## Estimating Composite Properties of an SMC-improved Soil under Lateral Loading

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### ABSTRACT

Maximisation of coal retrieval at the Sebuku mine in South Kalimantan required construction of a retaining wall to retain 10m deep near surface swamp deposits (protected land) between the crest of the pit high wall and the immediately adjacent coastline. It was decided to construct a cantilevered pile wall along the crest of the high wall, which was to be partly supported on the pit side of the wall by a natural soil berm, reinforced by soil mixed columns (SMC's).

It was realised that calculating the properties of the composite material (SMC's plus natural soil) by the conventional area ratio method would not be appropriate where lateral loading was applied. PLAXIS analyses of horizontal sections reinforced by columns in two different configurations enabled equivalent strength and stiffness values of the composite material to be obtained. Young's modulus of the material was calculated from the deflection under a uniform boundary load while shear strength was calculated from interpretation of bearing capacity under a finite load. The results showed that unless the columns were in contact there was little increase in stiffness and none in strength. Values from the area ratio method for comparison were too high and unconservative.

### 1. INTRODUCTION

Sebuku coal mine is located on the island of Sebuku, off the south east coast of South Kalimantan. It is operated as multiple open pits by PT Bahari Cakrawala Sebuku owned by Sakari Resources Ltd. At the Tanah Putih pit the target base coal seam is about 150m below ground level, overlain by secondary seams and mudstone and sandstone interburden and overburden materials. The near surface ground conditions comprise about 10 m of soft alluvial soil ('mud') over about 2 m of stiff residual soils, then very low to low strength mudstone.

In order to extend the mining operations as far as possible toward the sea (without disturbing the shoreline swamp within a protected land zone) it was proposed to construct a contiguous pile retaining wall incorporating alternating vertical and battered piles along the crest of the high wall, prior to deepening the pit to 150m. A berm was to provide further support on the pit side of the wall (Figure 1). To increase the strength and stiffness of the mud in the berm, soil mixed columns (SMC) were installed in the berm. Figure 1 shows the proposed layout of the piled wall and SMC-improved berms.

This paper sets out a method to calculate the equivalent strength and stiffness properties of the SMC-improved mud in front of the piled wall using PLAXIS modelling. Because the berm is subjected to lateral loading, the conventional approach to equivalent values based on the area ratio of the SMC gives unconservative results. The values from the PLAXIS modelling are compared with those estimated using a conventional approach.

*Figure 1: Photographs showing the secant pile wall, berm, SMC columns and high wall*

## 2. BERM GEOMETRY

The originally proposed design of the SMC-improved berm comprises two distinct zones of improved ground. Figure 2 shows a plan view of a typical layout in front of the contiguous pile wall. The two zones are:

i) An "open configuration" comprising 0.7 m diameter vertical SMC columns placed on a diamond pattern at 1.5 m centre to centre spacing. This zone extends a distance of 21 m beyond the 5 m 'closed configuration' zone. The columns are not in contact.

ii) A "closed configuration" zone comprising the open configuration with an additional 0.7 m diameter SMC column located between adjacent SMC columns. Adjacent SMC columns are assumed to be touching one another. This configuration extends over a 5 m zone in front of the wall.

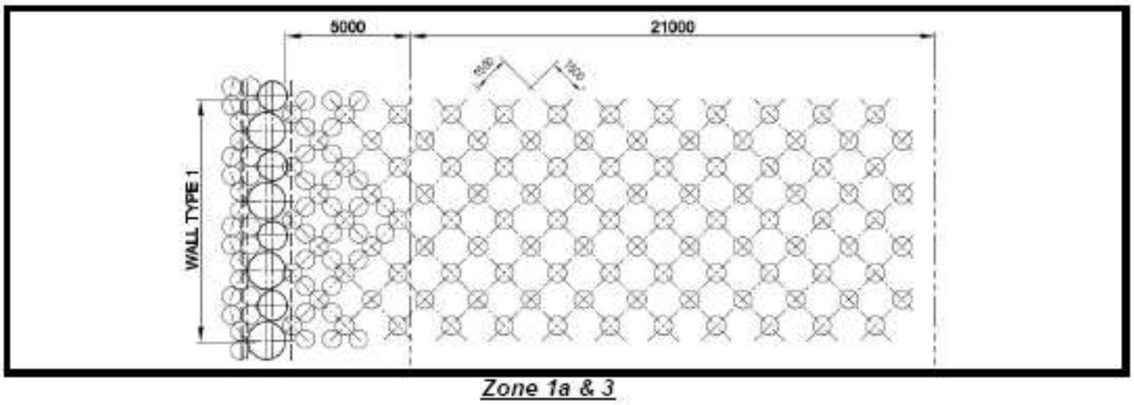



*Figure 2: Plan showing layout of pile wall, SMC's and soil berm*

## 3. ESTIMATING EQUIVALENT COMPOSITE PROPERTIES

### 3.1 Area-weighted method

The conventional approach to assess the "improved" ground properties is to use the area ratio method for estimating equivalent composite stiffness and strength properties for the areas improved with SMCs. This method is based on the weighted average of the properties of the mud and the SMCs based on the percentage of the area occupied by the columns.

This method for estimating equivalent composite properties of soil improved with SMCs was developed to estimate composite stiffness assuming axial loading of the SMCs (i.e. vertical loading). In the case of the application proposed here, where shear or lateral loading is applied, the method is not considered appropriate for estimating strength or deformation properties of the improved soil.

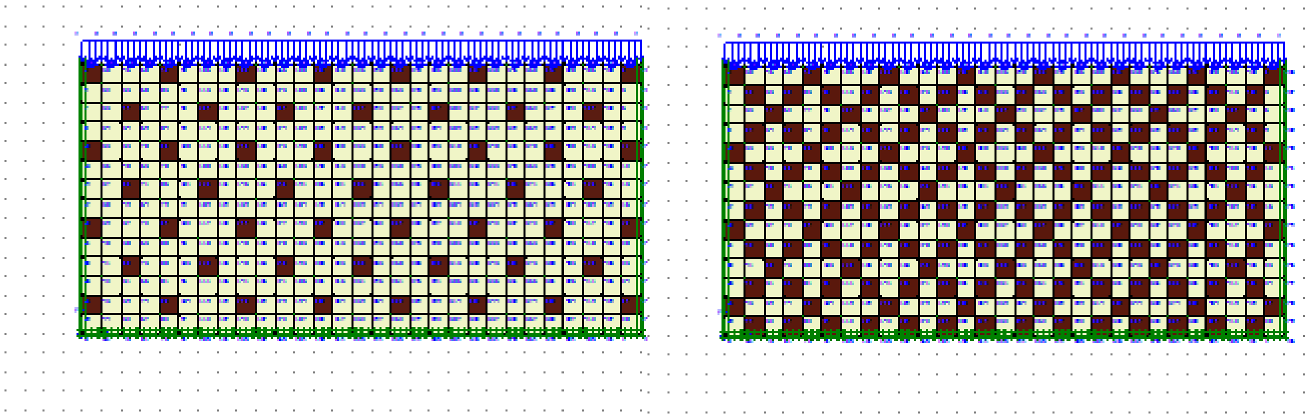
### 3.2 PLAXIS modelling approach

The performance of SMC-improved ground (and therefore the estimation of composite properties) subjected to lateral loading is complex and not amenable to simple hand calculations. PLAXIS modelling has been adopted as the primary analysis tool for this application. However, the PLAXIS analysis must be undertaken on horizontal (rather than vertical) cross-sections through the SMC-improved ground. Since the properties of the mud vary with depth, the modelling must be carried out at various depths, and the results combined to give a profile of properties versus depth.

#### 3.2.1 Mesh Geometry

Two models were used for the analyses: one for each of the 'closed' and 'open' configurations. These are shown in Figures 3 and 4, respectively, representing horizontal sections through the profile. The surcharge loading at the top of each of the figure represents the lateral load applied by the pile wall. In Figures 3 and 4, the SMCs are the shaded squares

It was not practical to adopt circular cross-sections for the SMC columns due to complications which arose during generation of the finite element mesh. Similarly, octagonal and hexagonal approximations of the circular SMC cross-section also proved to be impractical. As a result, the SMCs were modelled as square in cross-section with a side length of 0.75 m and located on a 1.5 m grid. This resulted in SMCs which have a slightly greater cross-sectional area than that provided by the 0.7 m diameter circular columns.



(a) (b)

*Figure 3: PLAXIS models of (a) 'open' and (b) 'closed' configurations*

### 3.2.2 Loading conditions

The primary purpose of these analyses is to estimate composite strength and deformation properties of the SMC-improved ground. To achieve this, two separate analyses were undertaken with different loading conditions:

i) One dimensional settlement analysis to estimate a composite Young's modulus. The loading condition for this case (which is shown in Figure 3) comprises a uniform 10 kPa surcharge applied to the full width of the mesh. One-dimensional Hooke's Law is then used to calculate the composite Young's modulus from the calculated settlement and the depth of the mesh.

ii) Analysis of a rigid footing on a finite layer ("footing analysis") to estimate both composite Young's modulus (as a check on method (i)) and composite shear strength. The footing load is applied across a limited width of the mesh as shown in Figure 4 for the open configuration. A similar loading condition was applied to the closed configuration. The footing load is gradually increased in discrete increments until bearing capacity failure occurs. The failure load is then divided by a bearing capacity factor to provide an estimate of composite shear strength. This bearing capacity factor was established by carrying out a similar analysis on homogeneous ground comprising soil of a known shear strength.

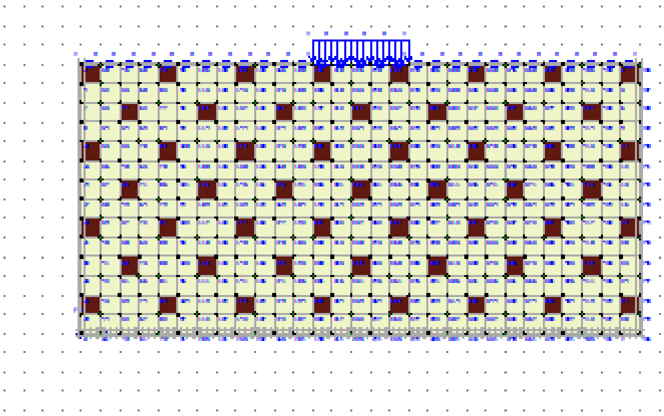


*Figure 4: Loading condition for estimation of composite shear strength (open configuration)*

### 3.2.3 Mud and SMC properties

A Mohr-Coulomb model was adopted for the PLAXIS analyses. While the Mohr-Coulomb model provides conservative results, potentially more accurate analyses could be undertaken using the hardening soil model available in PLAXIS. Fully drained analyses were carried out, which should also provide conservative results. The properties estimated for the mud and SMCs were therefore based on the assumption of fully drained analysis and the use of a Mohr-Coulomb model.

The cone penetrometer test (CPT) results undertaken in the mud indicated that the mud was essentially normally consolidated below a surface crust of about 3.5 m to 4.5 m thickness. The CPT results also indicated the surface crust material has a shear strength, $s_u$ of about 8 kPa to 10 kPa, whereas the normally consolidated material below this gradually increases in strength from about 8 kPa to around 18 kPa to 20 kPa at 10 m depth.

The field data was interpreted to estimate drained strength and deformation properties of the mud. To simplify the analyses, a uniform shear strength of 8 kPa was assumed for the upper crust material with a uniform drained Young's modulus of 800 kPa. The drained Young's modulus allows for the potential consolidation of the clay and for creep. For the normally consolidated material below about 4.5 m depth, a drained friction angle of 20.5$^o$, drained cohesion of 0 kPa and drained Young's modulus of 800 + 200 z kPa was assumed ( z is the depth below 4.5 m).

Two sets of properties were considered for the SMCs. These values are "mass strengths" and account for areas of the column that may not have been fully mixed:

i) shear strength of 250 kPa, drained Young's modulus of 75 MPa

ii) shear strength of 500 kPa, drained Young's modulus of 150 MPa

As the analyses to calculate composite properties are conducted on horizontal cross-sections through the SMC-improved ground at chosen depths below surface level, the strength and deformation properties of the mud need to be calculated for each depth.

For the analyses, gravity does not apply in the horizontal plane. The soil and columns are assumed weightless (again because gravity does not apply in the horizontal plane). The mud and SMC columns are assumed to have constant shear strength (cohesion) and Young's modulus appropriate to the depth at which the analysis is undertaken. Analyses were carried out for different depths using the appropriate modulus and strength values. These accounted for the increasing strength and stiffness of the mud with depth.

### 3.3 Results of PLAXIS analyses

3.3.1 Young's modulus

Selected results from the one-dimensional settlement analysis are presented in Figure 6 which compares the composite Young's modulus for mud and SMCs in open and closed configurations with the Young's modulus of the mud for a SMC Young's modulus of 75 MPa and 150 MPa.

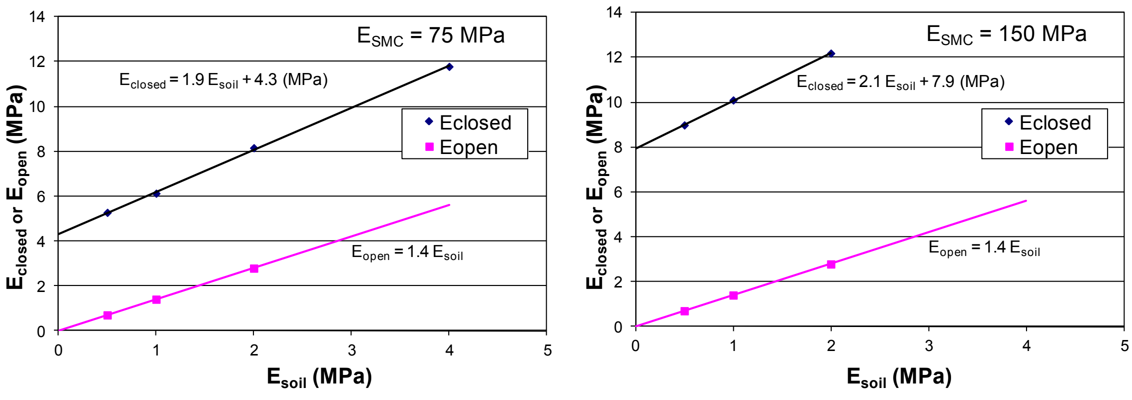



*Figure 5 - Composite Young's modulus values as a function of the Young's modulus of the mud - SMC Young's modulus= 75 MPa and 150 MPa*

The composite Young's modulus values calculated from the footing analyses are similar to those shown in Figures 6, which were calculated from the one-dimensional settlement analysis. Figure 5 indicates that the SMCs in an open configuration result in an increase in Young's modulus of the improved ground of about 40 % over the unimproved mud, independent of SMC Young's modulus. The columns are acting effectively as inert fillers in the mud.

The closed column configuration results in a significant increase in Young's modulus for the improved ground, because the columns are in contact and therefore transmitting load. The modulus of the SMCs also has an impact on the modulus of the composite material because of this contact.

### 3.3.2 Shear strength

Estimates of the composite shear strength of the SMC-improved ground calculated from the footing analyses are summarised in Table 1.

*Table 1: Composite shear strength values from footing analyses*

| SMC strength (kPa) | Mud strength (kPa) | Composite shear strength (kPa) | |
|---|---|---|---|
| | | Open configuration | Closed configuration |
| 250 | 10 | 10 | 25 |
| 250 | 20 | 20 | 39 |
| 500 | 10 | 10 | 32 |
| 500 | 20 | 20 | 50 |

Table 1 indicates that the composite shear strength in the open configuration is the same as for the mud alone. That is, the presence of the SMCs has no impact on the shear strength of the improved soil. For the closed configuration, the composite shear strength increases, with the amount of increase depending on the shear strength of both the mud and the SMCs. This is considered to occur because the columns are in contact and therefore transmitting load.

## 4. INTERPRETED COMPOSITE PROPERTIES

### 4.1 PLAXIS analysis drained values

The results from the PLAXIS analyses can be used to infer drained (effective stress) strength parameters appropriate to a Mohr Coulomb model. Knowing the applied vertical stress at each depth and assuming typical values for the A and B pore pressure parameters, the equivalent drained strength parameters can be calculated. The values are shown in Table 2.

*Table 2: Mohr Coulomb drained properties for mud and composite SMC/mud*

| Material | SMC strength (kPa) | Drained Properties | | |
|---|---|---|---|---|
| | | Cohesion (kPa) | Friction angle (deg) | Young's modulus (MPa) |
| Mud : below 4.5 m depth | NA | 0 | 20 | 0.8 + 0.2z |
| SMC/mud open configuration | 250 | 0 | 20 | 1.1+ 0.28 z |
| SMC/mud closed configuration | 250 | 11 | 21 | 5.8 + 0.38z |
| SMC/mud open configuration | 500 | 0 | 20 | 1.1 + 0.28z |
| SMC/mud closed configuration | 500 | 14 | 27 | 9.6 + 0.42 z |

*Note: z is the depth below 4.5 m depth*

### 4.2 Area ratio method

Separately, strength and stiffness values were calculated using the area ratio method. This method is based on the weighted average of the properties of the mud and the SMCs based on the percentage of the area occupied by the columns. The results are given in Table 3.

*Table 3: Properties for composite SMC/mud by area ratio method*

| | Cohesion | Friction angle | Young's modulus |
|---|---|---|---|
| Open configuration | 43 kPa | 16$^{o}$ | 19 MPa |
| Closed configuration | 107 kPa | 11$^{o}$ | 44 MPa |

It is considered that the stiffness and strength values set out in Table 3 are unconservative (i.e. too high) for this application where the material is subjected to lateral rather than vertical load. Adopting the Table 3 rather than Table 2 values would have a significant impact on the calculated performance of the wall and the design structural actions.

## 5. CONCLUSIONS

Based on the results of the analyses, the following conclusions can be drawn:

i) The calculated strength and stiffness properties of the composite material by the area-ratio method are unconservative compared with those from the PLAXIS approach.
ii) An estimate of Young's modulus of the composite material can be made from the PLAXIS approach by interpreting the deflection resulting from a uniform surcharge.
iii) An estimate of the equivalent shear strength of the composite material can be made from the PLAXIS approach by interpreting the bearing capacity of a rigid footing.
iv) The PLAXIS calculated Young's modulus values show about a 40% increase for SMCs in open configuration, and this increase is independent of the SMC stiffness for the configurations analysed.
v) Where SCMs are in contact, in the closed configuration, the increase in Young's modulus calculated using PLAXIS is of the order of 4 MPa and is increased with higher SMC stiffness.
vi) SMCs in open configuration do not increase the shear strength of the composite material.
vii) SMCs in closed configuration show a strength increase of about 200 % and is increased with higher SMC strength.

## 6. ACKNOWLEDGEMENTS

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