

Ground improvement by dynamic replacement and stone columns within maritime environment at Ichthys LNG project in Darwin

Amélioration de sol par plots ballastés dynamique et colonnes ballastés dans un milieu maritime à Darwin – projet LNG Ichthys

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ABSTRACT: In September 2011, Menard Oceania was engaged by MacMahonJohnHolland Joint Venture to provide ground improvement solution for the \$34bn Ichthys LNG development. With close to 400,000m² of mangrove swampland set to be reclaimed and improved, this project was a great opportunity to showcase the technical, commercial and environmental benefits that Menard techniques could provide. The ground improvement works involved complete design and construction for the Ichthys LNG site located at Blaydin Point on a low lying peninsula in Darwin Harbour. Dynamic replacement and stone columns technique were selected to treat intertidal mangrove mud to achieve required bearing strength, stability and limit settlement to an acceptable levels. The site was underlain by 3m to 5m thick densely vegetated mangrove muds with very soft shear strength ranging from 0kPa to 12kPa at depth. The site was exposed to daily sea water level tidal variations of up to 8m, which were creating significant constructability constrain and slope instability risks. This paper will present the design philosophy, the process involved in the selection construction methods, site constraints and review of Quality Assurance (QA) and post construction monitoring data results.

RÉSUMÉ : En septembre 2011 Menard Oceania a été engagea par le groupement MacMahonJohnHolland pour exécuter des travaux d'amélioration de sol pour le projet Ichthys LNG de 34 milliards de dollars australiens. La surface traité étant de 400 000m² et constitue mangrove, ce projet était une bonne opportunité pour mettre en évidence les avantages environnementaux, techniques et commerciales d'amélioration de sol propose par Menard Oceania. Les travaux d'amélioration de sol pour ce projet incluait la conception et la construction pour Ichthys LNG situé à Blaydin Point sur une presqu'île à basse altitude dans la bais de Darwin. Nous avons choisi d'améliorer le sol existant par substitution dynamique et colonnes ballastées afin d'augmenter la capacité portante de la mangrove, ainsi que garantir sa stabilité et diminuer les tassements. Le site reposait sur une couche de 3 à 5 m de mangrove, couvert par végétation, qui se caractérisait par une faible résistance au cisaillement variant de 0 à 12 kPa. Le site était aussi exposé aux variations de marée jusqu'à 8 m qui impactait la constructibilité du projet et provoquait des risques d'instabilité des pentes. Dans ce document nous allons présenter la philosophie du design, les études d'exécution, les contraintes du site, l'assurance qualité et la surveillance après la construction.

KEYWORDS: Ground improvement, dynamic replacement, maritime environment, mangrove muds.

1 INTRODUCTION

Inpex Browse, Ltd (Inpex) and its partner Total are developing the Ichthys gas field to pipe that gas to onshore facilities at Bladin Point on south side of East Arm in Darwin Harbour. The proposed LNG plant consist of gas receiving facilities, 2 x 4.2Mtpa nominal capacity LNG trains, LPG and condensate production facilities, product storage and export facilities, Module Offload Facility (MOF), flare pad (FP).

The proposed on-shore facilities are located on extremely soft intertidal mangrove muds, therefore an appropriate ground improvement was required to achieve required strength and stability of the site works and limit long term settlement to an acceptable level.

Various ground improvement techniques were studied to select the most suitable for the ground conditions and site constraints encountered at the Blaydin point site. Dynamic Replacement (DR) technique was selected for onshore section to improve soft mangrove mud to depth of 5.5m and Stone Columns (SC) technique was selected for off-shore section to improve soft deposits to a depth of 2.5m.

1.1 Site Location

The proposed onshore gas plant site is at Blaydin Point which is on peninsula of Darwin Harbour. The Blaydin Point peninsula covers an area of about 200ha and is vacant Crown land. The north, east and west boundaries of the site are surrounded by

water. The southern boundary extends to the junction of the site access road with seal road to Wickham Point.



Figure 1. Blaydin Point – Onshore plant layout.

MOF is a temporary 400m long causeway structure used for offloading large modules from ships to assemble LNG plant. The largest module weights 6500 tonnes. MOF causeway is linking onshore facilities with MOF jetty.

FP located south west consist of an rock filled pad with surface dimensions of 165m x 577m and raised by approximately 2.5m above mudflats. The flare system is required for disposal of hydrocarbon vapour and liquid streams.

1.2 Project Requirements

Ground treatment was design to improve existing soft marine clay or mud soils such that improved ground may safely and effectively support the defined loads while achieving the specified design criteria for bearing capacity, stability and settlement over design life of 28years.

1.2.1 Environmental Consideration

Ichthys project has very strict environmental requirements. Selected ground improvement method was required to minimise environmental impacts, including the impact on mangroves, preventing Potential Acid Sulphate Soils (PASS) disturbance, appropriately managing PASS and ASS, minimising turbidity, waste production, discharges and dust generation.

1.2.2 General Loading

Ground improvement works were designed to achieve bearing capacity and specific performance criteria under additional thickness of imported fill, considering all tidal ranges, construction and permanent loading applied at the finish surface level (see Table 1).

Table 1. Load cases for temporary and permanent works.

Loading\Area	Flare Pad	MOF
Temporary UDL (kPa)	40	100
Permanent UDL (kPa)	6	Nil
Additional fill thickness t (m)	2.5	4.0 to 8.0

1.2.3 Allowable Ground Movements

The maximum ground movements for the finished surface in general plant areas over a 28 years design life was limited to those given in Table 2.

Table 2. Maximum ground movements.

Parameter measured at any point on the finished Plant ground surface	Limiting Value
Vertical Settlement (mm)	50
Horizontal displacement (mm)	20
Differential settlement (-)	1:500

1.2.4 Slope Stability

The slope stability analyses have been carried out to validate that minimum required factors of safety (FoS) for all temporary and permanent slopes are satisfied. Analyses have considered all possible tide ranges, including highest (at +3.995m) and lowest astronomical tide, storm water surge levels as well as rapid drawdown case with full effect of residual pore water pressures within embankment. Minimum required FoS against slope instability is presented in Table 3.

Table 3. Minimum required Factor of Safety against stability failure.

Slope stability conditions	minimum FoS
Short Term (undrained) (-)	1.3
Long Term (drained) (-)	1.5
Earthquake (-)	1.2
Storm surge – short term stability (-)	1.1
Storm surge – long term stability (-)	1.2

2 TECHNIQUE DESCRIPTION

Two stone replacement techniques were selected, namely dynamic replacement where working platform could be constructed ahead the works and stone columns where ground improvement was required ahead of the platform construction.

2.1 Dynamic Replacement

Dynamic Replacement (DR) is one of the techniques optimised by Menard for improvement of highly compressible, organic and weak soils. During the works, the tamping energy drives granular fill material down into the compressible soils to form a large diameter soil reinforcement column, with a diameter of 2-3.5m. Stone pillars are formed by placing a blanket of granular fill material over the area to be improved, and the driven into the soil below by repeated tamping.

DR pillars are formed through a succession of tamping and back-filling sequences. DR pillars are formed by dropping a 20-25 tonnes weight pounder from a height of 10m-20m. This technique can deliver replacement ratios of up to 25% and treatment depth of up to 6m.

Material used for DR was quarry shot rock with up to 500mm of nominal size, fines content less than 10% and free from organic inclusions.

2.1 Stone Columns

A dry bottom feed method was selected to install stone columns due to selected construction method and less impact on environment in comparison to top feed method.

The marine dry bottom feed method involves the use of a vibroflot suspended from a crawler crane and the stone fed to the tube via a pressurized tank fed into by a lifting skip arrangement.

The proposed characteristics of stone backfill for the project is crushed stone (gravel) for column backfill that shall be clean, free from organics and other deleterious materials. The material to be used is 10 to 32mm aggregate with less than 5% fines content.

At the MOF site, stone columns of 1.0m diameter at 2.25m square grid spacing were installed by underwater operation using crawler crane from the already improved, advancing platform. This sequence of installation was providing the benefit of limiting platform requirements and significantly mitigating the generation of mud waves as filling would only take place on already improved ground.

The working platform integrated into permanent works ranges from 4m to 8m in thickness with batter formed in 1(V) to 2.5 (H). In order to reach ahead of already constructed section a 150t crawler crane Manitowoc M12000 capable of reaching as far as 31.5m was select

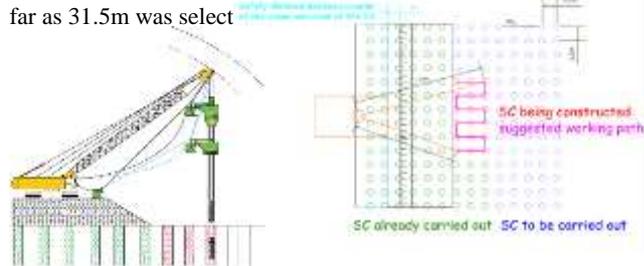


Figure 2. Typical SC works sequence on rolling on platform

3 GROUND CONDITIONS

3.1 Site Geology

The site is located on a low lying peninsula orientated north to south, which protrudes into Darwin Harbour. The coastline of the peninsula is fringed by tidal mud flats and mangroves. Immediately adjacent to the shore the mangrove area is sandy. Seaward from sandy mangrove areas, muddy mangrove areas

and intertidal channels dominate. Vegetation is generally dense woodland fringed by densely vegetated mangroves, approximately 4m tall.

3.2 Geotechnical Parameters

An extensive geotechnical field investigation has been carried out by Inpex in three (3) phases including Cone Penetrometer Testing (CPT), Standard Cone Penetration (SPT), Dynamic Cone Penetration (DCP), shear vane testing (SV) and geotechnical drilling supported by laboratory testing.

The subsurface ground profile has been found to comprise 2m to 6m of mangrove deposits, underlain by a 1m to 2m thick discontinuous lateritic horizon.

The intertidal soils comprise very soft clays with extremely low bearing capacity and present a high acid sulfate soil risk. Underlying lateritic horizons comprise gravels, sands which are loose to medium dense.

Parametric study of geotechnical parameters has been carried out on intertidal muds. The results of this assessment has been provided in Table 4.

Table 4. Soil Parameters adopted for Ichthys Site

Parameter\Site Location	MOF	Flare Pad
Moisture content Wn (%)	180	100-140
Liquid Limit WL (%)	75	100
Unit Weight γ (kN/m ³)	13	14
Vertical Permeability kv (m/s)	5x10 ⁻⁸	1.5x10 ⁻⁸
Compression Index C _{ce} (-)	0.330	0.329
Recompression Index C _{re} (-)	0.100	0.033
Creep Index C _{ae} (-)	0.018	0.011
Void Ratio e ₀ (-)	4.0	3.5
Undrained Shear Strength Su (kPa)	7 to 10	5 to 12
Layer thickness h (m)	2.5	2 to 5.5

4 GROUND IMPROVEMENT DESIGN

4.1 Settlement Analysis

Settlement analysis for SC/DR ground improvement was performed using two-dimensional axis-symmetrical finite element method (FEM) using PLAXIS v10. FEM was used to study short and long term settlement of improved mud/intertidal deposits beneath proposed embankment pad. The aim of the design was to estimate the required stone replacement ratio “a” to limit total settlements within performance specification limits.

The principle of axis-symmetrical FEM models centred on a column/pillar is to consider a given grid of pillars with a uniform load. Study of just one pillar/column and thanks to the rotation symmetry, the problem is equivalent to a 2D model.

In time dependent analysis we have accounted for 460days of lag time between end of ground improvement and handover to operation. This has significantly contributed in meeting the tight performance criteria. DR diameter of 2.5m at grid 5m x 5m was adopted found sufficient.

It has been estimated that settlement during construction works will yield 200mm to 450mm. A contour map was plotted to indicate where additional topping up of fill will be required prior to handover date. Long term settlement was estimated between 30mm and 45mm, hence within project specification limits.

4.2 Slope Stability Analysis

Slope stability calculations, were carried out using Slope W software and using a Morgenstern-Price limit-equilibrium method. For DR treated soil layers an equivalent parameters method (et al Barksdale and Bachus, 1983) was adopted. The equivalent parameters of the “composite” material were estimated using the following relationships:

$$\tan\phi_{eq} = (1-m) \times \tan\phi_{soil} + m \times \tan\phi_{DR} \quad (1)$$

$$C_{eq} = (1-a) \times C_{soil} + a \times C_{DR} \quad (2)$$

Where: c_{eq} = composite cohesion, ϕ_{eq} = composite internal friction, a = the ratio between the DR and the overall treated soil, m = load transfer ratio defined as the fraction of stress supported by DR pillar over the total stress applied to the reinforced soil, C_{DR} = cohesion of DR pillar (typical taken as 0kPa), C_{SOIL} = cohesion of soil between DR pillar, ϕ_{DR} = internal friction of DR pillar, ϕ_{SOIL} = internal friction of soil between DR pillar (for undrained conditions typical value is 0 degrees).

Based on the FEM axi-symmetrical analysis a value of $m = 50\%$ was derived and adopted in the slope stability assessment. The load transfer ratio coefficient “ m ” was reduced to $m = a$, under outward 2/3 of the embankment slope length to take into account reduced effective overburden pressure and lack of confinement pressure from adjacent pillars.

Based on stability assessment a 10m long stability berm was designed along the periphery of the platform to meet required FoS. The lowest factors of safety were calculated for short term (undrained) conditions for rapid drawdown cases and earthquake conditions for highest astronomical tide scenarios.

5 CONSTRUCTION WORKS

5.1 Working Platform Construction

Working platform for DR works and followed on construction works was designed using FEM method as CIRA 123 recommendations for tracked platform did not apply for very soft subbase (Su less than 15kPa). A minimum working platform thickness of 1.6m was found to be satisfactory to support construction plant.

No geotextile layers were used to reinforce platform but a separation layer of Bidim A64 only. Indeed, the use of high strength geotextile would reduce required platform thickness, however would also create a barrier detrimental to the installation of DR pillars or stone columns. Instead, a cleared mangrove roots were used to create a root mattress beneath the working platform to enhance platform stability. The long term effects of roots decay were studied however due to sufficient bridging layer on top of the DR pillars impact was negligible.

Construction of the 10m long peripheral stability berm has provided a barrier preventing an outward movement of mud during placement of second platform lift and confinement to DR installation. The function of the 10m leading berm was to counterbalance soft mud waving and to prevent exposure of ASS/PASS soils.

5.2 Tidal influence

The Blydin point is exposed to extreme tidal sea level variations. The level difference between highest and lowest astronomical tide is 8m (HAT +3.995m and LAT -4.105m, which poses significant construction difficulties and impact on long term movement performance.

During construction platform was required to allow construction activities in all tide ranges. To safely support construction plant the platform was elevated 0.5m above HAT level. For DR penetration, platform was required 1.0m above water level. Elevating platform by

additional 0.5m would significantly increase the platform cost, reduce DR pillars driveability and significantly increase required energy. The maximum platform thickness of 2.0m and 0.5m above HAT was adopted into design accounting for the fact that during HAT tide DR works would be suspended. In the areas where platform was in excess of 2.0m, pre-excavation to top of original surface level was introduced to allow pillar construction to required depth.

5.3 Environmental Consideration

During the DR works in-situ material is displaced laterally while pillar is formed. In the pad centre the soil will move to least resistance point, hence towards the ground surface, which in return generates platform heaving.

Heave and Penetration Tests (HPT) have been carried out to assess amount of heave generated. After initial compaction of the platform, the volume of heave increased fairly linearly and corresponded to approximately 60-70% of the incorporated material bulk volume. Graph showing the measured heave volume vs material volume is presented in Fig. 5.

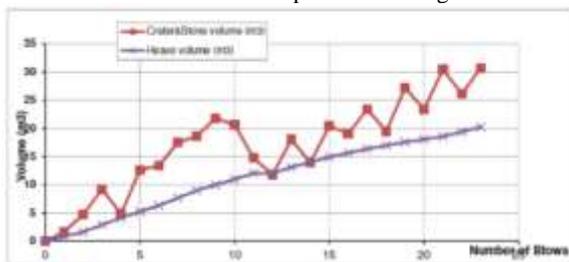


Figure 3. Heave and Penetration (HPT) test results

The HPT information has allowed to estimate required volume of rock to form DR pillar before excessive heave could be created. Monitoring of DR pillars formation was required to avoid uneven heave generation and in return an increased risk of resurgence and therefore exposure of ASS/PASS soils.

6 TESTING AND MONITORING RESULTS

6.1 Testing Production Works

An extensive verification regime was adopted to confirm that the executed DR works will perform as per design expectations. Down the Hole drilling was used to confirm column/pillar diameter and achieved depth. Pressuremeter testing was used to verify young modulus stiffness and DR depth. Plate load test on completed columns was used to verify top 1.5m stiffness. In addition, general heave monitoring and stone consumption during the works was recorded. The frequency of testing was 1 test per 20 000m² of completed area.

Testing results confirmed that DR pillars were installed to competent layer, achieved minimum diameter of 2.5m with an average across the site of 2.7m. Pillar stiffness was relatively consistent along pillar depth with Young modulus tested between 35MPa and 50MPa.

6.2 Post Construction Works Monitoring

The monitoring was required to confirm that design assumptions were met and that actual ground movements were within the levels predicted in during the design phase.

Monitoring consists of platform settlement and lateral movement monitoring during the ground improvement works and post construction to the end of the Performance Guarantee (PG) period.

Instrumentation used during monitoring period included installation and monitoring of Inclometers (IN), Settlement

Markers (SM); Settlement Plates (SP); Hydrostatic Profile Gauges (HPG) and Vibrating Wire Piezometers (VWP).

During the works the monitoring was limited to verification of stone consumption due to high risk of instruments damage. The stone volume consumption would be used to indicate presence of adverse ground conditions if exceeded by 60% of theoretical quantities of stone or depth on any one column,

In regards to long term performance, a three years post construction monitoring program and trigger levels were determined in order to monitor settlement and to demonstrate that settlement predictions and structure performance will continue to be met throughout the design life. Trigger levels were set as 30%, 40% and 50% of total settlement at 1, 2 and 3years post construction, respectively.

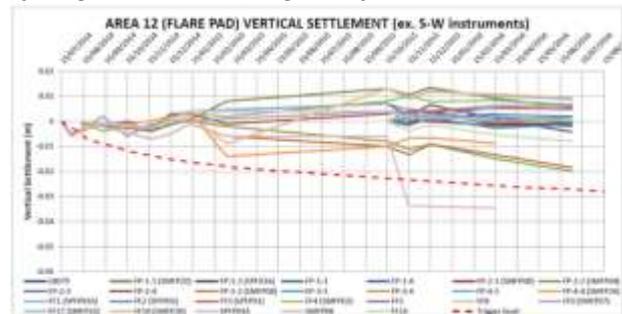


Figure 4. Results of long term monitoring at Flare Pad Area

The results from 2 years of monitoring (see Figure 5) show that actual settlement (and other instruments) is well within design predicted limits and indicate that settlement criteria at 28years of design life will be met.

7 CONCLUSIONS

Dynamic replacement works has been successfully completed with a treatment of approximately 350 000m² of mangrove mud areas. During the DR works 330 000m³ of stone material have been used to form pillars and 340 000 blows performed to install pillars to competent substratum. The maximum depth of pillar was 7.8m which is the deepest recorded by Menard in Australia. The Ichthys LNG project is believed to be the second largest DR project undertaken in Australia to date.

The DR method of ground improvement created environmental and economic benefits because the excavation and replacement of ASS/PASS materials were avoided and in-situ disturbance minimized. Amongst other ground improvement techniques considered at the time (Deep Soil Mixing, Rigid inclusions), DR methodology is by far the fastest to implement, further the absence of requirement to use cementitious imported materials means that it is also the least generative of CO₂ emissions.

The monitoring results two years following completion of the DR works have demonstrated the efficiency of the proposed concept and high quality of implementation achieved on site.

8 REFERENCES

- Barksdale R.D., and Bachus R.C. (1983). Design and construction of stone columns. Federal Highway Administration Office of Engineering and Highway Operations, Volume I and II, Washington, DC.
- Nyland G.W. and Gerner P.R. 1984. Engineering geology and foundation conditions in Darwin.
- Priebe H. 1995. The Design of vibro replacement.
- Wong P.K. and Lacazadiu M. 2004. Dynamic Replacement Ground Improvement – Field Performance versus Design Predictions for the Alexandria City Centre Project in Egypt.
- Wong P.K. 2004. Ground improvement case studies – chemical lime piles and dynamic replacement.