Design and Construction of a Landfill Containment Bund cum Seawall Supported on Stone Columns Installed in Very Soft Marine Mud in Cotai, Macau

Conception et construction d'un remblai de depôts 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.

RÉSUMÉ : La décharge de Cotai est la principale installation de réception de déchets de chantiers de construction à Macao. Comme le site d'immersion repose sur une épaisse couche de dépôts d'argile marine très molle à molle, les matériaux en vrac ont généré des écoulements de boue et ils interpénétraient les pieux soutenant les voies de circulation de l'aéroport international de Macao. Afin d'éviter des dommages potentiels futurs à la voie de circulation, le gouvernement de Macao a engagé AECOM Asie Co. Ltd.(AACL), pour concevoir une enceinte de confinement adjacente à la voie de circulation pour retenir les déchets et prévenir une nouvelle génération de coulée de boue qui aurait une incidence sur la voie de circulation. La conception durable établie par AACL comprend l'installation de colonnes ballastées installées dans des couches de plus de 20 m d'épaisseur, constituées d'argiles marines de consistance très molles à ferme, moyennement sensibles et d'argile alluviale, comme la fondation de l'enceinte de rétention des déchets. Ceci permet d'éviter le dragage et l'élimination hors du site d'un volume significatif de sédiments dragués. Cet article présente l'approche de conception et la construction des colonnes ballastées ainsi que le comportement de l'enceinte terminée.

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.

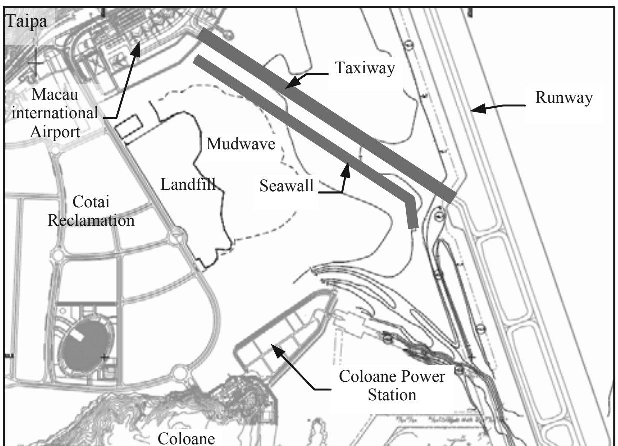


Figure 2. Site Layout Plan

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 constituentcy of the strata.

Table 1. Summary of Geological Strata

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

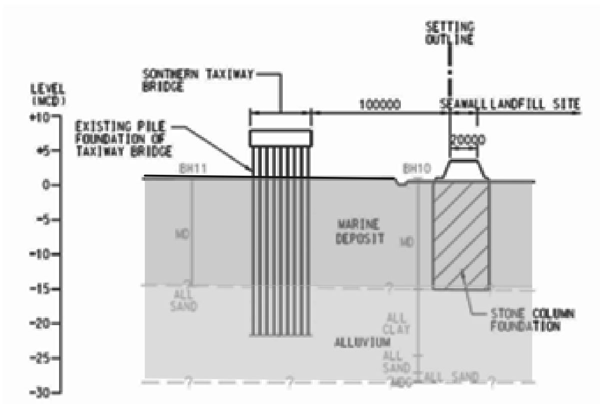


Figure 3. Typical Geological Section

3 DESIGN OF THE SEAWALL

The purpose of the seawall is to contain the dumped surfical clayey and other materials from spreading towards the STB, to prevent the further generation of the mudwaves that would impact the STB and to provide a stable and secure edge to the landfill. Since the founding material of the seawall is very soft to soft marine clay, ground treatment, by means of stone columns, are required to strength the foundation of the seawall in order to ensure the stability. It also improved the shear strength and stiffness of the soil mass to minimise the influence of the lateral load induced by the landfill soil mass that could possibly cause disturbance to the STB.

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.

$$a_s = C_1\left(\frac{D}{s}\right)^2 \qquad (1)$$

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

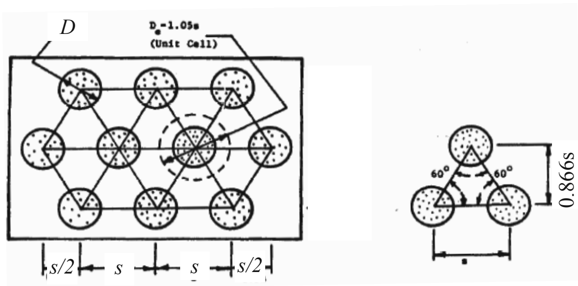


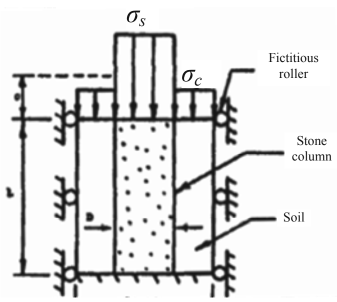
Figure 4. Replacement Ratio of Stone Columns

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:

$$n = \frac{\sigma_s}{\sigma_c} \qquad (2)$$

σ_s= stress in the stone column
σ_c= stress in the surrounding cohesive soil

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



σ_s - Stress in stone
σ_c -Stress in clay

Figure 5. Ideal Unit Cell of Stone Column

$$\sigma_s = n\,\sigma / [1+(n-1)\,a_s] = \mu_s\,\sigma \qquad (3)$$

$$\sigma_c = \sigma / [1+(n-1)\,a_s] = \mu_c\,\sigma \qquad (4)$$

μ_s =Ratio of stress in stone in relation to σ
μ_c= Ratio of stress in cohesive soil in relationto σ

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

$c_{avg} = (1 - a_s)\, c$ (5)

$\phi_{avg} = tan^{-1}\,(\mu_s a_s\, tan\phi_s)$ (6)

3.2 Stability Analysis

The stabilityanalyses 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 a_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°.

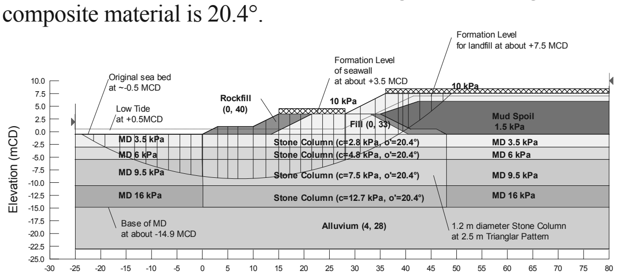


Figure 6. Geological Model for Slope Stability Analyses

To maintain the seawall stability, a 50m wide stone column treatment zonewas required. The seawall revetment and the landfill embankment slope profileswere proposed at a gradient of 1V:2H. A toe bund is provided as counterweight to stabilise the rockfill revetment. A typical section is shown in Figure 7.

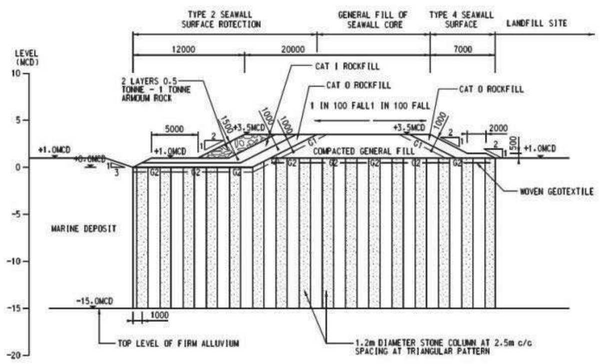


Figure 7. Typical Cross Section ofthe Seawall

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 Mud is only 25 kPa. Based on the radial consolidation theory and settlement reduction by the stone columns, 0.6 m settlement will occur within a year. Due to uncertainty in the drainage performance of the stone columns, the increase in the strength of the marine clay as a result of consolidation was not taken into account in stability analyses.

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.

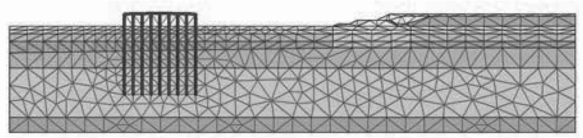


Figure 8. Finite Element Model

A Finite element model was developed (see Figure 9) using PLAXIS. The model adopted a geological profile with the deepest seabed level and thickest alluvium of the entire length of the seawall. The analyses were carried out with the marine clay behaving as an undrained material, which is considered to be an appropriate approach to model the actual behaviour of the soft clay. The structural elements included the beams and the PHC piles of the STBwere modelled as a continuous beam/wall element in the PLAXIS modelwith an influence zone of 3 times the diameter being adopted (LECM 2008b). The model simulates the full history of the site including the original ground conditions, formation of the STB, installation of the stone columns, formation of the seawall and landfilling operation behind it.

The results from numerical modeling show that the maximum additional bending moment due to stone column installation, seawall construction and landfilling activities is only 6 kNm near the top of the STB piles and the total load of the pile is still within the acceptable limit of the original design. The additional shear force is considered to be not significant. The maximum predicted movement of the nearest piles to the seawall is about 8 mm (Figure 9). This predicted lateral movement is likely to span across a few spans of the taxiway and the actual magnitude of relative movement between each span of taxiway structure is unlikely to be a concern asmovement joints have been provided between the taxiway spans and it should be capable of withstanding this relative movement.

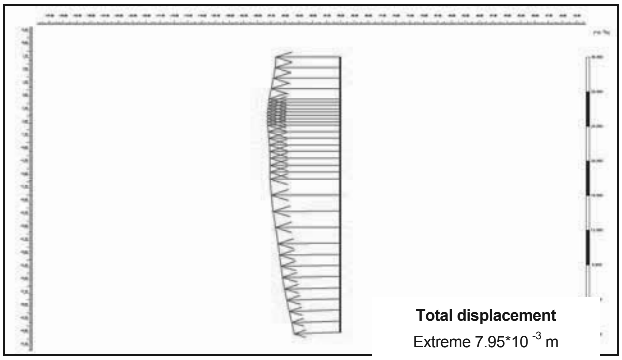


Figure 9. Predicted lateral Displacement of the Taxiway Foundation

3.4 Construction

Since the site is situated close to the MIA, there are certain physical constrains imposed by the Civil Aviation Authority of Macau on construction activities. The entire site is within the navigation restriction zone of the MIA (Figure 10). Marine access to the site is restricted and no mooring of vessels was allowed within the navigation restriction zone around the Airport. To avoid any disturbances on the movement of aircraft along the STB, all works were required to be carried out outside a zone of 57.5m from the centreline of the STB. Based on the information from the Civil Aviation Authority of Macau (AACM), the height restriction in the vicinity of the MIA along the runway is stringent and the use of high cranes was restricted. As a result, dredged seawall was adopted near the eastern end of the seawall.

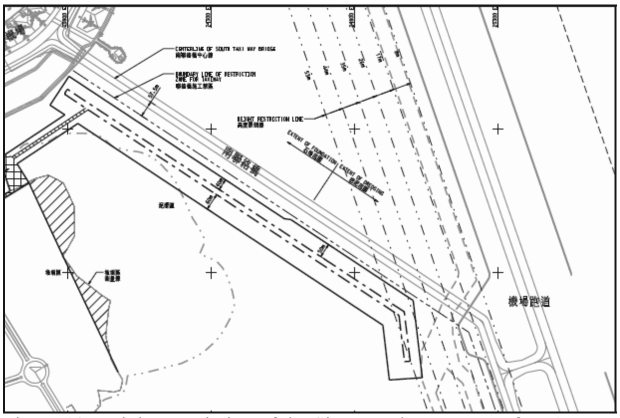


Figure 10. Height Restriction of the Site near the Runway of MIA

There was no readily available land access to the site as it is restricted by the landfill site and the MIA. Marine access was also limited due to the shallow draft and the contractor had to carry out additional dredging for navigation. The original design proposed a temporary platform for landbased stone column construction. During the construction stage, the contractor changed to marine based method for installation of the stone columns.

To ensure the mud will not be mixed with the stone aggregates due to collapse of hole or necking, wet bottom feed method was adopted (Figure 11). Acceptance of the stone column was based on the depth vsSC diameter plot, and degree of compaction (volume of aggregate, energy consumed)from the installation records. Site trial was carried out to determine the optimum arrangement on apparatus, setup, minimum required compaction time, amount of aggregate consumption per metre length, andmaximum energy consumption (Figure 12).

Figure 11. Stone Column Plant for Wet Bottom Feed installation

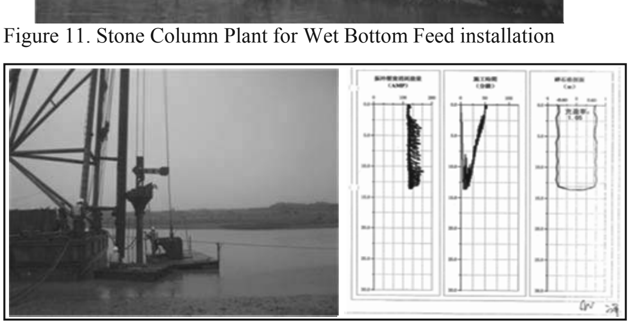


Figure 12. Site Trial Establishingthe Acceptance Criteria

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).

Figure 13. The Completed Stone Column Seawall

5 ACKNOWLEDGEMENTS

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