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Soft Ground Improvement by Granular Reinforcement for Transport Infrastructure

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Abstract. Structures founded on soft ground are likely to be exposed to disastrous consequences due to possible undrained failure or excessive settlement unless proper ground improvement is undertaken. Soft soil improvement by granular reinforcement has numerous benefits in terms of strength and stiffness as well as accelerated consolidation. Foundation soil supporting transport infrastructure are in addition subjected to cyclic loading initiated by traffic movement. This paper presents the load-transfer and consolidation characteristics relevant to stone column reinforced soft ground supporting transport infrastructure.

Keywords. Soft ground; Granular reinforcement; Stone column

1. Introduction

Soft ground improvement by granular reinforcement, especially by installing stone columns, has numerous benefits including increased bearing capacity due to significant column-to-soil stiffness ratio and accelerated consolidation due to higher hydraulic conductivity [1]. Foundations supporting transport infrastructure are subjected to cyclic loading resulting from traffic movement. Such load reversals induce progressively building up of excess pore water pressure which is capable to produce disastrous consequences [2]. The aims of this paper are to illustrate the load displacement and consolidation characteristics, optimizing column installation and studying influence of high frequency cyclic loads.

2. Theoretical Analysis

The theoretical analysis was done using advanced analytical and numerical modelling. The load transfer and consolidation characteristics of stone columns are captured based on unit cell analogy and free strain hypothesis [3]. The vertical stress distribution in soft soil has been quantified by the following equation:

$$w_r = w_{r_e} + (N - r/r_c)^2 F \tag{1}$$

where, r = radial coordinate, r_c & r_e = column and unit cell radii, F= An algebraic function of r_e, r_c

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and stress concentration ratio. The radial consolidation characteristics of soft ground are governed by Barron's radial consolidation Equation coupled with modified Cam-clay theory [4-6]. The basic differential equation is given by [7]:

$$[\nabla_r^2 - \nabla_t]u = 0 \tag{2}$$

The arching, clogging and smear effects have been included in the analysis. The lateral column deformation is quantified by the stress-induced deformation (ρ_z^e) plus the barreling component (ρ_z^s), as detailed in by the author elsewhere [8-9].

The effects of cyclic loading on reinforced soft ground has been incorporated using the modified Cam-clay model applying cycle-by-cycle analysis (Basack *et al.*[10-11].Comparison of computed results with field data (Fig.1) indicates accuracy of the analysis.

Laboratory Experimentations

Large-scale one-dimensional consolidation tests on instrumented single stone column in soft kaolin clay were conducted (Fig.2). The soft clay was prepared by mixing dry powder of kaolin with water to form a slurry. A pre-consolidation stress of 65 kPa was applied to achieve 95% degree of consolidation. The model stone column was installed via the replacement method to minimize the disturbed zone [12]. To measure the column lateral deformation, two fibre-glass strips with strain gauges were inserted into the sides of the column.

The stress concentration ratio was found to be influenced by time and particle size distributions. Post-consolidation exhumation of the column followed by CT-scan image processing quantified the lateral deformation as well as intrusion of fines (Fig.3). The reinforced soft soil performance was found to be largely dependent on particle morphology and reinforcement geometry.

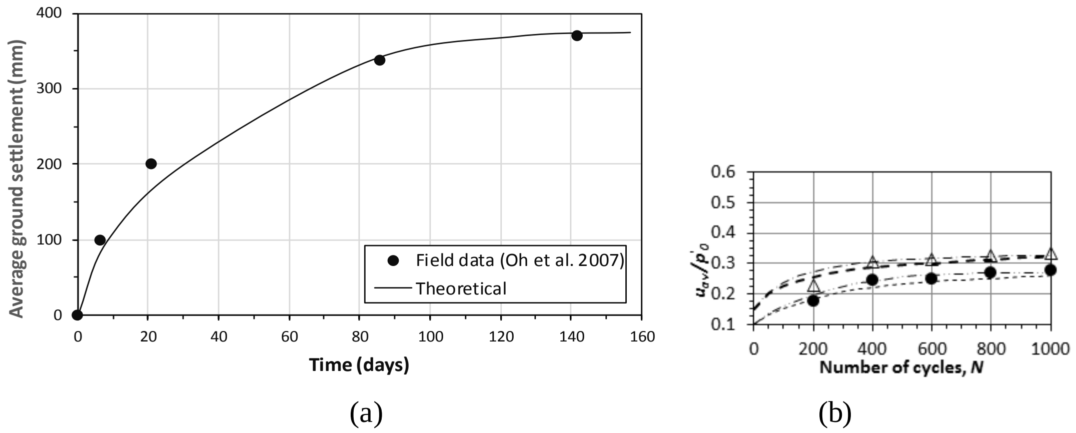

Figure 1. Comparison of theoretical results with: (a) field test data for static loading, and (b) laboratory test data for cyclic loading

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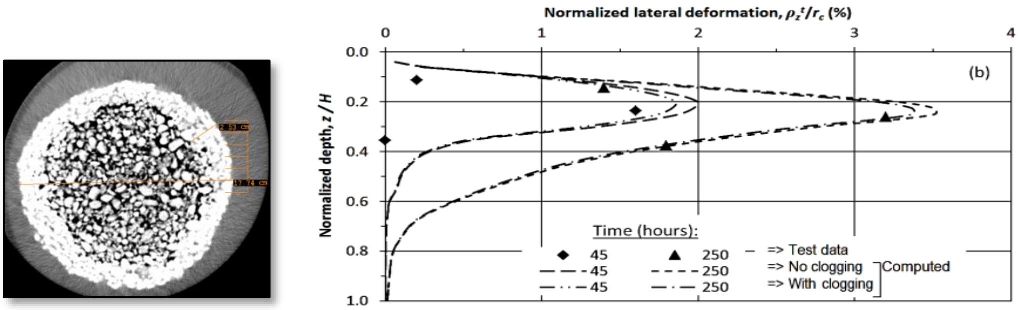
Figure 2. Large-scale one-dimensional consolidometer.



(a) (b)

Figure 3. (a) CT scan image of clogged column section, and (b) theoretical and experimental results

3.Field Test

With the initiative of Centre of Excellence for Geotechnical Science and Engineering (Australian Research Council), a group of test stone columns were installed at the Australia's national geotechnical field-testing facility at Ballina, New South Wales. The site consists of soft, compressible marine clay and the columns were installed by Keller Ground Engineering. The columns have been instrumented with inclinometers, extensometers, piezometers, pressure cells and settlement plates. Above the reinforced soft ground, an embankment was constructed in stages. A photographic view of site is given in Fig.4. More details of the field test have been published elsewhere [13].

Figure 5. Photo of site.

The factor of safety against undrained failure has been computed using current method and other existing methods and presented in Table 1 [8]. The load-settlement response of the ground in the vicinity of the central column is depicted in Fig.5. As observed, the computed factor of safety is close to the existing methods, with an average deviation of about 21%. The value obtained using the current method is higher, compared to those evaluated by the other methods. From Fig.5, it is observed that the average soft ground settlement obtained from the present numerical modelling is in proximity with those obtained from the field measurement.

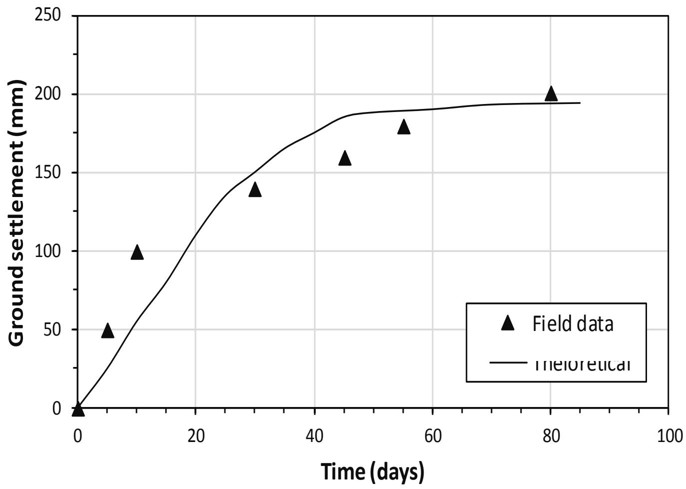


Figure 5. Load Settlement response.

Table 1: Factor of safety against undrained failure

Method of computation	**Time (days)**			
	2	10	30	50
Cao *et al.* [14]	8.3	3.6	2.1	1.9
Frikha and Bouassida [15]	9.2	4.3	3.2	2.4
Present analysis	10.7	5.3	4.1	3.3

4. Conclusions

- Soft ground improvement for transport infrastructure by stone column reinforcement is quite effective technique. To study the load transfer mechanism, consolidation characteristics and the influence of high frequency cyclic loading, advanced theoretical modelling, laboratory experimentations as well as instrumented field tests have been performed.
- The theoretical results were found to be in close agreement with the laboratory experimental data and field observations.
- The laboratory experimentations were conducted using a one-dimensional consolidometer. The CT scan image processing was done to visualize the clogging characteristics. The instrumented field trial, on the other hand, was done with earthen embankment being constructed in stages on the reinforced soft ground and the field data were recorded.

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Conflicts of Interest
The authors express that there is no conflict of interest.

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