Effectiveness of Stone Column Reinforcement for Stabilizing Soft Ground with Reference to Transport Infrastructure

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ABSTRACT: The use of stone columns for soft soil stabilization has numerous advantages compared to other methods. There are many factors controlling performance of stone columns including column geometry and particle morphology. The reinforced soft ground supporting transport infrastructure like the railways and highways is subjected to cyclic loading, usually initiating a partially drained condition. The study reveals that the stone columns are more effective in mitigating the built up of cyclic excess pore water pressure compared to conventional vertical drains. This paper presents a brief overview on the rigorous theoretical and experimental studies carried out by the Authors to investigate the effectiveness of stone column reinforcement for stabilizing soft ground with particular reference to transport infrastructure.

KEYWORDS: Arching, Clogging, Cyclic stress, Ground settlement, Radial consolidation, Stress concentration

1. INTRODUCTION

The use of stone columns for soft soil stabilization has been applied successfully since several decades. They dissipate excess pore water pressure significantly faster than prefabricated vertical drains (PVDs) due to large diameter and high hydraulic conductivity, and simultaneously provide effective load-transfer mechanism while environmental friendly compared to pile foundation. Thus, "*the stone columns not only act as reinforcement, possessing greater strength and stiffness in comparison with the surrounding soil, but they also speed up the time-dependent dissipation of excess pore water pressure caused by surcharge loading due to shortening the drainage path.*" (Indraratna *et al.* 2013). Installation of stone columns is also environmental friendly compared to the adoption of pile foundation.

There are many factors which control the performance of stone column including columns dimensions and spacing and the characteristics of aggregates, specifically the particle angularity and gradation. If incorrect particle sizes with insufficient angularity are used where the internal friction is compromised (e.g. use of river pebbles), then lateral bulging adversely affects performance of the reinforced soft ground whereby decreasing the bearing capacity (Indraratna *et al.* 2015; Basack *et al.* 2015a; 2016a; 2016b). It is well established that the stone columns derive their load capacity from the lateral confining pressure offered by the surrounding soil (Basack *et al.* 2015a). For reinforced clay, the load transfer mechanism (Madhav and Vitker 1978; Impe and Madhav 1992; Madhav and Impe 1994), and the long term performance (Shahu *et al.* 2000; Shahu and Reddy 2014) are important study areas.

The role of stone columns in reducing the settlement is immensely significant compared to the other ground improvement techniques. Recent research indicates that under the same imposed loading, the stone columns can reduce up to 30% of the settlement likely to occur in unreinforced soft clay (Basack 2010; Basack *et al.* 2011; Indraratna *et al.* 2013). There are also other numerous benefits of stone columns over other conventional ground improvement techniques, including increased bearing capacity and consolidation, reduced post-construction settlement and lateral movement, improved slope stability and liquefaction control, among others (Fatahi *et al.* 2012). Design of stone column reinforced soft ground has been proposed by several researchers (Bouassida and Hazzar 2012, Bouassida and Carter 2014).

The behaviour of a stone column reinforced soft ground supporting transport infrastructure like the railways and highways is subjected to cyclic loading with specific frequency and amplitude. This usually initiates a partially drained condition (Ni 2012). While there are a few existing theoretical models to cover this aspect (e.g. Seed and Booker 1977; Blewett and Woodward 2000), the Authors have developed a novel numerical model based on the modified Cam-clay theory to cover this study aspect (Basack *et al.* 2016a). The study reveals that the cyclic excess pore water pressure is largely dependent on number of stress cycles and frequency. Due to column-soil relative stiffness, significantly lesser excess pore water pressure has been found to develop compared to PVDs, under identical cyclic loading parameters. This observation confirms the efficiency of stone column reinforcement over PVDs specifically for soft ground supporting transport infrastructure.

The above evidences undeniably establish that the use of stone columns as an effective soft ground stabilization technique, if adequately designed with proper geometry and particle morphology, not only increases the foundation stability, they are also cost effective as well as easy to field implementation. This paper presents a brief overview on the rigorous theoretical and experimental studies carried out by the Authors to investigate the effectiveness of stone column reinforcement for stabilizing soft ground with particular reference to transport infrastructure.

2. NUMERICAL MODELLING

The model developed is based on unit cell analogy with free strain hypothesis considering arching, clogging and smear effects (Indraratna *et al.* 2013). Initially, the behaviour of reinforced soft ground under static loading is studied, followed by cyclic analysis. The idealized problem is axisymmetric, as depicted in Figure 1, where a single column of radius r_c is embedded fully into soft soil of initial depth of H, overlying a rigid, impervious base representing stiff clay or rock. The unit cell has an effective radius of r_e and its top surface is subjected to a uniformly distributed load with intensity, $w_{av} = w_{sur} + \gamma_e H_e$, where, w_{sur} is the surcharge load on the embankment having a height of H_e and unit weight of γ_e.

Due to installation, a zone of soil disturbance is produced around the column-soil interface, specifically termed as smear zone. The thickness of this zone usually varies from 10-15% of the column radius in most cases, with the permeability about 10-20% of that of the undisturbed soil (Han and Ye 2002; Wang 2009). Due to significant hydraulic conductivity at the interface, intrusion of fines from soft clay zone to the column pores is obvious, which produces clogging of column (Adlier and Elgamal 2004). Therefore, in the model, the unit cell cross section has been discretized into four distinct zones (Indraratna *et al.* 2013): undisturbed soil zone, smear zone and clogged and unclogged column zones (Figure 2).

2.1 Assumptions

The analysis is based on the assumption of purely radial flow of pore water towards the column obeying Darcy's law. The displacement compatibility was considered at the interface. The column and soil have been idealized as non-linear elastic.

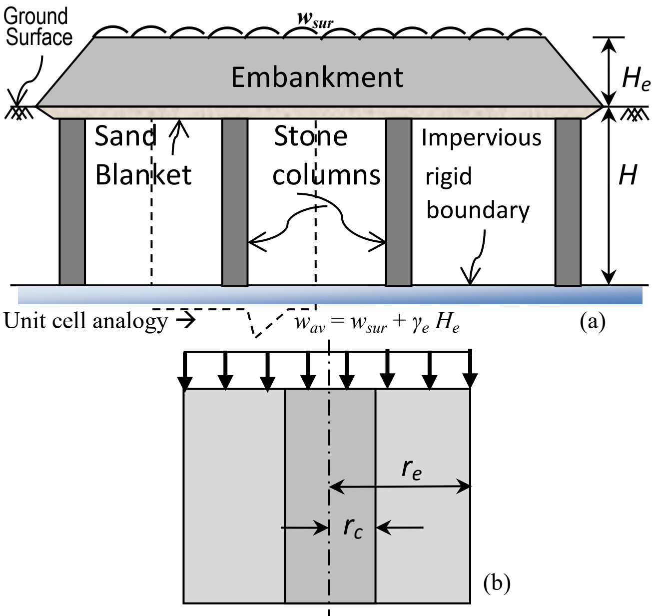


Figure 1 (a) Stone column reinforcement. (b) Unit cell idealization

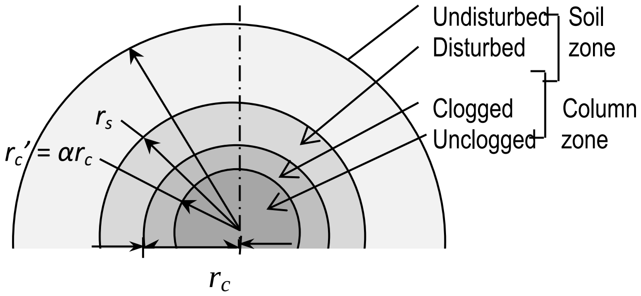


Figure 2 Cross section of the unit cell

2.2 Numerical Analysis

For computation, the unit cell is discretized radially and depth-wise into number of elements n_r and n_z respectively (Figure 3), while the computational time is also split into n_t divisions. The numerical model involves forward, backward and central difference techniques coupled with explicit procedure where grid size is adjusted in each of the computational steps performed.

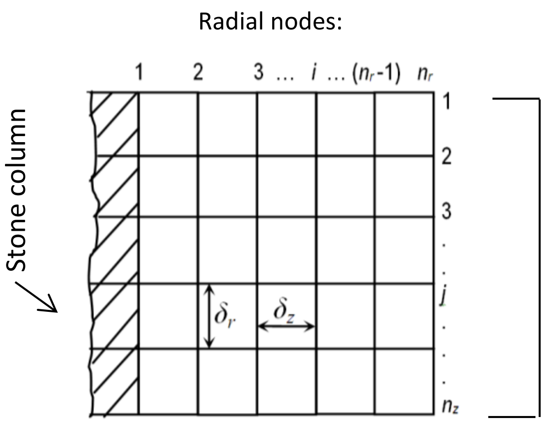


Figure 3 Finite difference discretization of unit cell

2.3 Load Transfer

Immediately after the embankment load is applied on the reinforced ground surface, elastic settlements occur in both the column and the surrounding soil (Deb 2010). As the deformations progress, the arching of embankment over the soft soil takes place due to significant column-to-soil stiffness ratio. The arching initiates a parabolic load distribution on the soft clay surface (Indraratna *et al.* 2013). The intensity of imposed vertical stress on the soft soil surface at given radial distance of r is expressed as:

$$w(r) = w(r_e)[1 - (N - r/r_c)^2 F(N, n_s, w_{av})] \tag{1}$$

where, n_s is the steady state stress concentration ratio, defined as the column to soil vertical stress ratio at the interface, $N = r_e / r_c$, $F(N, n_s, w)$ is the arching function and $w(r_e)$ is the vertical stress on soil surface at the unit cell boundary. More detailed description on this analysis has been published elsewhere (Indraratna *et al.* 2013).

Previous studies suggest that the value of n_s depends upon the elastic moduli and Poisson's ratio of soil and column, varying between 2-5 for most of the soil types (Han and Ye 2001; 2002). Experimental observation (Siahaan *et al.* 2014) reveals that n_s varies during the initial loading, but stabilizes to a steady state value in a short time. Similar observation has also been found by Han and Ye (2001).

2.4 Radial Consolidation

The soil consolidation is incorporated by Barron's radial consolidation theory (Barron 1948) coupled with modified Cam-clay theory to incorporate the non-linear correlation between void ratio and effective stress. The governing equations (further details published in Basack *et al.* 2015b) are given by:

$$\frac{\partial u_{rt}}{\partial t} = \frac{m_{v_{rt}}}{k_h \gamma_w}\left(\frac{1}{r}\frac{\partial u_{rt}}{\partial r} + \frac{\partial^2 u_{rt}}{\partial r^2}\right) \quad \text{... (2)}$$

$$m_{v_{rt}} = \frac{3\lambda/(1+2K_s)}{p'/p'_0[\vartheta_0 - \lambda \ln(p'/p'_0)]} \quad \text{... (3)}$$

where, u_{rt} is the nodal excess pore water pressure at space-time coordinate (r, t), $m_{v_{rt}}$ is the volumetric compressibility of soft clay, k_h is the horizontal soil permeability, γ_w is the unit weight of water, λ, p_0' and v_0 are the modified Cam-clay parameters, p' is the effective stress in the clay and K_s is the earth pressure coefficient.

2.4.1 Clogging

The effect of column clogging is included in the model after the recommendation of Indraratna *et al.* (2013) and Basack *et al.* (2015b), where the effective drainage radius in the column is taken as αr_c, with α being a non-dimensional parameter in the range of $0 \leq \alpha \leq 1$. The permeability in the clogged zone is taken as α_k times the smear zone permeability, where $0 \leq \alpha_k \leq 1$.

2.4.2 Ground Settlement

The nodal and average ground settlements have been computed using the following expressions respectively:

$$\rho_{rzt} = -\int_0^t \int_z^H m_{v_{rt}} \frac{\partial u_{rt}}{\partial t}\, dz\, dt \tag{4}$$

$$\rho_{av_t} = \frac{2}{r_e^2 - r_c^2} \int_0^H \int_{r_c}^{r_e} \rho_{rzt}\, r\, dr\, dz \tag{5}$$

where, ρ_{rzt} and ρ_{av_t} are the nodal and average ground settlements respectively.

2.5 Column Lateral Deformation

The lateral column deformation is quantified by the stress-induced deformation (ρ_z^e) plus the barrelling component (ρ_z^s). The governing Equations are:

$$\rho_z^e = \frac{\mu_c r_c}{E_c}\left[\sigma_z^v + \left(1 - \frac{1}{\mu_c}\right)\sigma_z^r\right] \tag{6}$$

$$\rho_z^s = \xi(z^2 - Hz) + \rho_z^e \frac{z}{H}(1-\eta_b) + \rho_z^e\left(1-\frac{z}{H}\right)(1-\eta_t) \quad (7)$$

$$\int_0^H \rho_z^s \left(r_c + \frac{\rho_z^s}{2}\right) dz = 0 \quad (8)$$

where, μ_c and E_c are the Poisson's ratio and elastic modulus of the column, σ_z^v and σ_z^v are vertical and radial column stress components at depth *z*, *H* is the soft soil thickness and ξ, η_t and η_b are appropriate non-dimensional coefficients.

2.6 Cyclic Loading

The behaviour of stone column reinforced soft ground under sinusoidal cyclic loading is being studied using yield surface contraction incorporating appropriate degradation functions. During loading halves, pore water pressures are built up, while in the unloading halves, partial dissipation takes place. These phenomena are mathematically computed by the model, the details of which have been described elsewhere (Basack *et al.* 2015b).

3. LABORATORY MODEL TESTS

Large-scale uniaxial consolidation tests on instrumented single stone column in soft kaolin clay were conducted. The test set up is shown in Figure 4. The clay had a liquid limit of 56%, plasticity index of 28%, undrained cohesion of 15 kPa and permeability 1 x 10^{-9} m/s. The stone column was installed in the remoulded clay bed by replacement technique. Highly angular stone particles (C_u = 2; C_c = 1.02; ϕ_p = 57^0) were used as stone column material, detailed particle morphology has been published elsewhere (Siahaan *et al.* 2014). The diameter of mould was 300 mm. The initial diameter and length of column was 100 mm and 600 mm respectively. In each test, the unit cell was allowed to consolidate at a constant pressure. When 90% consolidation is attained, the next level of sustained pressure was applied and the procedure was followed for several stress levels. At completion of the consolidation tests, the column was exhumed to study the shape of the deformed column and the intrusion of fines. This was done by Computer Tomography (CT) scan image processing.

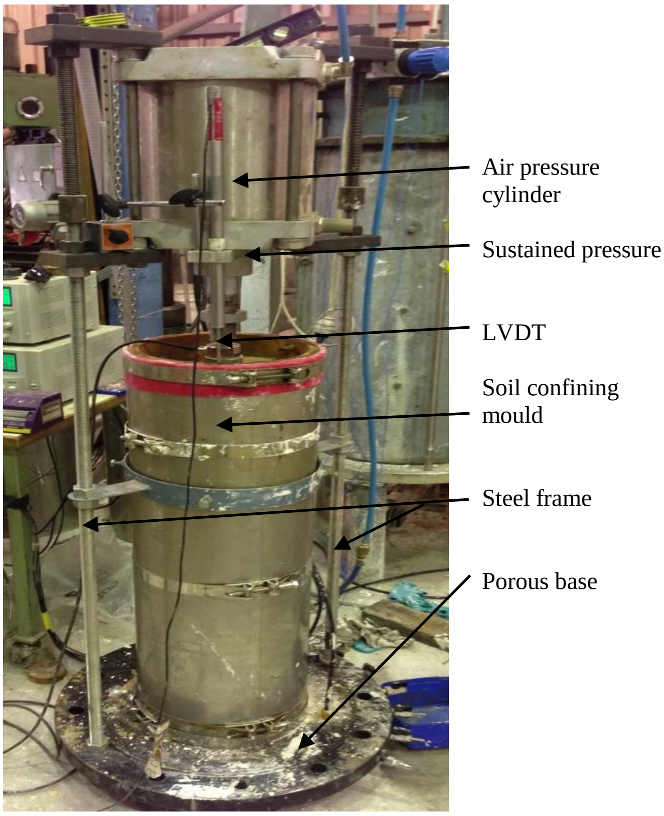


Figure 4 The test set up: photographic view

4. INSTRUMENTED FIELD TRIAL

With the initiative of ARC-Centre of Excellence for Geotechnical Science and Engineering, a group of test stone columns were installed at the Australia's first national geotechnical field testing facility at Ballina, New South Wales, Australia. The columns have been instrumented with inclinometers, extensometers, piezometers, pressure cells and settlement plates (Figure 5). The details of field instrumentation have been portrayed in Figure 6. Currently embankment construction is complete; the elevation and a photographic image is shown in Figures 7 (a) and (b) respectively. The construction history has been given in Figure 11(a). In future, this will be followed by application of cyclic load. The proposed embankment has been designed as: 6m square at top, 3 m height and 1*V* : 1.5 *H* side slope. The excavated trench will be filled up by medium gravel to allow for free drainage of water.

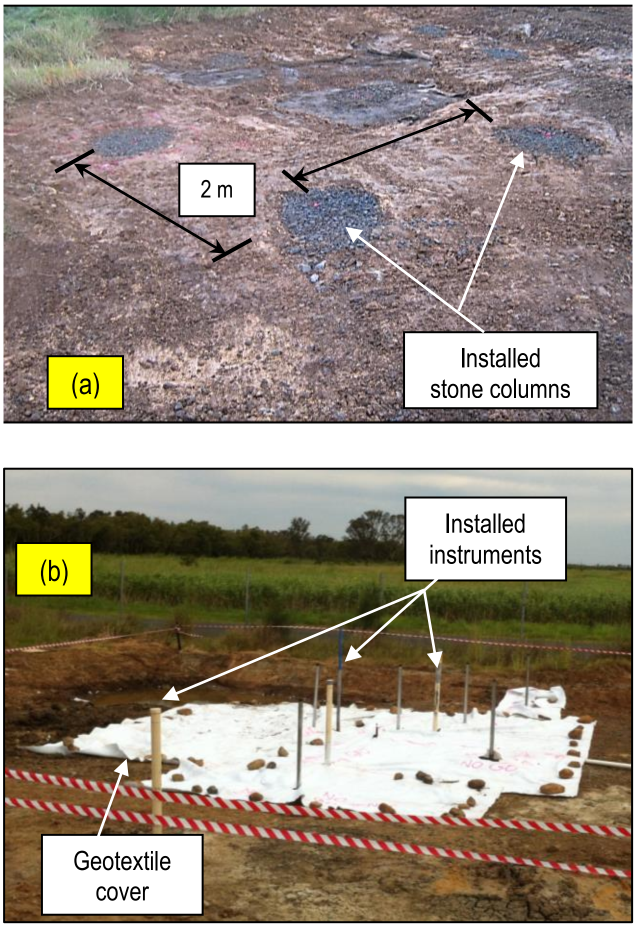


Figure 5 Instrumented field trial: (a) Exposed columns, and (b) Installed instruments

5. RESULTS AND DISCUSSIONS

The experimental and computed load-settlement response is given in Figure 8. A good agreement between the numerical and test data has been observed, which justifies the validity of the proposed model.

The CT scan images for the column cross section, exhumed column and the lateral deformation quantification is shown in Figure 9. The CT scan image of column cross section confirms occurrence of clogging during consolidation. From the view of exhumed column, the bulging has been found to take place. The lateral column deformation has been quantified by means of strain gauge readings. The bulging took place at a normalized depth ranging as $0.2 \leq z/L \leq 0.25$. With the length of stone column as 600 mm, this range varies between 120 – 150 mm which is less than twice the column diameter (= 100 mm). Since the net confining pressure imparted on the column surface gradually increased with depth, lower confinement at shallow depth produced bulging. Detailed theoretical studies on the bulging of columns have been published elsewhere (Basack *et al.* 2017).

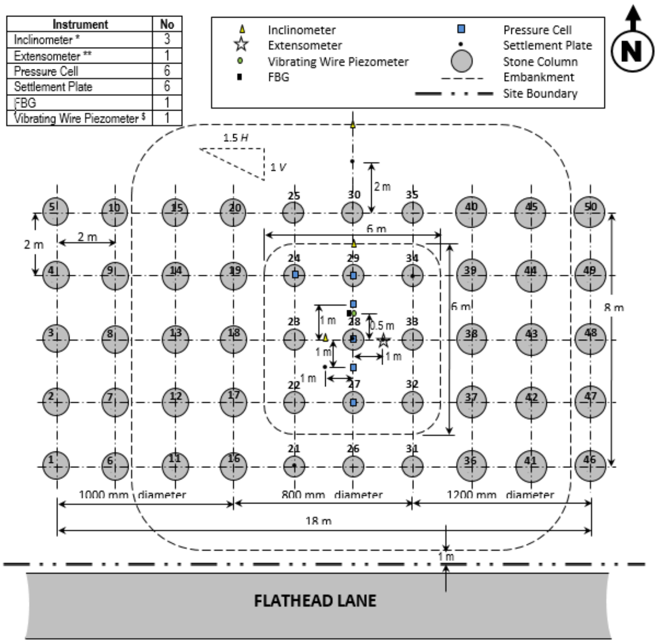


Figure 6 Instrumentation plan

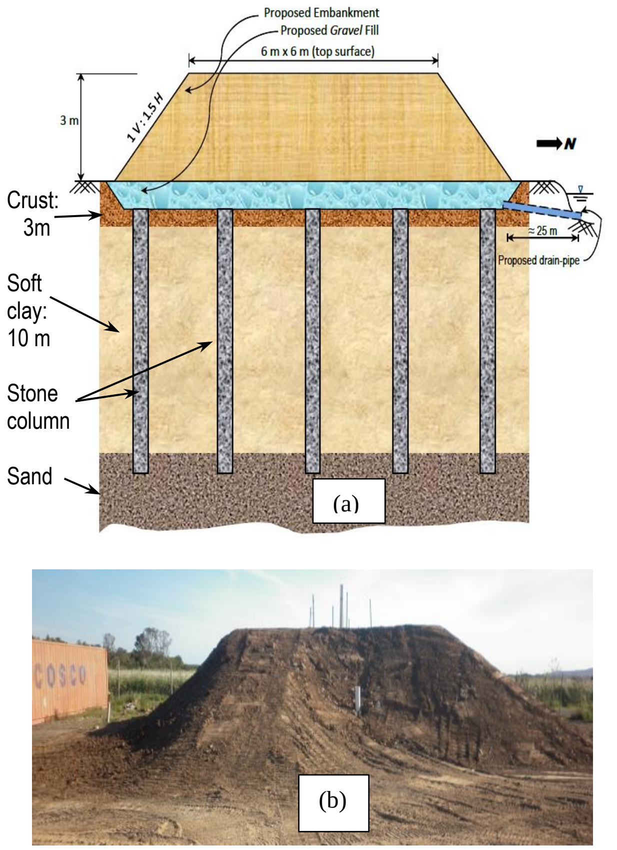


Figure 7 The embankment: (a) schematic diagram, and (b) photographic image

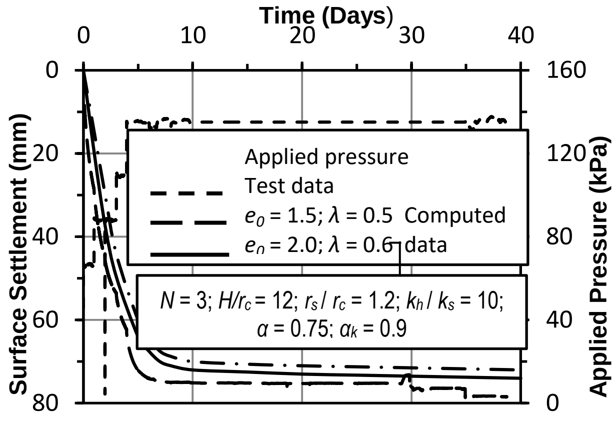


Figure 8 Load settlement response (modified after Basack *et al.* 2015b, with kind permission from ICGI-2015)

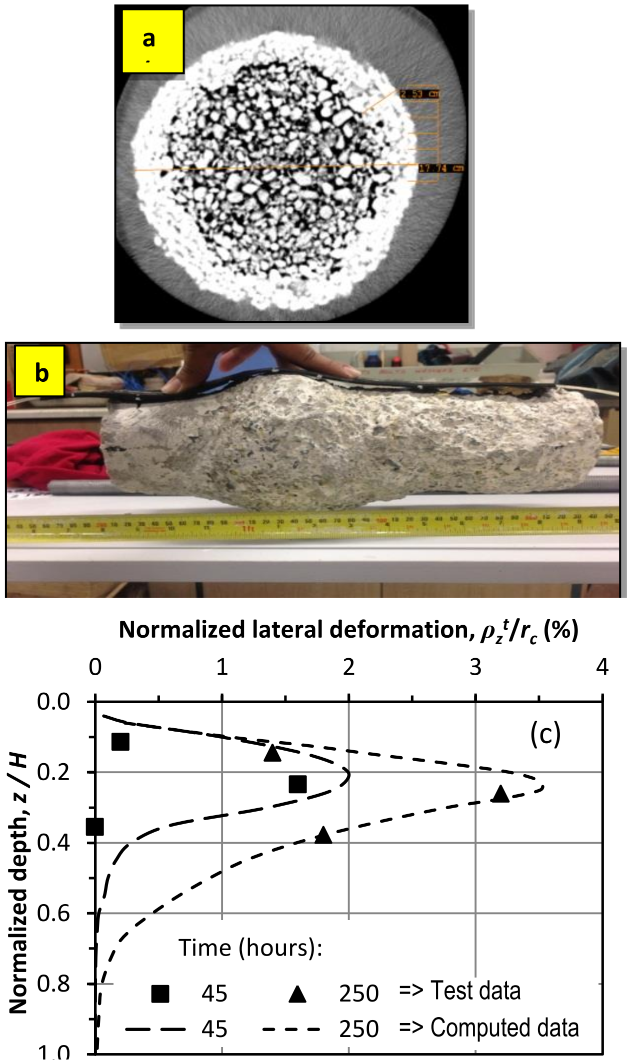


Figure 9: (a) CT-scan image of column cross section, (b) exhumed column, and (c) lateral deformation-depth plot

The behaviour of stone column reinforced soft ground under sinusoidal cyclic loading is being studied using yield surface contraction incorporating appropriate degradation functions. Comparison of preliminary results with laboratory test data (Figure 10) of Indraratna *et al.* (2009) and solutions of Ni (2012) implies acceptable accuracy of the analysis performed.

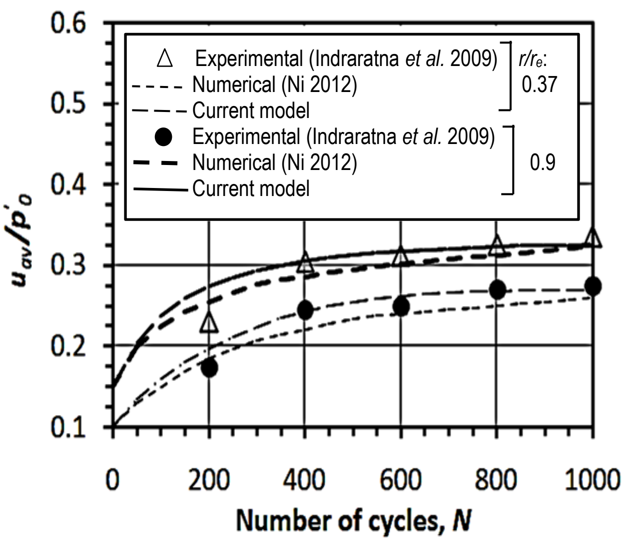


Figure 10 Cyclic loading analysis (modified after Basack *et al.* 2016a, with kind permission from ASCE)

For the initial loading period, the field observation on the load-settlement response of the soft ground adjacent to the centrally located column is plotted (Figure 11b). A reasonably good agreement with the numerical results has been found, with an average deviation below 15%. At the end of 80 days after the commencement of construction (i.e., 28 post-construction days), the field ground settlement has been measured as 72 mm against a numerically obtained value of 70 mm.

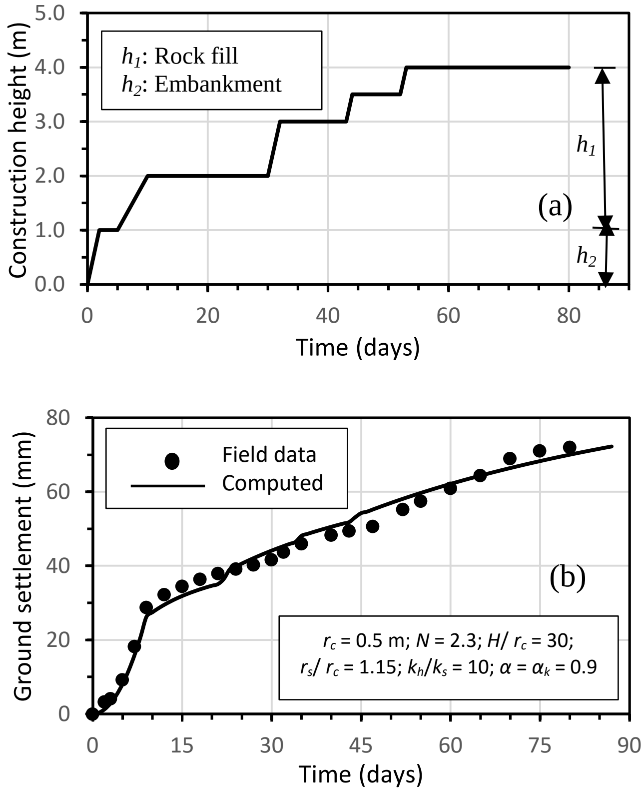


Figure 11 (a) Construction history, and (b) Load-settlement response

A series of peizocone tests have been conducted at the site (Figure 12) to assess the installation effects on the soft ground. The test results indicate significant alteration in soft ground properties due to stone column installation (Figure 13).

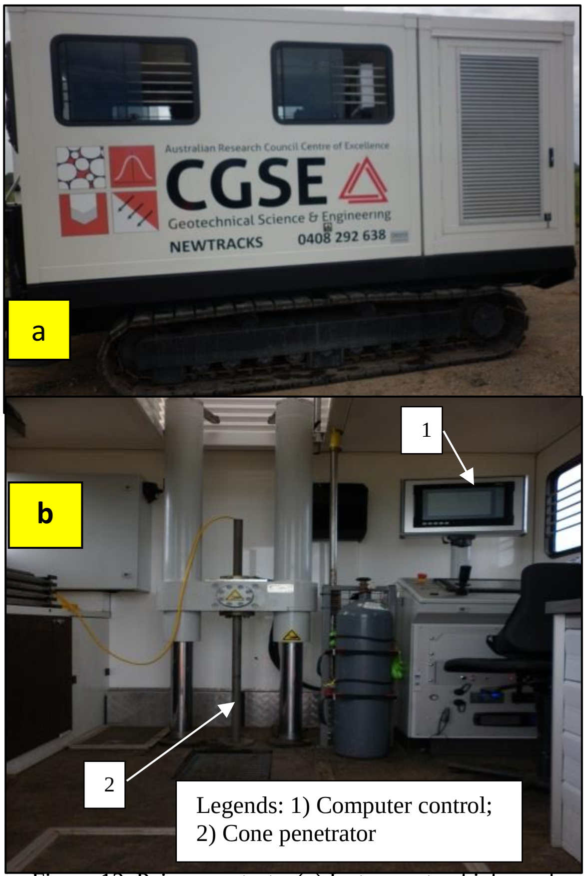
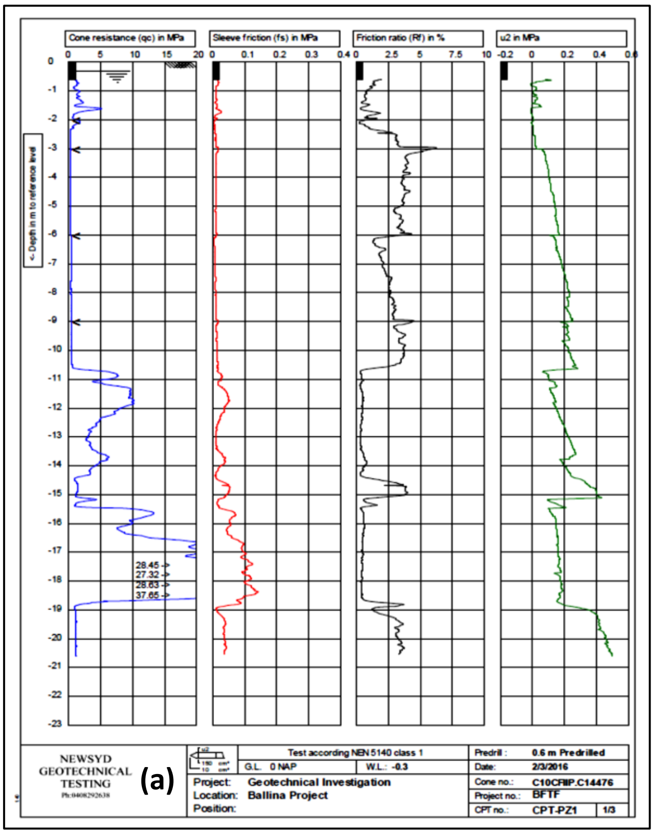


Figure 12 Peizocone tests: (a) Instrument vehicle, and (b) Interior of the vehicle



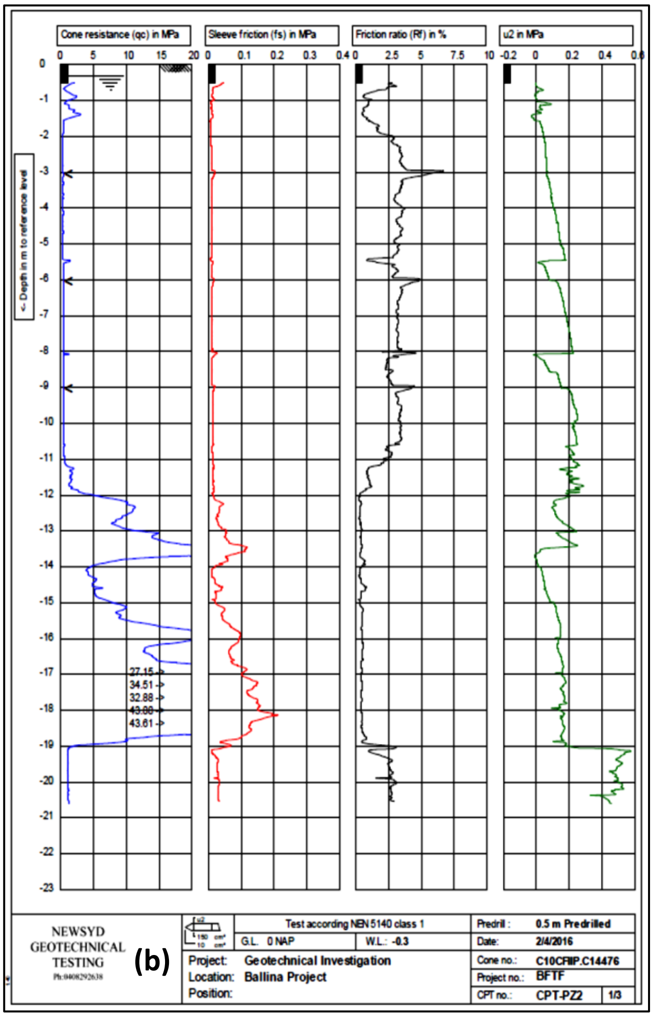


Figure 13 Piezocone test data: (a) Outside the stone column area, and (b) Within the stone column area

The available field and design data have been utilized to estimate the short and long term anticipated ground settlements with and without stone column reinforcement, as presented in Table 1. It is observed that the inclusion of stone columns reduce the ground settlements up to about 15-30% which indicates the efficiency of stone column reinforcement in reducing ground settlement because of column-soil relative stiffness.

Table 1 Anticipated ground settlements

Embankment Height (m)	**Anticipated ground settlement (m)**					
	3 months		6 months		12 months	
	R	U	R	U	R	U
3.0	0.17	0.24	0.25	0.31	0.29	0.34
4.0	0.26	0.37	0.36	0.44	0.40	0.47
4.5	0.31	0.43	0.41	0.51	0.45	0.53
5.0	0.35	0.49	0.45	0.56	0.50	0.59

R: Reinforced with stone columns;
U: Unreinforced soft ground;

The field observation on the load-settlement response of reinforced ground for the initial loading period exhibits good agreement with the numerical results.

The anticipated reinforced ground settlements obtained from numerical model has been found to be 15-30% less than the unreinforced ground, which indicates the efficiency of stone columns in reducing settlement.

A good agreement between the numerical and experimental load-settlement response has been found, which justifies the validity of the proposed model. From cyclic analysis, the agreement between the numerical and the experimental results was satisfactory. The CT scan image of the column cross section indicated the occurrence of clogged zone. The shape of the exhumed column revealed occurrence of bulging.

6. CONCLUSIONS

The stone column reinforcement has been found to be quite effective in stabilizing soft ground supporting transport infrastructure. In the proposed numerical modelling, appropriate consideration for arching, clogging and smear has been considered. Apart from short term and long term load-settlement response of the reinforced soft ground, the lateral column deformation and ultimate bearing capacity are some of the essential features taken care of by the model. The analysis under cyclic loading has been performed as well.

In the laboratory model test, soft kaolin clay and angular stone column were used. Tests were conducted in a large scale uniaxial consolidation cell.

The instrumented field trial was conducted at Ballina, New South Wales, Australia. Although the installation of instruments is complete, the embankment is yet to be constructed.

From the cone penetration tests conducted at the site, significant deviation of the soft soil characteristics due to column installation was observed. This indicates the occurrence of smear zone around the newly installed stone columns. This observation is consistent with the assumed zone of disturbance around the column lateral surface in the soil zone of the unit cell, as shown in Figure 2.

7. ACKNOWLEDGEMENTS

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8. LIST OF NOTATIONS

The following notations were used in the model:
F = stress function;
H = thickness of the soft clay deposit;
K_s = earth pressure coefficient at rest;
k_h = horizontal soil permeability;
k_s = horizontal permeability of smear zone;
m_{vrt} = soil volume compressibility;
$N = r_e / r_c$;
n_s= steady state concentration ratio;
r = radial coordinate of unit cell;
r_c = radius of stone column;
r_c' = radius of stone column excluding the clogged zone;
r_e = radius of influence of one stone column;
r_s = radius of smear zone;
t = time coordinate;
u_{rt} = excess pore water pressure;
$\overline{w}$ = surcharge load intensity on ground surface;
w_{sur} =average vertical stress on embankment;
α = radius factor for clogging;

α_k = permeability factor for clogging;
η_t ,η_b = restraint factors;
γ' = effective unit weight of soil;
γ_e = unit weight of embankment material;
γ_w = unit weight of water;
λ = slope of *e - ln p'* curve;
ρ_{av} = average ground settlement;
$\rho^p{}_z$ = stress induced component of column deformation;
$\rho^s{}_z$ = shear component of column deformation;
ρ_{rzt} = vertical displacement of a soil nodal point;

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