

# CONTROLLING HORIZONTAL DISPLACEMENT OF REINFORCED SOIL WALL CONSTRUCTED OVER STONE COLUMN TREATED GROUND

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## ABSTRACT

In recent years, stone columns have been increasingly used to support reinforced soil wall structures when they are constructed on soft foundations. Whilst the installation of stone columns have been considered as an economic solution to increase bearing capacity, reduce settlement and enhance global stability of the reinforced soil walls, they are less effective in limiting the horizontal displacement since stone columns are geotechnical elements without significant bending stiffness. This paper presents a design solution using a dead-man anchor to control the horizontal displacement of the reinforced soil wall (RSW). It is shown that when a dead-man anchor is adopted to tie back the ground beam of the RSW into the retained embankment fill, the horizontal displacement of the RSW facing can be substantially reduced to a tolerable design level. Moreover, the RSW and the anchored ground beam can be considered as a single soil reinforcement unit. The minimum embedment of this unit as required for scour or future trenching can be achieved by embedding the ground beam to below the ground surface without excavating the entire reinforced soil block area. This is particularly advantageous from the construction point of view as soil excavation within stone column treated soft ground may be subject to various constraints including the damages of the stone columns and the disposal of the excavated soft soil. Finally a case study is described where an RSW in conjunction with a dead man anchor were constructed over soft ground treated by stone columns. Comparisons between construction monitoring results and design predictions are provided.

## 1 INTRODUCTION

The reinforced soil wall (RSW) structure has been used successfully worldwide over the last 50 years in association with almost the full range of foundation conditions. Although many structures have been constructed on good foundation, including rock, there are increasing occasions where the RSW are to be founded on soft soil foundation. The conventional design methods for RSW distinguish between the stability (i.e. internal, external and global stabilities) and the deformation assessment. The latter is normally considered separately from the stability criteria. This is not the case, however, for the RSW founded on poor ground where foundation settlement limitations often dictate the allowable capacities. On many occasions some form of ground improvement is necessary in order to satisfy the displacement and stability criteria for the RSW. Therefore understanding of the deformation mechanism and the soil-structure interaction is paramount for the design of RSW on soft ground.

The fundamental difference in the deformation of RSW on rigid and soft soil foundations is outlined in this paper. Different techniques for improving existing foundation soils are also briefly discussed. In particular, the influence of stone columns on RSW deformation is investigated based on the 2D plane strain finite element analysis (FEA), in which the modelling of stone columns in 2D FEA has been based on equivalent strip method proposed by Chan and Poon (2012), Poon and Chan (2013). A highlight of this method is provided in the current paper. A number of design and construction issues of RSW on stone column treated soft ground are identified. To overcome these identified issues, an inexpensive design solution using deadman anchor is presented. Finally, a case study is described to demonstrate the applicability of the deadman anchor solution for RSW construction on stone column treated soft soil.

## 2 PROBLEM ANALYZED

Figure 1 shows the “standard” problem analysed, where a typical 7m high RSW is constructed over soft soil foundation. There are several factors that influence the response of the RSW, including RSW block width, soil and fill properties, reinforcement configurations and construction procedures. To avoid undue complication, an elasto-plastic analysis for the assessment of long term deformation is adopted, in which the decay of excess pore pressure with time is not considered. The foundation soil is a uniform 8m thick layer and although the material type may vary (see Section 3), it is assumed to be soft clay for most of the discussion in this paper with the adopted drained parameters given in Figure 1. Note that the adopted drained Young’s Modulus,  $E'$ , of the soft clay is 3MPa, which is commensurate with an undrained shear strength  $s_u$  of about 20kPa (based on  $E_u = 180s_u$ ;  $E' = 0.86E_u$ ). The reinforcements are 200mm wide inextensible steel ladder reinforcement spaced at 0.5m vertically and 1m horizontally. The axial rigidity  $EI$  of each strip and the RSW select fill properties are given in Figure 1. Although the RSW block width is to be varied (see Section 3),

the minimum adopted width is 10m, which has been determined on the basis of satisfying the internal stability in accordance with RMS R57 (2012) (RMS Publication), as well as the external and global stability under drained condition. It should be noted that the analyses assume that the rate of consolidation is in advance of the rate of loading such that excess pore pressure is dissipated sufficiently thereby increasing its shear strength and consequently satisfying the short term (undrained) stability requirement.

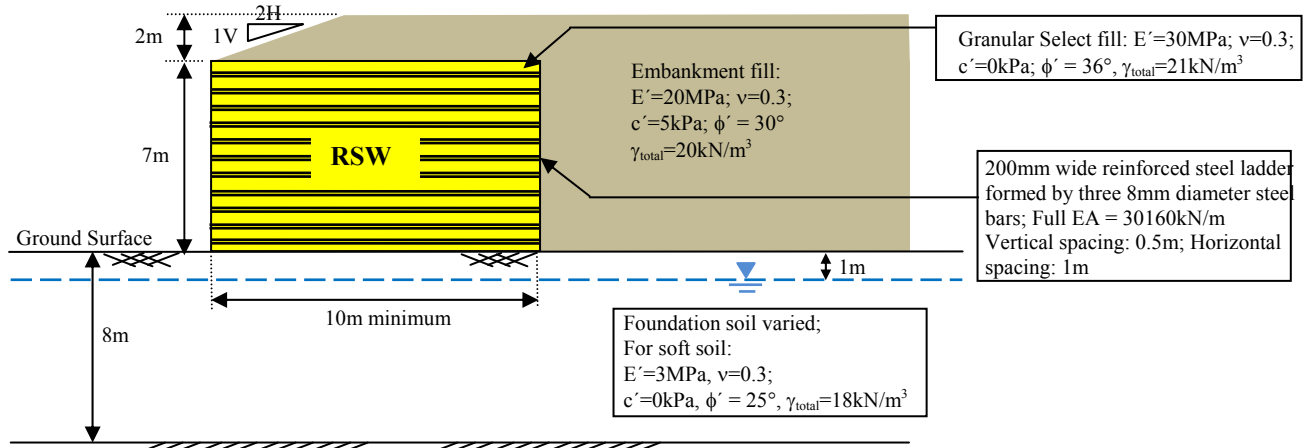


Figure 1: “Standard” problem analysed

The “standard” problem of the RSW depicted in Figure 1 is considered to be satisfactory for stability, but may experience varying degree of deformation depending on the soil stiffness and the amount of soft ground improvement. The present study concentrates on the displacement control of the RSW. In particular, the influence of stone columns on settlement and horizontal displacements are investigated based on 2D plane strain finite element analysis (FEA) using PLAXIS software programme.

### 3 DEFORMATION MECHANISM OF RSW ON SOFT SOIL FOUNDATION

The nature of the foundation type will have a great influence on the overall behaviour of the RSW structure. It is therefore illuminating to discuss the deformation mechanism of RSW, especially on soft soil foundation, prior to the consideration of any ground treatments.

Figures 2a and 2b present the exaggerated deformations of RSW on rock and soft soil foundations, respectively, as obtained from the FEA. In the case of elastic rock foundation, it is reasonable to assume a trapezoidal bearing pressure distribution beneath the RSW block. The front face of the structure will tend to rotate about the toe with an active mechanism away from the fill. With the soft soil foundation the self-weight of the RSW block and the weight of the retained embankment fill will cause settlement of the foundation soil and the RSW structure will tend to rotate in a negative sense (Figure 2b). Thus the behaviour of the RSW on soft ground is fundamentally different to that on a rigid foundation.

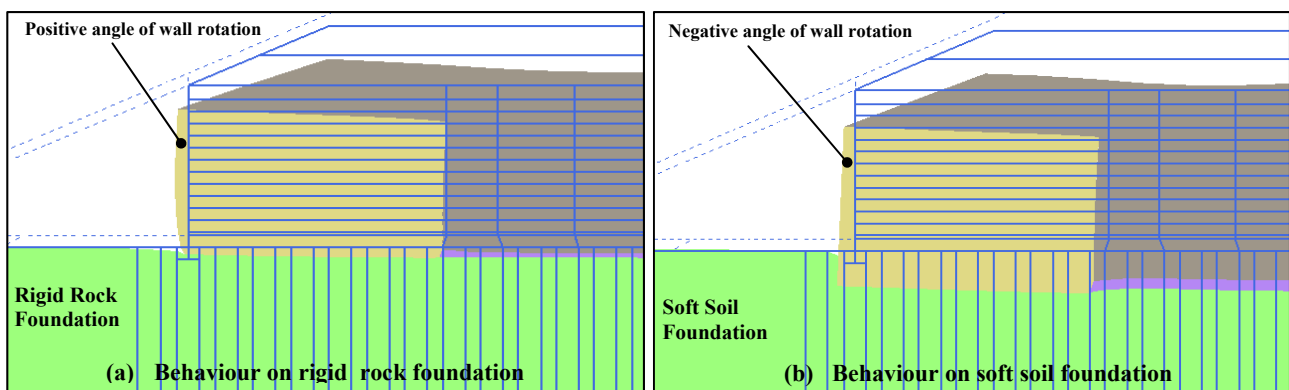


Figure 2: Deformation mechanism of RSW on (a) rigid rock foundation and (b) soft soil foundation

Figure 3 presents the changes in displacements of the RSW facing with different foundation types varying from soft soil foundation to high strength rock. Note that the foundation types are represented by their Young’s moduli on the horizontal-axis in logarithmic scale. Figure 3d summaries the adopted properties of the different foundations. Inspection of the results provides the following insights for RSW design:

- For soil Young's modulus of about 50MPa or greater, the wall face is assessed to rotate in a positive sense. This indicates that for RSW founded on hard clay/residual soil or better, the wall face has a propensity to rotate forward, although the magnitude may be quite small or even unnoticeable in reality.
- For RSW founded on stiff/very stiff to hard clay (Points C and D with  $E' = 20\text{MPa}$  to  $50\text{MPa}$ ), the wall face rotates backwards but both settlement and horizontal displacements are well within 50mm.
- As the foundation soils graduating from stiff to soft consistency, the wall face settlement, horizontal displacement and the backward rotation increase exponentially. For soft soil with  $E' = 3\text{MPa}$ , the settlement and the wall toe horizontal displacement are in excess of 300 and 150mm, respectively.

As for the design of RSW on soft ground, it is important to realise that significant wall movements, both vertical and horizontal displacements, could be expected at the toe. Limiting the wall toe displacements is therefore critical for the satisfactory performance of the RSW.

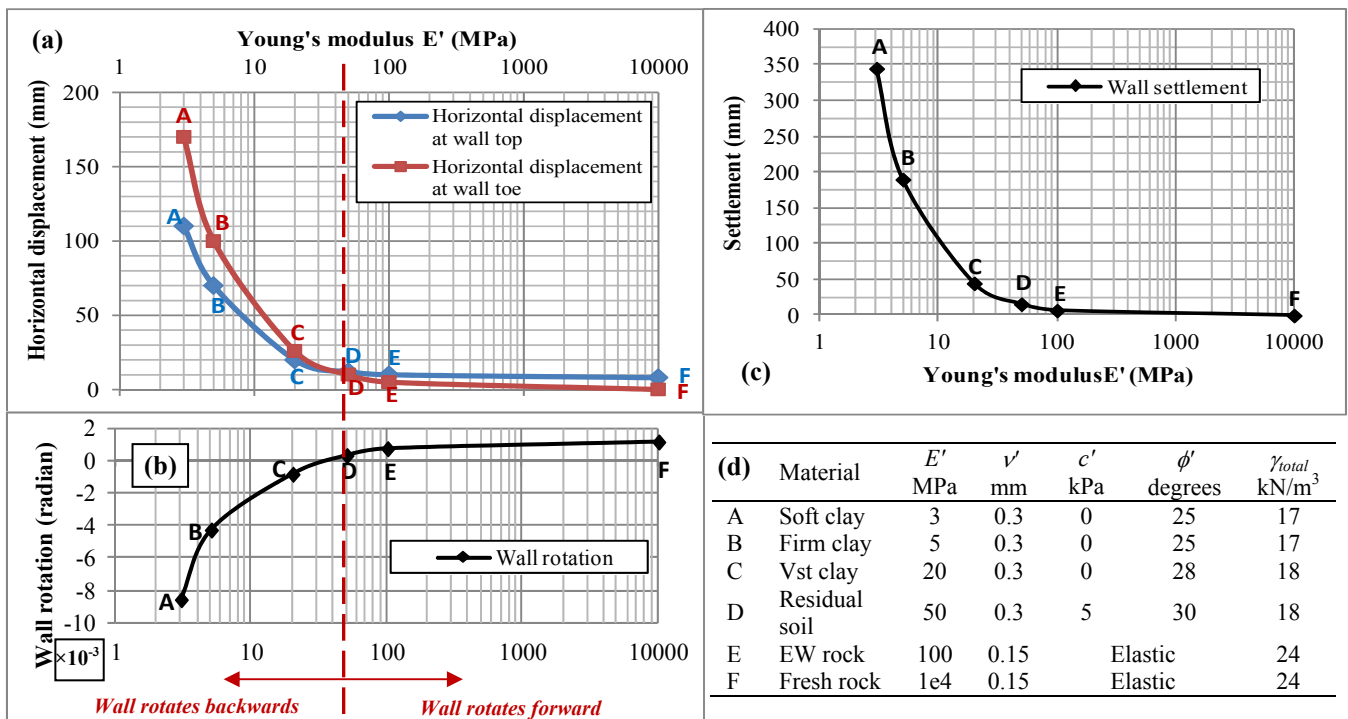


Figure 3: Deformation of RSW facing on different foundation types, (a)..., (b) ... (c) ... and (d) ...

#### 4 GROUND TREATMENT USING STONE COLUMN

In many situations ground improvement is necessary in order to satisfy the RSW design criteria. There are a number of techniques for ground improvement. Perhaps the simplest method involves pre-loading, normally with a surcharge embankment in conjunction with wick drains. A more positive treatment, if neither time nor space permits the use of surcharge, is the installation of columnar elements. This method improves the bearing capacity of foundation soils and subsequently reduces settlements. There are different column types, which can be classified based on their rigidity varying from flexible to semi-rigid and rigid. Flexible columns such as stone columns have lower load capacity and stiffness. Semi-rigid columns, such as deep soil mixing and geosynthetic encased stone columns have the load capacity and stiffness between flexible and rigid concrete columns. Of the different column types, the flexible stone columns are generally less expensive and can be used for mitigation in deep soft soil profile. This paper considers the use of stone columns for ground improvement underneath RSW structures.

##### 4.1 MODELLING STONE COLUMNS USING 2D FEA WITH EQUIVALENT STRIPS

Conventionally, the design of stone columns involves the prediction of settlements using a composite material approach in which equivalent strength and deformation parameters are derived using semi-empirical correlation to represent the entire improved soil. While these approaches have been accepted as reasonable methods for settlement prediction, they are less certain for the prediction of horizontal displacement. The current analyses have been based on a methodology proposed by Chan and Poon (2012) and Poon and Chan (2013) in which stone columns are idealized as equivalent strips in 2D FEA. The equivalent design parameters for the 2D strips account for, in a 3D sense, the load transfer mechanism between stone columns and the surrounding soil with depth. This section provides a brief outline of the methodology.

In the proposed 2D equivalent strip method, the width of the column strips,  $a$ , can be made to be equal to the width of an equivalent square for the cross-sectional area (Figure 4). The spacing of the strips is equal to the actual spacing,  $b$ , for square column arrangement and  $\sqrt{3}b/2$  for equilateral triangular arrangement. The stone column strips are modeled as Mohr-Coulomb materials with Poisson's ratio of 0.3, which is taken to be the value of the soil itself. The equivalent Young's modulus  $E_{eq}$  and the cohesion  $c_{eq}$  of the strips can be calculated based on weighted average approach as given by Equation

$$E_{eq} \text{ (or } c_{eq}) = \frac{E_{soil} \text{ (or } c_{soil}) \cdot A_{soil} + E_{column} \text{ (or } c_{column}) \cdot A_{column}}{A_{soil} + A_{column}} \quad (1)$$

where  $A_{soil}$  and  $A_{column}$  are the areas of the soil and column inside a unit cell within the 2D strip as shown in Figure 4.

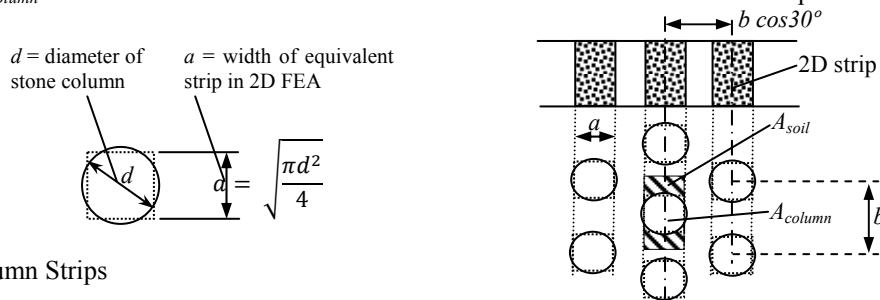


Figure 4: 2D Column Strips

The equivalent friction angle  $\phi_{eq}$  of the strips can be derived based on force equilibrium approach as given by

$$\tan(\phi_{eq}) = \frac{A_{soil} \tan(\phi_{soil}) + n \cdot A_{column} \tan(\phi_{column})}{A_{soil} + n \cdot A_{column}} \quad (2)$$

The determination of  $\phi_{eq}$  requires a presumption of stress concentration,  $n$ , which is defined as the ratio of the average applied vertical stress within stone column to the average applied vertical stress of the surrounding soil at the same level. For stone columns founded on rigid base,  $n$  can be assessed using the design chart as given in Figure 5 in which a series of curves for  $n$  are plotted against the normalised depth  $z \cdot \gamma / q_a$  for different column to soil modulus ratios ( $E_{column} / E_{soil}$ ), column spacing ( $b/a$ ) and column friction angle ( $\phi'_{column}$ ). Note that  $z$  is depth along the column below ground surface,  $\gamma$  is the total unit weight of soil surrounding the columns and  $q_a$  is the applied embankment fill stress.

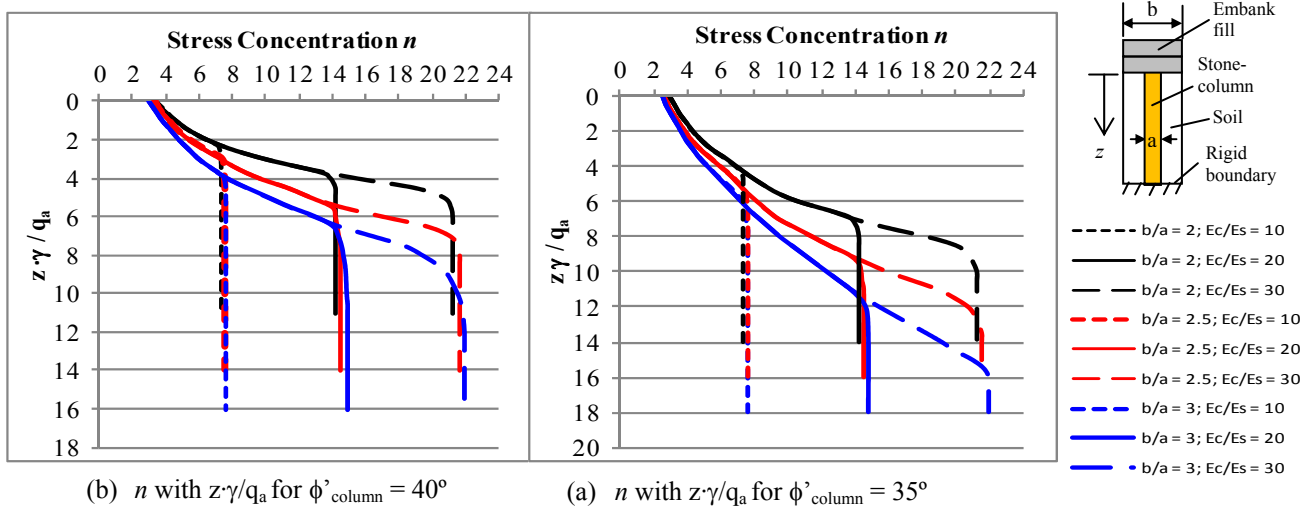


Figure 5: Variation of stress concentration  $n$  in column with  $z \cdot \gamma / q_a$  for incompressible base

For stone columns founded on compressible soils, there exists a lower equal settlement plane, below which the columns move more than the soil to mobilise positive shaft resistance of the soil. More load is transferred from the column to the surrounding soil and therefore the stress concentration  $n$  reduces (see Figure 6a). Figure 6b shows a plot of normalised distance from the column base  $y/a$  ( $y$  and  $a$  defined in inset in Figure 6b) versus stress concentration reduction ratio  $r$  ( $= n / n_{max}$ ) for the corresponding elastic FEA results given in Figure 6a. The  $n_{max}$  is the maximum computed  $n$  without the influence of compressible base as given in Figure 6a. The value of  $r$  near the column base can be approximated by the following logarithmic relationship

$$r = 1 - \frac{1}{m} \left[ \log \left( \frac{\xi}{y/a} \right) \right] \quad (\text{for } y/a \leq \xi) \quad (3)$$

where  $\xi$  is the influenced zone (also normalized by the column diameter  $a$ ) that is measured from the base of the column to the equal settlement plane (where  $r = 1$ ). The magnitude of  $m$  controls the rate of reduction of  $r$  with  $y/d$ . The higher the  $m$  the more rapid reduction of  $r$  would be towards the column tip. Figure 6b indicates that as the Young's modulus  $E_{base}$  of the soil beneath the columns increases, the extent of  $\xi$  reduces. Also, the ratio  $r$  reduces more rapidly towards the column tip (i.e.  $m$  increases) as  $E_{base}$  increases. The values of  $\xi$  and  $m$  have been computed based on FEA and are given in Poon and Chan (2013) for the different  $E_{base}/E_{column}$  and  $E_{base}/E_{soil}$  ratios.

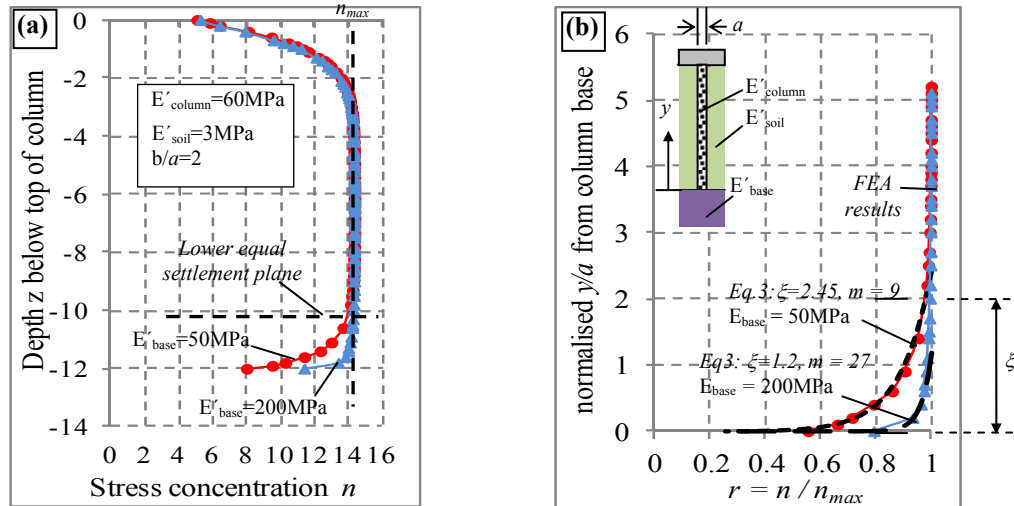


Figure 6: Stone column with compressible base

4.2 RESULTS FOR STANDARD PROBLEM WITH STONE COLUMN GROUND TREATMENT

The ‘‘Standard’’ problem outlined in Section 2 has been analysed with the modelling of equivalent stone column strips in the foundation soil. While the stone column properties are set to be constant with  $E_{col} = 50\text{MPa}$ ,  $\phi_{col} = 40^\circ$  and  $c_{col} = 0\text{kPa}$ , the area replacement ratio,  $a_r$ , is varied from 0% up to 30%. Figure 7a summarises the equivalent strip parameters used in the different analysis cases. Note that in all cases, the RSW block widths are kept at 10m; the stone columns are 1m in diameter and installed in triangular pattern. Interface elements are used at the column-soil contact in the 2D FEA but the interface strength remains the same as that of the surrounding soil. The equivalent friction angle of the stone column strips have been derived based on the average value of the stress concentration ratios,  $n$ , along the upper half (i.e. upper 4m depth) of the stone column. The  $n$  values have been assessed based on the design chart given in Figure 5.

(a)

$a_r$ (%)	$E_{eq}$ MPa	$c_{eq}$ mm	$\phi_{eq}$ degrees
10	17.0	0	34.5
15	19.8	0	34.8
20	22.7	0	36.8
25	25.0	0	37.5
30	28.0	0	38.0

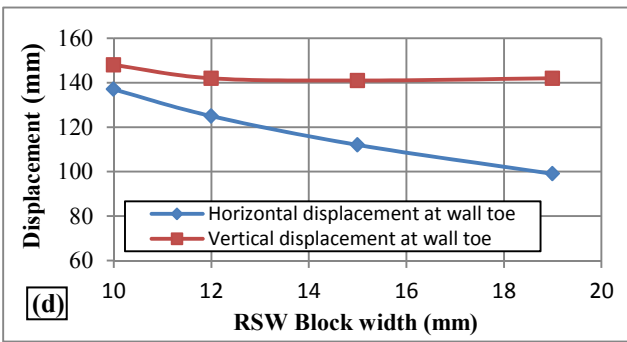
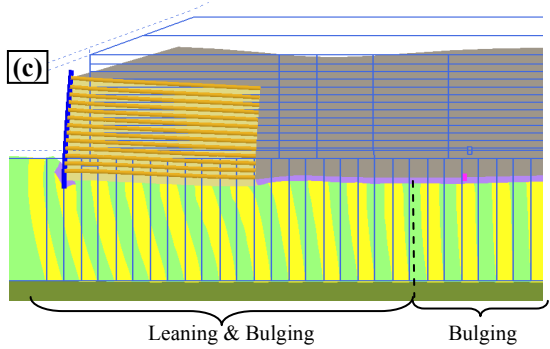
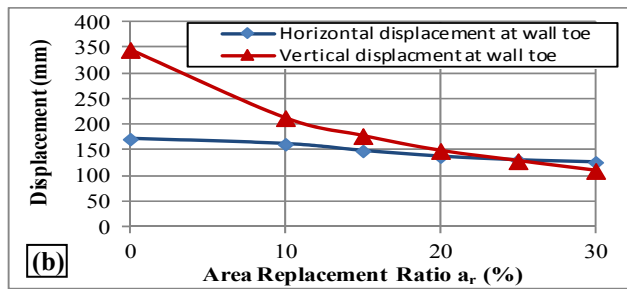


Figure 7: RSW on stone column treated ground: (a) Equivalent strips parameters, (b) Wall toe displacements (block width = 10m), (c) Exaggerated deformed mesh, (d) Reduction of wall toe by increasing RSW block width ( $a_r = 20\%$ )

Figure 7b shows the analysis results regarding the settlement and the horizontal displacement at the toe of the RSW facing. It can be seen that while there is a substantial reduction of wall settlement (from about 345mm to 110mm) as  $a_r$  increases from 0% to 30%, the reduction in horizontal displacement is small (from about 170mm to 130mm). Figure 7c shows an exaggerated deformed mesh of the analysed case with  $a_r = 20\%$ . Away from the RSW, the stone columns are, by and large, subject to axially symmetric loading condition and underwent vertical deformation by “bulging”. Towards the RSW facing, the columns underwent both vertical and horizontal deformations by “bulging” and “leaning”. There is also a localised overstress yielding zone within the foundation soft soil at the toe of the wall (see Figure 9d). The numerical prediction of the deformation appears to be consistent with the results of the centrifuge model test carried out by Stewart and Fahey (1994) for a stone column foundation system supporting stockpile and railway embankment.

To reduce the horizontal displacement, the RSW block width is increased while the area replacement ratio of the stone columns is kept at 20%. Figure 7d shows that the RSW block width needs to be increased quite substantially (from 10m to 19m) in order to achieve a 30% reduce of horizontal displacement at the wall face (from about 140mm to below 100mm). Moreover, widening of the RSW block has essentially no effects on RSW settlement reduction.

The numerical solutions presented in this section indicate that while stone columns serve to reduce settlement of the RSW, they are less effective in controlling the horizontal displacement. The RSW block width can be increased to control the horizontal displacement but is deemed uneconomical.

**5 CONTROLLING HORIZONTAL DISPLACEMENT USING DEADMAN ANCHOR**

In the light of the issues identified in the previous section for the RSW situated on stone columns treated ground, an inexpensive deadman anchor design solution is proposed. The design configuration is outlined in Figure 8. In essence, the 10m wide RSW is built upon a working platform (typically 0.5m to 0.75m thick) that was constructed for stone column installation. To limit the total and differential settlements of the wall facing, a structural ground beam element spanning over a row of stone columns is provided to support the precast wall panels. To limit the applied horizontal force on the supporting stone columns underneath the ground beam, a deadman anchor system is adopted to tie back the ground beam into the retained embankment fill. The size of the deadman anchor block should be large enough without causing failure at the passive side (typically a continuous beam with 1m (H) × 1m (W)). The anchor block must be located away from the active wedge behind the RSW block. For the present “Standard” problem the distance is 20m from the RSW wall facing.

The RSW and the anchored ground beam can be considered as a single soil reinforcement unit. The required embedment of this unit can be achieved by merely embedding the ground beam to the required depth without excavating the entire reinforced soil block footprint.

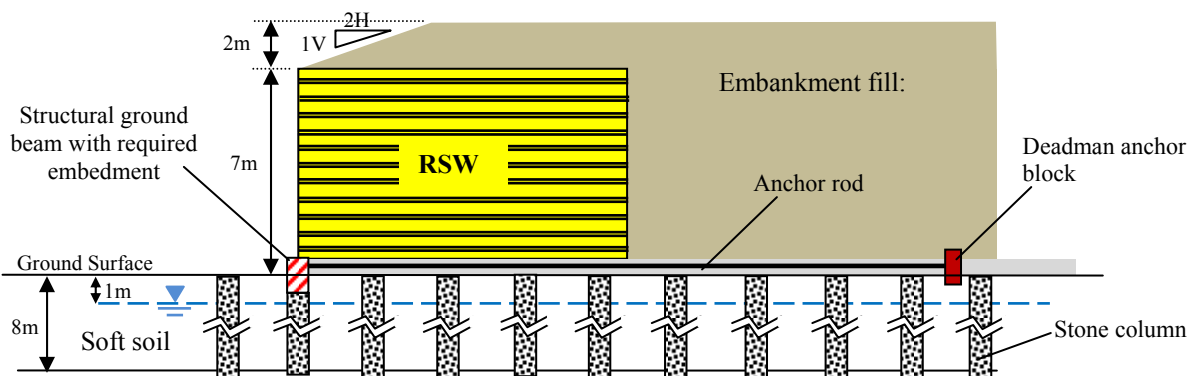


Figure 8: Deadman anchor configurations

Figure 9 shows the performance of the anchored RSW on stone column treated ground. Also shown in the figure are the previously analysed results without the deadman anchor for comparison. Figure 9a shows that by using the deadman anchor solution, the horizontal displacement,  $u_x$ , of the RSW ground beam can be reduced by about 25% (e.g. the assessed  $u_x$  reduced from 137mm to 103mm for  $a_r = 20\%$ ). However, the deadman anchor does not reduce the settlement of the RSW (Figure 9b). Figures 9d and 9e present a comparison of the soil yielding zone beneath RSW for the case of  $a_r = 20\%$  with and without the deadman anchor. The introduction of deadman seems to reduce the amount of soil at yield quite significantly, especially within the block and in front of the deadman anchor. This behaviour, and the amelioration effected by using deadman anchor can be understood by reference to the axial force distribution along the ladder reinforcement at the base of the RSW as shown in Figure 9c. This indicates clearly that the role of the deadman

is to provide additional lateral restraining force at the wall toe such that the axial force of the RSW reinforcements and hence the wall toe horizontal displacement can be reduced.

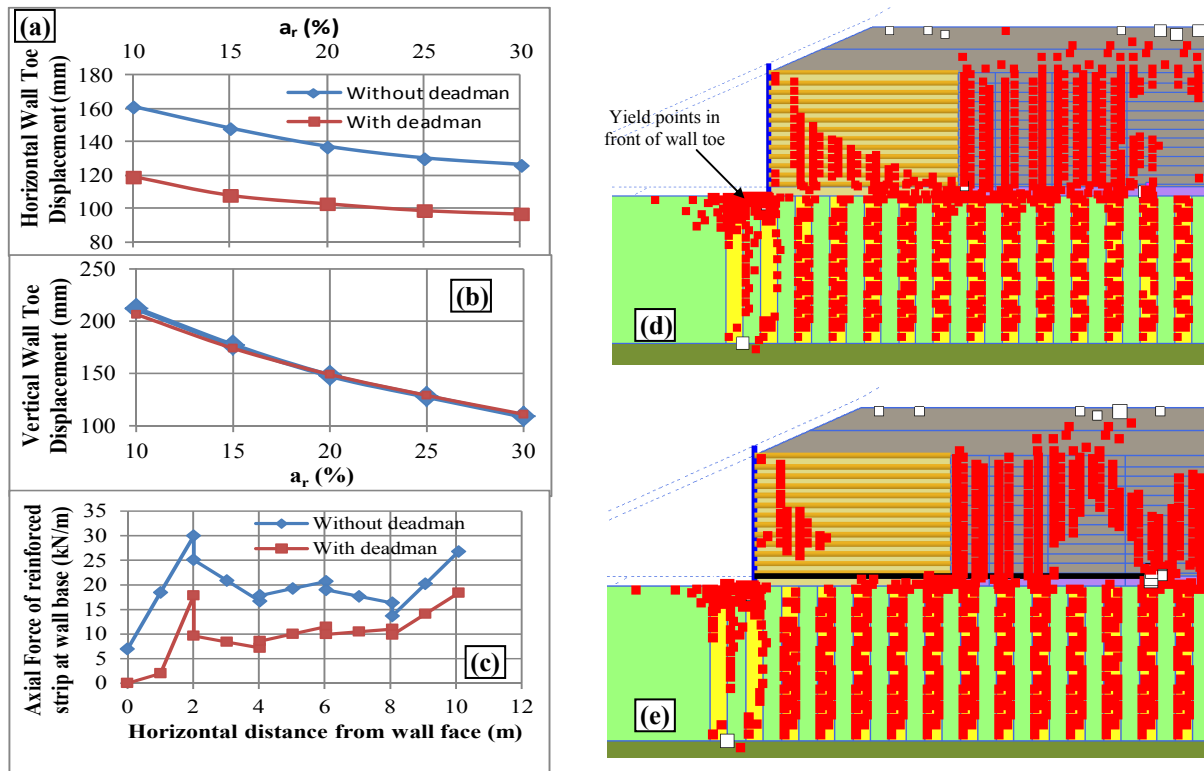


Figure 9: Performance of RSW on Stone Column Treated Ground in conjunction with Deadman Anchor. (a) Horizontal wall toe displacement; (b) Vertical wall toe displacement; (c) Axial force distribution of reinforced strip at wall base; (d) Plastic zone for RSW without deadman anchor; (e) Plastic zone for RSW with deadman anchor

## 6 APPLICATION TO A CASE STUDY

As part of the ongoing program of works to upgrade the Pacific Highway that connects Sydney to Brisbane, the Ballina Bypass Alliance was established in 2007 to construct a 11.5km long four lane dual carriageway to divert the traffic away from the township of Ballina. The northern end of the Ballina Bypass, known as Upper Sandy Flat, lies in a valley where soft estuarine soils have been deposited. The soft soil thickness is up to 5m, and the maximum design embankment height is about 9m. The adopted soil model is given in Table 1.

A 16m span arch culvert supported by piles was proposed to underpass the embankment fill. The culvert is flanked by two reinforced soil wing walls at the northern (Wing Wall A) and southern (Wing Wall C) as shown in Figure 10. The adopted ground treatments for the culvert approach as well as the RSW footprints included installation of dynamic replacement (DR) columns in conjunction with surcharge fill. Wick drains were installed after DR formation to increase the consolidation rate even though the DR columns would already facilitate radial drainage in soft clay.

DR columns were introduced into the ground by a heavy weight dropped repeatedly on to a gravel layer while the craters created by the impact are backfilled with gravel. The resulting DR columns are relatively large in diameter (about 2.5m in diameter), have high carrying capacity, and are rapid to install. However, following the installation of the DR columns, it was discovered that the DR treatment did not extend to the base of the soft clay at some locations, leaving about 0.7m thick soft clay untreated. Remedial ground treatment using stone column (SC) and extra surcharge fill were subsequently introduced. The finally adopted ground treatments are summarised in Table 2 and outlined in Figures 10 and 11. Relevant instrumentations are shown in Figure 10, which included two settlement plates (BSP\_046\_003 and BSP\_046\_010) located behind the wing walls; and two pressure cells (BT46/1 and BT46/2) installed on top of two floating DR columns near the arch culvert. The horizontal and vertical movements of the wing walls were measured by survey monuments placed on the ground beam of the wing walls.

The wing wall facings are aligned next to the spandrel wall of the arch culvert. A special detached joint with a 170mm gap has been designed to accommodate the anticipated wall face movements. The design maximum horizontal movement of the wall face was set to 150mm over 100 years to avoid closure of the 170mm clearance. To limit the horizontal movement, the RSW in conjunction with a tie-back deadman was designed as outlined in Section 5.

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Table 1: Geotechnical Model and Design Parameters

Layer	Thick-ness m	CR	CRR	OCR	$c_h$ m <sup>2</sup> /yr	$\gamma$ kN/m <sup>3</sup>	$s_u$ kPa
1	0.5	0.2	0.03	70	20	18	30
2	0.5	0.35	0.05	11.6	5	15	20
3	0.5	0.35	0.05	4.3	5	14.5	11
4	0.5	0.35	0.05	3.6	5	14.5	11
5	1	0.35	0.05	2.8	5	14.5	11
6	0.5	0.35	0.05	2.4	5	14.5	15
7	0.5	0.35	0.05	4.5	5	14.5	20
8	0.5	0.3	0.05	5.3	5	15	25
9	0.5	0.3	0.05	7.3	5	15	35
10	4.5	0.1	0.015	23.5	50	19	150

Table 2: Adopted Ground Treatments at Upper Sandy Flat

Ground Treatment	Details
DR (dynamic replacement) column	Nominally 2.5m in diameter; 5m equilateral triangular spacing; Area replacement ratio <sup>(1)</sup> , $a_r = 23\%$
Stone Column (SC)	Nominally 1m diameter; 5m equilateral triangular spacing; Area replacement ratio <sup>(1)</sup> , $a_r = 3.6\%$
Wick Drain	Installed after DR formation at 1.2m equilateral triangular spacing

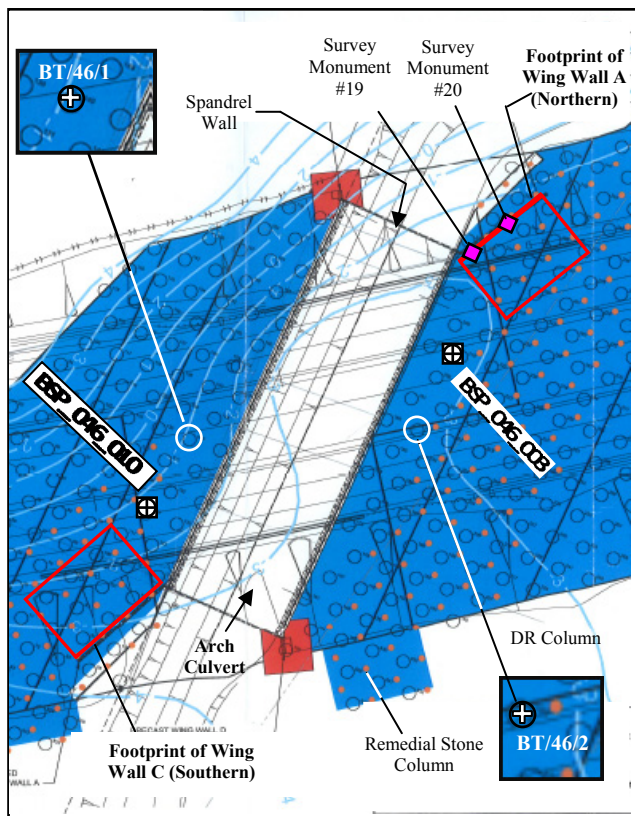


Figure 10: Ground treatment and monitoring plan

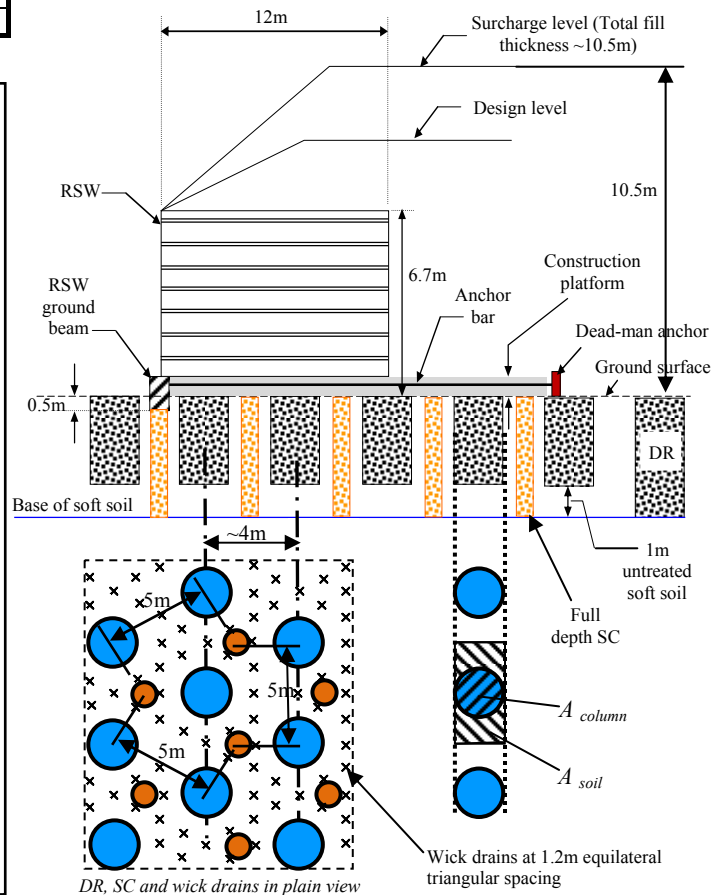


Figure 11: Reinforced soil wing wall design configuration

The design analyses of the RSW have been carried out based on the 2D FEA approach as outlined in Section 4.1. Prior to the 2D modelling, a pilot 3D group analysis for the SC/ DR columns (Figure 12a) was carried out to verify the stress distribution between columns and soil. In addition, the 3D analysis also involved coupled consolidation such that time-settlement can be assessed. Details of the 3D group analysis have been given in Poon et al (2011). It has been shown that except for the first 1m depth, the stress concentration ratio  $n_{sc}$  (for SC) is about 4.5 and it is fairly constant with depth. Due to load transfer from the floating DR to the surrounding soil and SC, the stress concentration  $n_{dr}$  (for DR) is however reduced from a peak value of about 4.3 at 1m depth to about 3 at the column base. These predictions are consistent with the pressure cell measurements, as well as the assessed value based on design charts given in Figures 5 and 6.

Figure 12b shows a comparison of the predicted time settlement response from the 3D SC/DR group analysis and the measured data from settlement plate BSP\_046\_003. It is emphasised that the prediction was by no means obtained from back analysis, thus the agreement between the two results, especially towards the end of the consolidation, is considered quite satisfactory. A noteworthy point about the analysis is that wick drains were not included in the 3D group model. However the results as shown in Figure 12e might have suggested that such an omission in the SC/DR treated ground was compensated for also not modelling smearing of the remoulded soft soil surrounding the SC/DR columns

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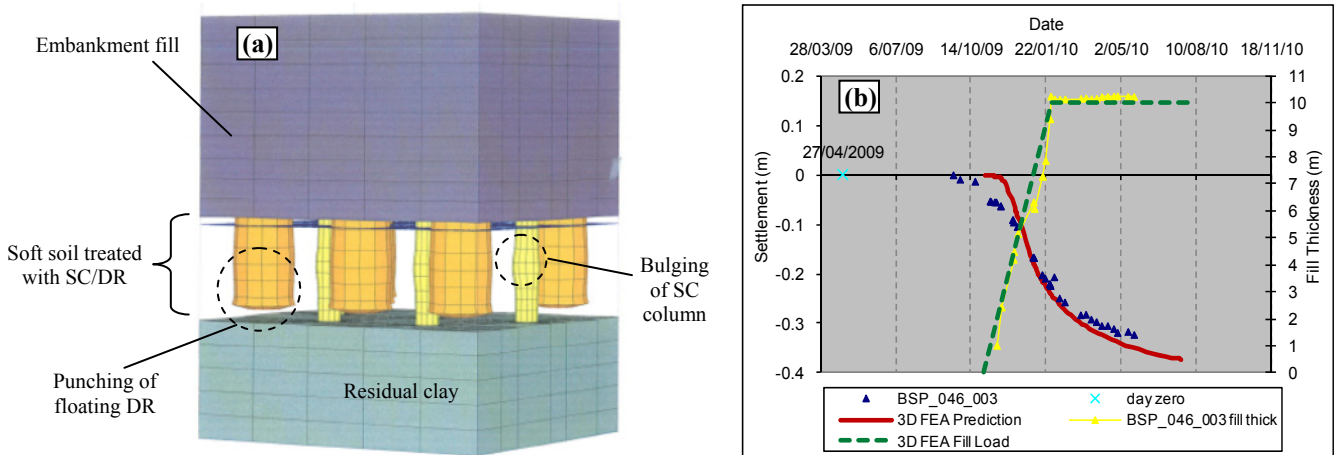


Figure 12: 3D Group Analysis; (a).... and (b)....

Figure 13a shows an exaggerated deformed mesh of the RSW wing wall under preloading with surcharge. The RSW deforms in a backward tilting mode, with the predicted settlement at the wall facing and behind the RSW block being equal to 210mm and 300mm, respectively. These results are in good agreement with the field measurements; refer Figure 13b for settlement at wall facing and Figure 12e for settlement behind RSW block. Also note that the time for the stabilisation of the wing wall facing is about 5.5 months according to the survey monument #19 at the ground beam (Figure10). This is consistent with the measured data of the settlement plate BSP\_046\_003 behind the RSW block, as well as with the 3D analysis result (Figure 12b). Figure 13c shows the measured horizontal movement of the ground beam at the toe of the RSW. It can be seen that the measured value (60mm) is within the design limit of 150mm.

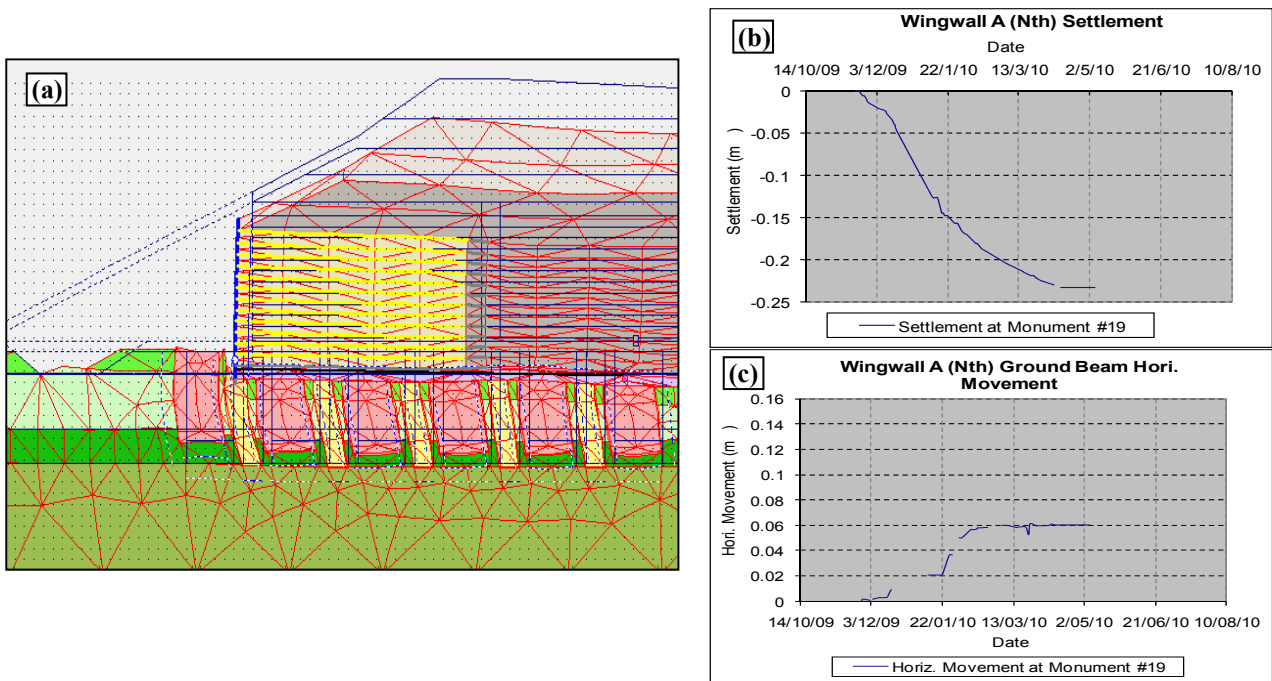


Figure 13: 2D FEA results. (a) Exaggerated deformed mesh for Wing wall A; (b) Measured and predicted settlement at Wing wall A facing; (c) Measured and predicted horizontal displacement at ground beam level of Wing wall A

**7 CONCLUSIONS**

Understanding of the soil-structure interaction has become important for RSW situated on soft soil foundation, for which the foundation settlement limitations often dictate the allowable capacities. The behaviour of RSW on soft ground is fundamentally different to that on strong foundations. For stiff/rigid foundations, the front face of the RSW will tend to rotate about the toe with an active mechanism away from the fill, whereas for soft soil foundations the self-weight of the RSW block and the weight of the retained embankment fill will cause the structure to rotate in a negative

sense. As for the design of RSW on soft ground, it is important to realize that significant wall movement, both vertical and horizontal displacements, could be expected at the toe. Therefore, limiting the wall toe displacements will more effectively reduce the overall deformation of the RSW.

On many occasions ground improvement is necessary in order to satisfy the RSW design. There are a number of techniques for improving existing foundation soils including removal and replacement of the soft foundation soils with compacted material, surcharge with wick drains, and installation of columnar elements such as stone columns, deep soil mixing and concrete piles. This paper has focused on the use of stone columns, and in particular, the appraisal of the interaction between stone column treated soft ground and the RSW structure using 2D FEA. One of the key features in the 2D FEA is the modelling of the stone columns as equivalent strips that account for, in a 3D sense, the load transfer mechanism between stone columns and the surrounding soils.

The numerical study has shown that while stone columns serve to reduce settlement of the RSW, they are less effective in controlling the horizontal displacement. Increasing the area replacement of the stone columns has only resulted in marginal reduction of the horizontal wall movement. Increasing the RSW block width can reduce the horizontal displacement, but invariably lead to unrealistically wide RSW block size.

In light of the issues identified, an inexpensive deadman anchor solution has been proposed, in which the RSW wall facing is underpinned by a structural ground beam that spans over a row of stone columns. The ground beam is also tied back to the retained embankment fill by a deadman anchor. The benefit of using this system is threefold. Firstly, the wall face total/differential settlements can be reduced with the proper support of the structural ground beam (rather than levelling pad) installed over stone columns. Secondly, the RSW and the anchored ground beam can be considered as a single soil reinforcement unit, and the required embedment of this unit can be achieved by merely embedding the ground beam to the required depth without excavating the entire RSW footprint. Finally, it has been shown that the use of the deadman anchor can reduce the wall toe horizontal displacement quite substantially by about 25%.

The concept of the deadman system, in conjunction with ground treatment using stone columns, has been successfully applied in the construction of RSW wing walls of the Upper Sand Flat arch culvert on Ballina Bypass Project. In addition to the satisfactory outcome of the RSW performance, it emphasises the importance of the collaboration between structural and geotechnical engineers in pursuit of the detached connection system that allows for maximum tolerable movements between the wing wall and the spandrel wall of the arch culvert. This has made possible a more economical solution using stone columns in conjunction with deadman anchor without wandering into the hard treatment options such as piled foundation.

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