T_{90}(month)	3	7	<3	3-4	<3	3-4	3-4	3-4
S_{sc}(25 yrs.)	50-70	60-80	120-160	40-60	130-150	50-70	50-70	50-70
S_T(25 yrs.)	200-250	210-260	400-480	160-220	340-380	170-230	170-230	150-200

70kPa loading analyses indicated that the reclamation area does not have sufficient bearing capacity to adequately support the proposed load without allowing the soft ground undergo consolidation under a lower load first or undertaking some form of ground improvement.

8 CONCLUSIONS

The geotechnical investigations results and the reclamation history of the Port of Townsville's eastern reclamation area enabled the site to be categorised into areas that considered likely to have a similar settlement performance. The site history of each area (pond) was established by analysing dredge logs, reclamation progress reports, and aerial photos. Information gathered from the field investigations and laboratory testings conducted on the eastern reclamation area has informed the most likely values of soil parameters of the reclaimed land fill and the subsurface materials that required for ground settlement analysis. The following conclusions can be drawn from the Port of Townsville's eastern reclamation area settlement analysis study:

A- The consolidation rates were observed to be relatively fast which can be attributed to the silt and sand component in the compressible soil layers facilitate the pore water dissipation process.

B- The estimated settlement magnitudes were found to be manageable by surcharging and deep soil mixing ground improvement techniques at reasonable cost.

C- The treated ground can adequately support the loading to be imposed by the future port infrastructure that is anticipated to be constructed on the eastern reclamation area.

D- For the low bearing capacity mitigation, staged loading by allowing the soft ground to undergo consolidation under lighter load first, prior to application of heavier loads is found to be practical.

The eastern reclamation area settlement analysis outcome has assisted the Port of Townsville to refine its established consolidation lead times guidelines, ground improvement methods selection and to appreciate the likely performance of the treated ground. The port has successfully stabilised its reclaimed land by applying ground improvement techniques ranging from surcharging, lime stabilisation, to lime column and stone column replacement/ dynamic compaction in the past. Guided by structures sensitivity to ground deformation and the performance of the improved ground, the Port of Townsville had constructed different structures on shallow and deep foundations.

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APPENDIX: NOTIFICATIONS

S_i	Immediate Settlement
S_T	Total Settlement
S_c	Primary Consolidation Settlement
S_{sc}	Secondary Consolidation Settlement
e_0	Initial Void Ratio
e_p	Void Ratio at the End of Primary Consolidation
C_v	Coefficient of Vertical Consolidation
C_c	Compression Index
$C_\propto$	Secondary Compression Index
H	Thickness of Soil Layer
$\sigma_0^{'}$	Initial Effective Stress
t_1, t_2	Time
T_v	Time Factor
T_{90}	Time Factor for 90% of Primary Consolidation Complete