
Conception et construction d’un remblai de dépôts avec une enceinte sur des colonnes ballastées installées dans un sol marin très mou à Cotai, Macao

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ABSTRACT: The Cotai Landfill is the main receiving facility in Macau for building construction waste. As the dumping site is underlain with a thick layer of very soft to soft marine clay deposits, the uncontrolled end-tipped material has generated mud waves and they were encroaching the piles supporting the Macau International Airport taxiway nearby. In order to prevent future potential damage to the taxiway, the Macau Government engaged AECOM Asia Co. Ltd.(AACL), to design a containment bund adjacent to the taxiway to retain the waste and to prevent further generation of mudwaves that would affect the taxiway. The sustainable design prepared by AACL comprised the installation of vibrocompacted stone columns installed in over 20 m thick, very soft to firm, moderately sensitive marine clay and alluvial clay, as the foundation to the waste retention bund, thereby avoiding the dredging and off-site disposal of a significant volume of dredged sediments. This paper presents the design approach and construction of the stone columns and the behaviour of the completed seawall.

KEYWORDS : Soft Clay, Ground Treatment, Stone Column, Mudwaves, Seawall.

1 INTRODUCTION

In 2000s, Macau experiencing a major construction boom, the site formation and building works for major casinos, roads and infrastructure on reclaimed land as well as demolition of existing structures generated a large volume of construction waste. It comprised predominantly of spoil materials from basements excavations and piling works.

Cotai Landfill is the main receiving facility in Macau for building construction waste materials. Due to the rapid development activities in late 2000s, the landfill material is being generated at a much faster rate than initially anticipated. In 2008, it was observed that dumping of the construction waste have spread out as well as caused the underlying soft marine mud to displace in the form of mudwaves towards the Macau International Airport (MIA) Southern Taxiway Bridge (STB) and the cooling water intake at the Coloane power plant located in the vicinity of the Landfill (Figure 1).

Figure 1. View of the Landfill Site and Mudwaves

This paper present the work for the initial phase of the protection measures against the mudwaves along the STB of MIA. The purpose of the proposed works is to achieve the following objectives:

a) prevent the propagating of mudwaves toward the MIA to protect the STB;

b) maintain the operation of the landfill site as well as maximise the capacity of the landfill site, and;

c) to facilitate the future development of the MIA extension project.

Figure 2. Site Layout Plan
2 SITE GEOLOGY

The superficial deposits within the study area comprise marine deposit (MD) of the Holocene age overlying a layer of alluvium of the Pleistocene age. Underlying the alluvium is the saprolitic soil consisting of completely decomposed granite (CDG). The solid geology comprises coarse-grained granite of Jurassic-Cretaceous age. Fill material has been subsequently placed over the marine soft clay deposit by the landfilling activities. Figure 3 shows the typical geological section of the site. Table 1 shows the typical thickness and constituency of the strata.

Table 1. Summary of Geological Strata

<table>
<thead>
<tr>
<th>Strata</th>
<th>Thickness (m)</th>
<th>Constituent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>4 to 7</td>
<td>C&amp;D waste comprised disturbed mud, silty clayey, sand, concrete, bricks, wood, steel</td>
</tr>
<tr>
<td>Marine Mud</td>
<td>13 to 28</td>
<td>Very soft to soft, dark grey, clay to silty clay with occasional shell fragments.</td>
</tr>
<tr>
<td>Alluvium</td>
<td>0 to 58 average 30</td>
<td>Soft to stiff, mottled yellowish brown light grey to brown, silty CLAY, CLAY/SILT</td>
</tr>
<tr>
<td>CDG</td>
<td>0 to 10</td>
<td>Sandy silty to silty fine to coarse SAND</td>
</tr>
<tr>
<td>Bedrock</td>
<td>-</td>
<td>Moderately strong to strong, moderately to slightly decomposed granite.</td>
</tr>
</tbody>
</table>

Figure 3. Typical Geological Section

3 DESIGN OF THE SEAWALL

The purpose of the seawall is to contain the dumped surficial deposit (MD) of the Holocene age overlying a layer of alluvium of the Holocene age. Underlying the alluvium is the saprolitic soil consisting of completely decomposed granite (CDG). The solid geology comprises coarse-grained granite of Jurassic-Cretaceous age. Fill material has been subsequently placed over the marine soft clay deposit by the landfilling activities. Figure 3 shows the typical geological section of the site. Table 1 shows the typical thickness and constituency of the strata.

3.1 Principle of Ground Improvement by Stone Column

Stone column construction involves the partial replacement of the very soft subsurface soils with compacted, vertical columns of stone that completely penetrates the weak strata. The stronger and stiffer material will attract more stresses (i.e. the stone columns) and therefore the composite ground comprising stone columns and soft clay (Barksdale, R.D. & Bachus R.C. 1983) will be stronger and stiffer and capable of carrying a larger load originating from the landfill behind, preventing the formation of mudwaves. The stone columns will also act as vertical drains within the soft clay facilitating the rapid dissipation of the excess pore pressures allowing it to quickly consolidate and gain in strength, thus further increasing the stiffness of the composite soil mass over time.

The strength of the composite ground depends on the percentage of soil replaced by the stone columns, i.e. the replacement ratio, $a_s$, as defined by (1) and illustrated in Figure 4.

$$ a_s = C_1 \left( \frac{D}{s} \right)^{2} $$

$D$ - Diameter of the compacted stone column  
$s$ - Centre to centre spacing of stone columns  
$C_1$ - Constant depending on stone column configuration pattern

Figure 4. Replacement Ratio of Stone Columns

For this project, a 1.2 m diameter stone column at 2.5 m c/c spacing in a triangular pattern was adopted. The replacement ratio $a_s$ is about 21%. Since the stone aggregate columns are much stiffer than the soft clay, the stresses will concentrate at the stone columns. The distribution of the stresses can be expressed by the stress concentrated factor $n$, defined as:

$$ n = \frac{\sigma_s}{\sigma_c} $$

$\sigma_s$ = stress in the stone column  
$\sigma_c$ = stress in the surrounding cohesive soil

The stresses over the soft soil and the stone column in terms of $a_s$ from (1) and the average overall stress on the ground surface, $\sigma$, is illustrated in a unit cell concept in Figure 5.

Figure 5. Ideal Unit Cell of Stone Column

$$ \sigma_{st} = n \sigma / (1 + (n-1) a_s \mu_s \sigma) $$  
$$ \sigma_{sc} = \sigma / (1 + (n-1) a_s \mu_s \sigma) $$

$\mu_s$ = Ratio of stress in stone in relation to $\sigma$  
$\mu_c$ = Ratio of stress in cohesive soil in relation to $\sigma$

Using the expression of $\mu_s$ in (3), the stone column foundation can be modeled as a composite material with the average shear resistance expressed as:

$$ \bar{\sigma}_{st} $$
The stability analyses of the stone column seawall were carried out using the computer software “Slope/W” with automatic circular failure mode and sliding block failure modes. The stone column foundation was modelled as a composite material with the embankment of landfill in place behind the seawall (Figure 6). With $\alpha_s$ of about 21%, the average cohesion of the composite material immediately after placing the stone columns will range from 2.8 kPa to 12.7 kPa; and the average friction angle of the composite material is 20.4°.

The stone columns will also act as vertical drains to provide drainage path for the excess pore water pressures arising from the vertical load of the embankment. With a typical 15 m thick marine deposit and an equivalent rectangle embankment width of about 30 m, the average increase in the effective stress of marine deposit and an equivalent rectangle embankment width the vertical load of the embankment. With a typical 15 m thick drainage path for the excess pore water pressures arising from 2.8 kPa to 12.7 kPa; and the average friction angle of the material immediately after placing the stone columns will range as part of the landfilling operation.

3.3 Assessment of Impact on Taxiway Pile Foundation

Since the STB is a critical facility to the MIA any damage to the STB will significantly affect the operation of the MIA. In order to control the additional load imposed from landfill site to the STB, numerical modelling was carried out to assess the impact to the STB during installation of the stone columns, construction of the seawall and when filling behind the seawall as part of the landfilling operation.
3.5 Monitoring of Taxiway and Taxiway Piles

The movement of the taxiway pile foundation and the MIA seawall were closely monitored during the seawall construction phase. No significant movement of the taxiway, the piles and the seawall was measured. Monitoring will continue during the future landfilling operation stage when the loading is maximized in the landfill.

4 SUMMARY AND CONCLUSIONS

Construction waste was dumped over very soft marine mud at the Cotai Landfill of Macau. This uncontrolled dumping pushed the very soft mud and generating mudwaves that were then encroaching onto the piles supporting the taxiway bridges of the Macau International Airport.

Due to the seriousness of the problem, government of Macau commissioned AECOM Asia Co. Ltd., to develop a robust solution to contain the construction waste being dumped in the area and to protect the taxiway bridge of the Macau Airport. The design solution developed was to construct a containment bund/seawall that is founded on a stiffened and strengthened soil block by improving the soft clay with stone columns. This paper presented the design approach of the containment bund including the limited equilibrium stability analysis and the numerical analyses carried out that demonstrated that the solution is appropriate as the bund will contain the landfill with minimal impact on the taxiway bridge piles. The analyses also demonstrated that the impacts during construction are also negligible.

During construction, the taxiway and seawall was monitored by independent parties and survey results indicate the installation of the stone columns and construction of the bund had minimal impact on the taxiways foundation piles. The seawall has been completed in November 2011 (Figure 13).

5 ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of Gabinete para o Desenvolvimento de Infra-estruturas of the Macau SAR Government.

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