MARINE AND LAND BASED COMPACTION WORKS AT THE PORT BOTANY PROJECT, SYDNEY

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Abstract: The paper presents two different compaction techniques used on the Port Botany Expansion Project in Sydney- Australia: Deep Dynamic Compaction and Vibroflotation. The Expansion Project relied on the reclamation of 63 hectares of land within the Botany Bay to create a new container terminal and required geotechnical works to densify the reclaimed fine sandy materials as well as bands of in situ geotechnical units rich in fines and clayey particles. Whilst treatment of homogeneous geotechnical profiles has received great attention the implication for both Dynamic Compaction and Vibroflotation of geotechnical variability has been seldom studied and requires further analysis. The execution of hundreds of geotechnical testing pre and post treatment on the Port Botany site will provide an opportunity to assess the relevance of historical approaches in the dimensioning of such soil improvement techniques.

Keywords: Dynamic compaction; vibroflotation; energy transfer; seismic wave; cone penetrometer test; relative density; dredging; reclaimed land.

1. INTRODUCTION

In 2007 Sydney Port Corporation has selected the joint-venture formed by Bauldstone and Jan de Nul to undertake the design and construction of the Port Botany Expansion Project.

Austress Menard (Menard) was awarded the “Deep Compaction Works” subcontract for this new container terminal at Port Botany in Sydney. The works include traditional Menard Deep Dynamic Compaction technique and marine and land Vibroflotation, for which technical and logistic assistance are provided by Menard’s
cousin and specialist company The Vibroflotation Group. These geotechnical works involve several phases of compaction to be carried out over a period of 2 years for the overall 63 ha of reclaimed platform:

— Early works: the first sand reclamation of the project was carried out at the back of the container yard, along the existing container terminal and nearby the existing shore line, in order to set-up the facilities for the quay wall precast construction. These included a precast yard for fabrication and storage of the heavy concrete segments (600t), a haulage road on top of the east berm and a temporary wharf to load out the precast elements to a mega-barge. Being incorporated at the end into the permanent works these areas had to be compacted to the final criteria, using either dynamic compaction or vibroflotation.

— “Trench” compaction works: the precast quay elements will be founded at PD-17.5 m on reclaimed sand fill and gravel mattress replacing the unsuitable in-situ clayey materials. Along the 1800 m quay, the existing sea-bed is trenched-out to a depth of up to PD-30 m and then backfilled with clean sand from Botany Bay. The vibroflotation of the 800,000 m³ of sand is to be carried out offshore; it is proposed to use the powerful V48 vibrating-probe handled by a 150 t crane mounted on a barge.

— After seating the quay wall, the yard will be backfilled at its rear with hydraulic sand fill. A 35 m strip, immediately at the back of the quay counterfort wall, is designed to be improved to full depth by 20 m deep vibroflotation. This is to be carried out by a tandem of V48 probes suspended to a 150 t land-based crane.

— The remaining part of the container yard, approximately 450,000 m², is to be improved by means of high energy dynamic compaction down to depths of 13 meters.

Figure 1 below presents the various areas of compaction.

Trial tests commenced on site in October 2008 for the dynamic compaction works and in January 2009 for the vibroflotation works. The early set-up of these facilities was required for the preparation of a pre-cast yard for the future concrete counterfort elements. The first counterforts are due to be launched in March 2009.

Production operations are expected to extend over a 24 months period to accommodate the fast tracked construction programme of the overall project.

The present paper details the technical challenges encountered during the set up of the various equipments and the establishment of optimal parameters for the different compaction methods carried out across the site. A particular attention is given to the assessment of the characteristics of the fill material placed on site and its response to the trialed compaction methods with the analysis of an extensive array of laboratory and site testing.
2. SUBSOIL INVESTIGATION AND SITE CONDITIONS

2.1. CPT tests

Where carried out, the Pre CPT campaign confirms the expected geology of the site highlighting the presence beneath the reclaimed sand of various soil units as presented in Fig. 1 below.

Several clayey marine deposits were encountered on the early package of the works at the original seabed elevation as well as at the seabed elevation that followed.

Figure 1. Site Plan View.

Figure 2. Geotechnical cross section.
the reclamation works in the 70’s on the existing Brotherson Dock North. Within these clayey marine deposits CPT friction ratios of up to 4–5% were recorded and induced a number of difficulties in the implementation of the different proposed soil improvement techniques.

3. SOIL IMPROVEMENT WORKS

As a result of its design work, the Engineer provided a series of target specifications formulated as CPT Qc depth profiles to be achieved by the Contractor. In order to meet the settlement and stability design criteria, the equivalent cone resistances required versus depth were derived from target minimum relative density ($D_r$) and friction angle ($\phi$) based on the assumption of clean sand.

3.1. Dynamic Compaction

MENARD dynamic consolidation is a technique optimised by MENARD for compacting soils to great depths. The basic principle consists in the transmission of high energy impacts to the surface of the ground which is initially loose and with low bearing capacity and drastically improve its characteristics.

Depending on the nature of the soil (saturated or unsaturated), Menard dynamic consolidation has an immediate or a long term effect. On an unsaturated ground, the compaction involves a quick decrease of void ratio of the soil and the instantaneous settlement of the ground under the impact. In the case of saturated soils, the increase of pore water pressure can lead to a local liquefaction of the ground. It is thus necessary to wait for the pore pressure dissipation allowing the rearrangement of soil particles.

3.2. Vibroflotation

Vibro Compaction is a deep compaction technique for densifying sandy soils in place by means of an electric vibrating unit. Under the influence of simultaneous vibration and saturation, loose sand particles are repacked into a more compact state, and lateral confining pressure within the sand mass is increased.

The vibrator consists of a hollow cylindrical body with 300–400 mm diameter connected by means of a special elastic coupling to the follow-up tubes of a slightly
smaller outside diameter. Eccentric weights in the lower part of the Vibroprobe are driven by an electric motor operating in a horizontal plane. Horizontal centrifugal force is thus generated, creating horizontal amplitudes at the tip of an unconstrained Vibrator. The total length of the probe is adjustable by the addition/removal of sections of follow-up tubes. With the V48 vibroflot, vibroflostation takes place in the ground in intervals of approximately 1.00 m raising the probe stepwise.

The Vibro-compaction technique is most suitable for medium to coarse grained sand with less than 10% material finer than 75µm (ASTM sieve #200) and clay content (particle size less than 0.002 mm) of less than 2%. Cohesive soils consisting of silt and clay material do not respond to vibratory compaction.

3.3. Densification Effect and Formulation

3.3.1. Densification effects

The sand and gravel particles rearrange into a denser state leading to a reduction of the void ratio; this reduction can be characterised by the change in relative density and the enforced settlement of the soil mass: they range from 5 to 15%. As a direct consequence the bearing capacity is increased and the stiffness modulus can be improved 2 to 4 fold.

3.3.2. Correlation between relative density and q_C

Relative density is defined as follow: 
\[ D_R = \frac{(e_{max} - e_0)}{(e_{max} - e_{min})} \]

with \( e_{max} \), \( e_{min} \) and \( e_0 \) the maximum, minimum and in-situ void ratios. In order to link the relative density and the CPT cone resistance, Jamiolkowski 1985 correlation can be taken into account:

\[ D_R = -98 + 66 \log(q_C/\sigma_v^{0.5}) \]  

with \( D_R \) in % and \( q_C \): tip resistance in t/m² and \( \sigma_v^{0.5} \): effective vertical stress in t/m².
3.3.3. Energy requirements for given improvement in $D_R$

Usual vibroflotation and dynamic compaction energy requirements are in the order of 15tm/m$^3$ ($\approx 150$ kJ/m$^3$) to 30tm/m$^3$ ($\approx 300$ kJ/m$^3$) to reach 5% to 10% enforced settlement.

3.4. Energy Transfer Mechanism

The reorganization of the granular soil skeleton required to obtain the target improvement occurs through the liquefaction and displacement of soil grains within the material to be improved. Liquefaction is triggered by an increase in ground pore water pressure generated through cyclical solicitation of the ground by transfer of stress waves. The following sections provide a brief description of the propagation of the imparted energy within the ground and its dissipation.

3.4.1. Geometric Energy Dissipation

Energy conservation leads to the estimation of the amplitude particle velocity decay. For waves generated by a point source the particle velocity amplitude decreases with the inverse of the radius to the source point.

$$E_2 = E_1 \iff I_2 S_2 = I_1 S_1 \iff I_2 4\pi r_2^2 = I_1 4\pi r_1^2 \iff I_2 = I_1 \left(\frac{r_1}{r_2}\right)^2$$

And

$$\rho w^2 u_2^2/2 = (r_1/r_2)^2 \rho w^2 u_1^2/2 \iff (u_2 = (r_1/r_2) u_1) \quad (1)$$

Where $E$ is the total energy applied on the surface $S$ and $I$ the energy flow at a given radius to the source point.

3.4.2. Intrinsic Energy Dissipation

As impact waves travel through the ground they cause small distortions or strains of the mineral grains. Since the ground is not perfectly elastic, some energy is lost due to frictional and viscous dissipation mechanism. Field investigations indicate that such energy dissipation due to absorption or intrinsic absorption is given by:

$$A_2 = A_1 e^{-\alpha (r-r_1)} \quad (2)$$

Where $A_1$ is the amplitude of vibration at distance $r_1$ from the source, $A_2$ is the amplitude of vibration at distance $r$, and $\alpha$ the absorption coefficient a function of the type of material subject to the impact waves.

Finally after consideration of the geometrical spreading and energy absorption:

$$A_2 = A_1 (r_1/r_2)^{\mu_2} e^{-\alpha (r-r_1)} \quad (3)$$
3.4.3. Energy transfer at material interface (Reflection and Refraction)

Wave reflection is the return of all or part of a wave beam when it encounters a change in media, the angle of incidence and reflection are equal.

Refraction is the transfer of a wave between two different media, direction of the refracted rays are given by the Snell’s law:

\[
\sin \theta_1 / v_1 = \sin \theta_2 / v_2
\]

(4)

With \( v_1 \) and \( v_2 \) the wave velocity in media 1 and 2 respectively.

3.4.4. Reflection and Transmission Coefficient

The Reflection coefficient \( R \) is the ratio of reflected to incident wave amplitude and is related to the materials acoustic impedance and angle of wave beam incidence as follows:

\[
R = \frac{\left( \frac{Z_2}{Z_1} \right) - \sqrt{1 - \left( \frac{\rho_2}{\rho_1} \right)^2 \tan(\theta_1)^2}}{\left( \frac{Z_2}{Z_1} \right) + \sqrt{1 - \left( \frac{\rho_2}{\rho_1} \right)^2 \tan(\theta_1)^2}}
\]

(5)

With:

- \( Z_1 \) and \( Z_2 \) the impedances in Rayles of the involved media and \( Z = \rho v \),
- \( \rho_1 \) and \( \rho_2 \) the respective material densities in N.m\(^{-3}\),
- \( v_1 \) and \( v_2 \) the respective wave velocities in m.s\(^{-1}\),
- \( \theta_1 \) the angle of incidence.

Finally, the transmission coefficient \( T \) is the ratio of refracted to incident wave amplitude. Conservation of energy at the interface induces:

\[
T = \sqrt{R^2 - 1}
\]

(6)
3.5. Modelisation and Prediction

The above equations were used to assess the effect of a 1 meter thick clay layer at various elevations within the treated in situ and dredged sand. For the purpose of these calculations, assumptions were made based on available information in regards to various damping coefficients, wave propagation velocity and impedance. The following chart presents several curves of energy flow reduction ($\Delta(z,r)$) calculated as per Eq. (7):

$$\Delta(z,r) = \frac{I_b(z,r) - I_o(z,r)}{I_o(z,r)}$$  \hspace{1cm} (7)

With: $I_o(z,r)$ the unimpeded energy flow at depth $z$, distance $r$ from pounder axis, $I_b(z,r)$ the energy flow with presence of a 1 m thick clay layer at elevation $h$.

3.6. Influence of Clay layers on dynamic compaction

Geometrical effects linked to wave reflection and refraction at the interface between sand and clay layers indicate that some energy is unable to penetrate the deeper layers. It is estimated that between 15% and 50% of the body wave energy may be lost due to this effect. In addition and for a given depth, the “reflection” effect is increasingly important as the distance from the pounder axis increases (increasing the angle of wave beam incidence) which may lead to the reduction of print spacing in order to achieve equivalent improvement. Other effects in clayey material such as the increased damping coefficient and the reduced decrease in pore water pressure dissipation also play important roles in further decreasing the dynamic compaction effects.

Figure 7 hereafter shows typical results achieved during the early works Dynamic Compaction (results showed prior to Ironing of 2.5 m top layer).
It can be noted that a clayey layer of variable thickness (0.3 to 1m typically) is found between depth of 7 m and 8.5 m; this is believed to be the location of the sea bed before reclamation. The improvement in this clayey layer by means of DC is measurable (from 1MPa to approximately 2 MPa) albeit limited compared to the improvement obtained in sand layers.

Improvement above the clay layer is generally very good with increase of Qc values by a factor of 2 to 3 (final Qc values of 10 to 20 MPa) whilst improvement underneath the clay layer (unit 1) is clearly lower with increase in Qc values by a factor of approximately 2 (average Qc ranging from 7 to 10 MPa).

4. CONCLUSION

Dynamic compaction and vibroflotation are well suited techniques to improve the reclaimed sand at Port Botany. Post CPT results have shown that satisfactory densification was achieved in the Early Works. However, the damping effect of some clay layers at the original sea bed made it necessary to compensate for the slightly reduced efficiency in the underlying clean sand layers by an overcompaction of the upper part of the profile.
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