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Sudip Basack
*University of Wollongong*, sudip@uow.edu.au

Buddhima Indraratna
*University of Wollongong*, indra@uow.edu.au

Cholachat Rujikiatkamjorn
*University of Wollongong*, cholacha@uow.edu.au

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## Abstract

This paper presents an analytical and numerical study on the behavior of stone column stabilized soft ground supporting transport infrastructure. Analysis has been carried out on the response of reinforced soft ground under static and cyclic loadings relevant to transport corridors.

## Keywords

analysis, soft, column, ground, stone, infrastructure, transport, supporting, behaviour, stabilized

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# Analysis of the Behaviour of Stone Column Stabilized Soft Ground Supporting Transport Infrastructure

Sudip Basack[1*], Buddhima Indraratna[1]and Cholachat Rujikiatkamjorn[1]
[1]*Centre for Geomechanics and Railway Engineering*
*University of Wollongong,NSW 2522, Australia*
*sudip@uow.edu.au, indra@uow.edu.au, cholacha@uow.edu.au*

**Abstract**
This paper presents an analytical and numerical study on the behavior of stone column stabilized soft ground supporting transport infrastructure. Analysis has been carried out on the response of reinforced soft ground under static and cyclic loadings relevant to transport corridors.

*Keywords:*Consolidation, cyclic load, settlement, soft clay, stone column

## 1 Introduction

Stabilizing soft ground by installation of stone columns has numerous benefits including improved bearing capacity, accelerated consolidation, increased slope stability and liquefaction control (Fatahi*et al.* 2012). Compared to prefabricated vertical drains (PVDs), the stone columns are stiffer and provide for faster dissipation of excess pore water pressure from soft clay (Basack *et al*. 2015a).

Transportation routes subject the ground to cyclic loading due to passage of vehicles in addition to the dead loadfrom an embankment (Basack *et al.* 2015b). The embankment loading induces a non-uniform strain condition across the embankment cross section, i.e., a ‘freestrain’condition (Indraratna *et al.* 2013).

This paper developsan analytical and numerical model based on fast lagrangian finite difference technique on the behavior of stone column stabilized soft ground under static and cyclic loads. The solution is based on unit cell approachassuming free strain vertical deformation. The arching, clogging and smear effects are taken into account (Indraratna *et al.* 2013). The modified cam-clay theory (Roscoe and Burland 1968) is employed to study the soil behaviour. The solutions developed have been validated and applied to selected case studies. The analyses performed, observations made and the conclusions drawn are described in this paper.

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[*] Corresponding Author

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## 2 Analytical and Numerical Modelling

The solution developed is based on unit cell analogy with free strain hypothesis considering arching, clogging and smear effects (Indraratna *et al.* 2013). The idealized problem (axisymmetric) is depicted in Figure 1a, 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 surface is carrying a uniformly distributed load with intensity,$\bar{w} = w_{sur} + \gamma_e H_e$, where, $w_{sur}$ is the surcharge load on the embankment having a height of $H_e$and unit weight of $\gamma_e$. The analysis is based on the assumption of purely radial flow of pore water towards the column, obeying Darcy's law. For computation, the unit cell is discretized radially and depth-wise into number of elements $n_r$ and $n_z$ respectively (Figure 1b), 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.

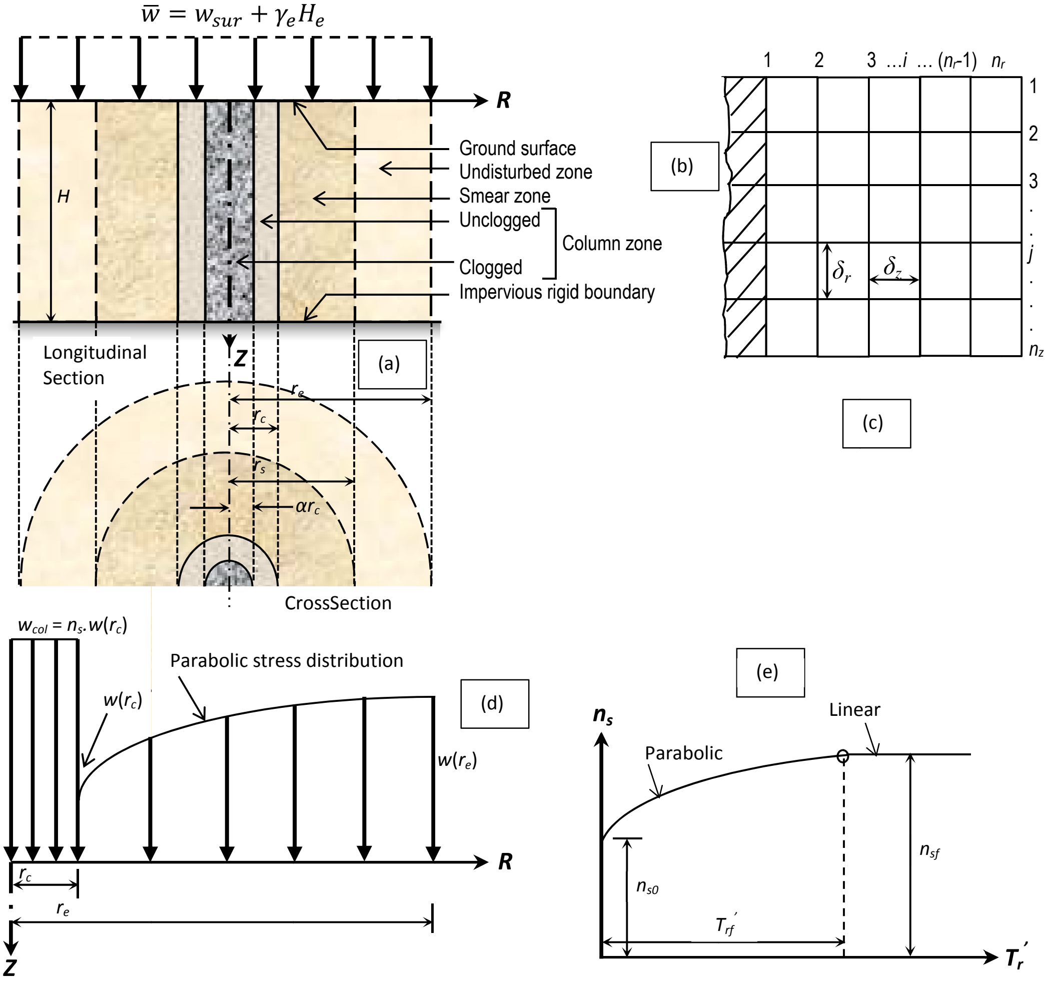

Figure 1: The idealized problem:(a) Unit cell sections, (b) Discretization of unit cell, (c) Stress components in column element, (d) Imposed vertical stress distribution, and (e) Variation of stress concentration ratio.

## 2.1 Column-Soil Load Transfer

Immediately after the embankment load is applied on the reinforced ground surface, both the column and the surrounding soil undergo undrained elastic settlements (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 (see Figure 1d):

$$w(r) = w(r_e)[1-(N-r/r_c)^2 F(N,n_s,\bar{w}] \qquad \ldots \qquad (1)$$

where, $n_s$ is the steady state stress concentration ratio, $N = r_e / r_c$ , $F(N, n_s, \bar{w})$ 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 observations (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 byHan and Ye (2001). Thus, the stress concentration ratio has been expressed mathematically as (see Figure 1e):

$$n_s = n_{s0} + n_{sf}\left[2\frac{T_r'}{T_{rf}'} - \left(\frac{T_r'}{T_{rf}'}\right)^2\right] \quad \text{for } T_r' < T_{rf}'$$

$$= n_{sf} \text{for} T_r' \geq T_{rf}' \ldots \qquad (2)$$

where, $n_{s0}$ and $n_{sf}$ are the initial and steady state stress concentration ratios, the modified time factor (Basack *et al.* 2011) is given as: $T_r' = c_h t/H^2$ , where, $c_h$ is the coefficient of radial consolidation (Barron 1948) and $t$ is the time. The parameter $n_s$becomes constant for$T_r' \geq T_{rf}'$.

## 2.2 Soft Soil Consolidation and Ground Settlement

Thesoil model is based on the modified Cam-clay theory to incorporate the non-linear correlation between void ratio and effective stress. Only radial drainage is considered.The governing equations (further details in Basack *et al.* 2015b)are given by:

$$\frac{\partial u_{rt}}{\partial t} = c_h\left(\frac{1}{r}\frac{\partial u_{rt}}{\partial r} + \frac{\partial^2 u_{rt}}{\partial r^2}\right) \qquad (3a)$$

$$m_{v_{rt}} = \frac{3\lambda/(1+2K_s)}{p'/p_0'[\vartheta_0 - \lambda \ln(p'/p_0')]} \qquad (3b)$$

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, $\lambda, p_0'$and $\vartheta_0$ are the modified Cam-clay parameters, $p'$ is the effective stress in the clay and $K_s$ is the earth pressure coefficient.

The effect of column clogging is included in the model, where the effective drainage radius in the column is taken as $\alpha r_c$, with$\alpha$ being a non-dimensional parameter in the range of $0 \leq \alpha \leq 1$. The permeability in the clogged zone is taken as $\alpha_k$ times the smear zone permeability, where $0 \leq \alpha_k \leq 1$. The expression for the clogging parameter $\alpha$ is given by (Basack *et al.* 2015c):

$$\alpha = \alpha_f + (1-\alpha_f)exp(-\alpha_t T_r') \qquad (4)$$

where, $\alpha_f$ and $\alpha_t$ are non-dimensional clogging parameters in the range of 0-1.

The nodal and average ground settlements have been computed using the following expressions (Basack *et al.* 2015b) respectively:

$$\rho_{rzt} = -\int_0^t \int_z^H m_{v_{rt}} \frac{\partial u_{rt}}{\partial t}\, dz\, dt \qquad (5a)$$

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

where, $\rho_{rzt}$and $\rho_{av_t}$ are the nodal and average ground settlements respectively.

## 2.3 Influence of Cyclic Loading

Cyclic loading has been idealized as regular sinusoidal (see Figure 2a). Application of cyclic loading in soft clay initiates progressive built-up of excess pore water pressure (Carter *et al.* 1982).The same has been captured by applying modified Cam-clay theory. Salient features of the model (more details in Basack *et al.* 2015b)are included briefly below.

Under cyclic loading, the stress path of a specified point within the soft soil in the *q-ln p'* spacefollows *ABCDEF*, as shown in Figure 2. The deviatoric stress *q* and the mean effective stress *p'* are respectively expressed by:

$$p' = [w(r) + \gamma_s' z - u_{rt}]\frac{1+2K_s}{3} \quad (6a)$$

$$q = [w(r) + \gamma_s' z - u_{rt}](1 - K_s) \quad \ldots \quad (6b)$$

where, $\gamma_s'$ is the effective unit weight of soil. The deviatoric stress and mean effective stresses in the soil relevant to the points *A, B, C, D* and *E* have been obtained by modified Cam-clay theory introducing a soil degradation parameter (Basack *et al.* 2015b; Ni *et al.* 2014).

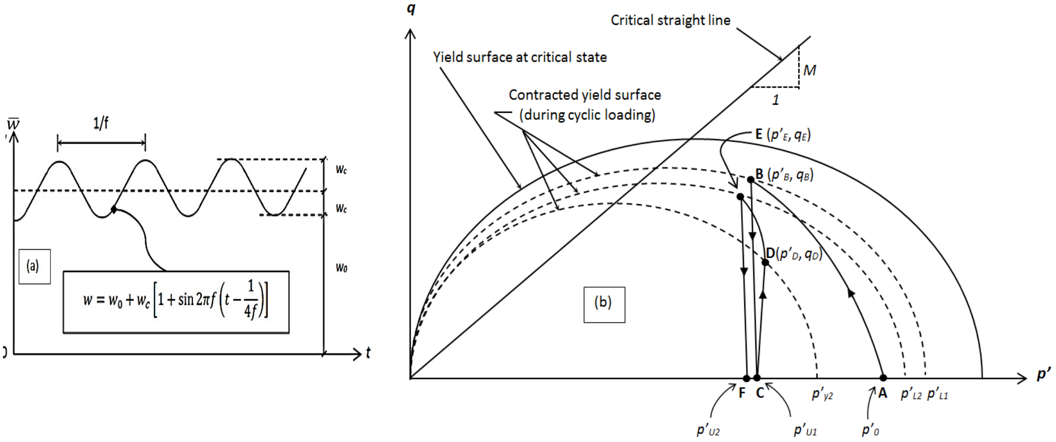

Figure 2: Analysis for cyclic loading: (a) Time pattern of variation of imposed load on reinforced ground surface, and (b) Cyclic stress path in *q-ln p'* space(Modified after Basack *et al.* 2015b, with permission from ASCE).

The analysis for static and cyclic loads has been performed using a user friendly program COLMCC written in Fortran 90 language.

# 3 Results and Discussions

The results obtained using the model has been compared with available field test data to ensure the accuracy of the formulations developed. Thereafter, further parametric studies have been carried out. The analysis and their interpretations are presented here.

The Pacific Highway linking Sydney and Brisbane at Ballina, New South Wales, Australiawas constructed on a compressible and saturated marine clay deposit, which was stabilized by a group of stone columns installed and tested at the site(Siahaan *et al.* 2011). A comparison of the computed load-settlement response with the observed field data is presented in Figure 3. The computational input parameters taken from Siahaan *et al.* (2011) and Indraratna (2010) and are presented in Table 1.

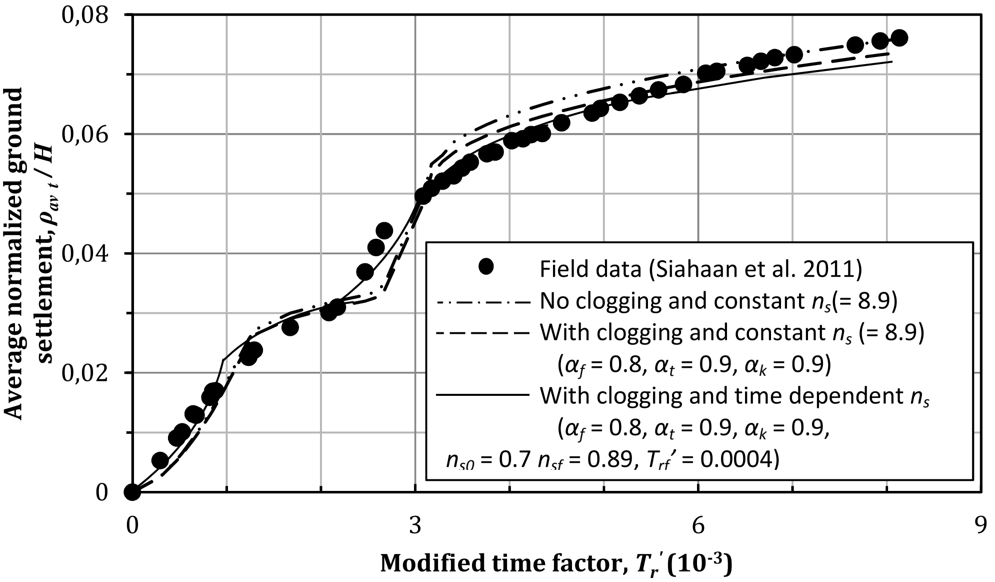

Figure 3: Validation of the model with field data and previous solutions.

| Soft Clay | $k_h$ (m/s) | $m_v$ (m$^2$/N) | $e_0$ | $\lambda$, $\kappa$ | $k_h/k_s$ | $r_s/r_c$ | $H$ (m) | $\gamma_s$ (kN/m$^3$) | Cyclic parameters: $a_N$, $a_f$, $b_f$ |
|---|---|---|---|---|---|---|---|---|---|
| | 1 x $10^{-9}$ | 3 x $10^{-6}$ | 3.9 | 0.57, 0.06 | 10.0 | 1.15 | 10 | 18 | 0.28, 320.0, 125.0 |
| Embankment | Passive earth pressure coefficient | | | | | Unit weight (kN/m$^3$) | | | |
| | 3.0 | | | | | 20 | | | |
| Stone column | $r_c$ (m) | | $r_e$ (m) | | Unit weight (kN/m$^3$) | | | Earth pressure coefficient, $K_s$ | |
| | 0.5 | | 1.16 | | 17 | | | 0.8 | |
| *Notations and values of each of the parameters are explained in details elsewhere (Basack *et al.* 2015b) | | | | | | | | | |

Table 1: Computational data* (after Siahaan *et al.* 2011)

Because of limited information on the input data such as clogging parameters ($\alpha_f$, $\alpha_t$, $\alpha_k$) and stress concentration ratio ($n_{s0}$ and $T_{rf}'$), their values have been assumed based on available literature (e.g.: Siahaan *et al.*2014; Basack *et al.* 2015c). As observed from Figure 3(b), the clogging retards the consolidation and settlement of soft clay significantly. With appropriately chosen clogging parameters, the computed ground settlements are observed to be close to the field data. When the stress concentration ratio is taken as time dependent, the computed results are even closer to field observations for initial loading period, compared to those computed with constant value of $n_s$.

For cyclic analysis, additional parameters such as $\lambda$,$\kappa$ and $e_0$are chosen (more details inBasack *et al.* 2015b). The Figure 4 shows the pattern of building up of excess pore water pressure. As observed, for initial load cycles, the pore water pressure is being built up rapidly and gradually stabilizes with increasing number of cycles. The frequency, amplitude and initial excess pore water pressure also affect the cyclic analysis. When clogging is considered, building of pore water pressure in the soft clay increases, due to the retarding effect of clogging. It should be noted that the cyclic model described here is valid only for low frequency and small amplitude. For higher magnitudes of cyclic loading, rotation of principal stress axes with induced shear stresses in the clay influences the results.

To justify the validity of the proposed analysis, the computed cyclic resultshave also been compared with available field test data (Raju *et al.* 2013; Basack *et al.* 2015b). The variation of residual ground settlement against peak load intensity is studied (Figure 5). The curves are observed to increase in a parabolic manner with ascending slopes. With the stress concentration ratio $n_s$ being taken as function of time, as described above, the residual settlement is observed to provide a better matchthan the case of constant $n_s$.

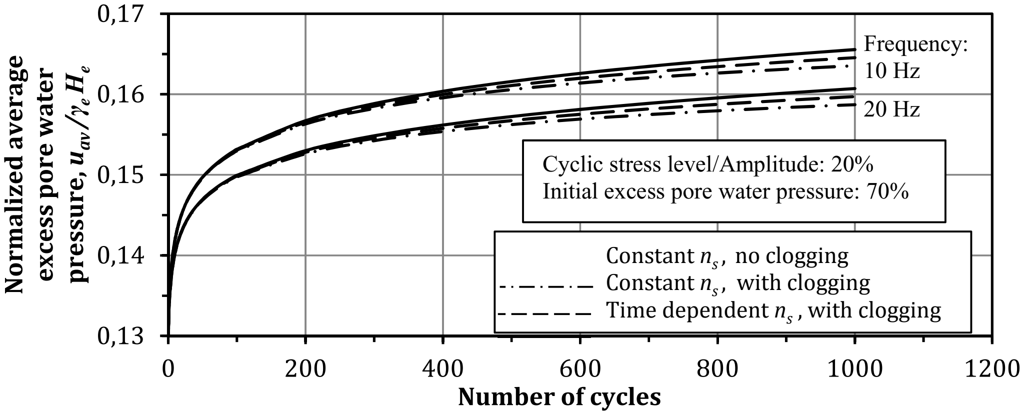

Figure 4: Variation in average excess pore water pressure with number of cycles (Modified after Basack *et al.* 2015b, with permission from ASCE).

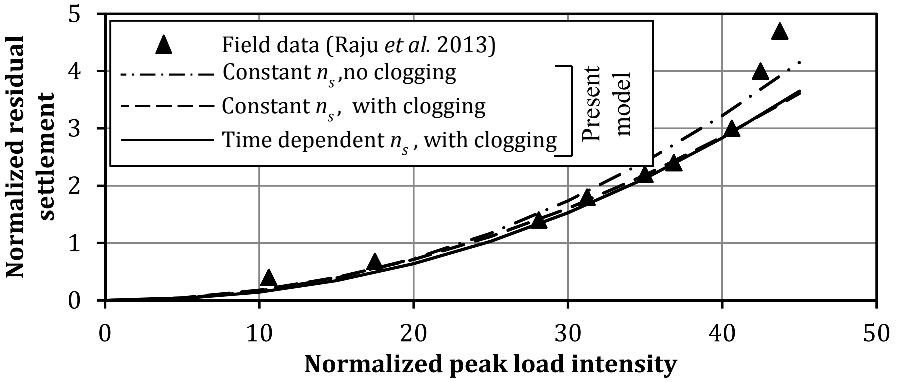

Figure 5: Comparison of the computed cyclic results with field data(Modified after Basack *et al.* 2015b, with permission from ASCE)..

# 4 Conclusions

Analysis of the behaviour of soft ground reinforced with stone columns under static and cyclic is carried out by means of numerical analysis. The methodology is based on appropriate consideration of arching, clogging and smear effects. A time dependent column-soil stress concentration ratio has been considered, while for clogging, an exponentially increasing clogged zone is taken. Comparison of computed data with available field test data justifies the accuracy of the solutions developed.

Column clogging was observed to retard the consolidation and settlement of soft clay significantly. With appropriately chosen clogging parameters from available literature, the computed ground settlements are found to match closely with field embankment. When the time dependencyof stress concentration ratio is considered, the computed results are closer to field observations specifically for initial loading period, compared to those computed with constant value of the stress concentration ratio.

For cyclic analysis, the pore water pressure was found to increase up rapidly for initial load cycles, and gradually stabilizes. The pattern of variation depends on frequency, amplitude and initial excess pore water pressure. Clogging retards pore water pressure dissipation, thus further building up of pore water pressure in the soft clay.

The residual ground settlements observed in experimental data are predicted by the proposed model. When clogging is included, the predictions match better with the experimental values.

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