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Analysis of improved ground with geonet reinforced stone columns

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ABSTRACT: This paper presents the results of analysis of soft ground improved by stone-columns wrapped with layers of geonet and needle punched geotextile by using nonlinear FEM and testing in laboratory and field. The validation of needle-punched geotextile on improving the filtrating function of crushed stone-columns is elucidated by combining with the results of laboratory test. According to the comparison between the results of calculation and measurement, and the influence of column spacing on the settlement of soft soil ground, the rationality of column arrangement scheme is expounded and proved. Besides, the reinforcing function of geonet on crushed stone-columns to resist bulging failure near the tope end of stone-column is also discussed by using limit state equilibrium theory.

1 INTRODUCTION

Two main problems will be encountered in the application of crushed stone-columns. The first one is that during drainage the tiny particles in soft soil will be carried into the crushed stone-columns by seepage flow, which will block effective drainage way in the crushed stone-column. The other one is, due to the heaped preload and construction load or other loads, the crushed stone-column may be damaged at the depth approximately equal to 2 to 3 times the radius of the crushed stone-column near the top of column due to bulging. The reason for this is the shear strength of soft soil near the top end of the stone column is fairly low and the soft soil is unable to provide sufficient resistance to the bulging. When these problems become more serious, there will be loss of the capacity of improved ground with crushed stone-column. To solve these problems, some researchers have used layers of geogrid in stone-column (Madhav et al. 1994, Sharma 1998, Zhou et al. 1998) to reinforce the stone column near its top end. Similarly, crushed stone-column improved by wrapping layers of geosynthetics materials including geonet and needle punched geotextile around it are used when we deal with soft soil ground in section K31+946~K32+045 of National Road 320 in Hunan Province. Results of test carried out in field trial have proved that this is an effective method.

In order to interpret the action of geosynthetics materials on crushed stone-column, following will present the study by using FEM based on Biot consolidation theory and Duncan-Chang nonlinear model for soft soil, the limit state equilibrium theory, and field and laboratory tests.

2 FEM BASED ON BIOT CONSOLIDATION THEORY

2.1 *Nonlinear FEM*

For axial symmetrical question, 8-noded isoparametric is selected. Equilibrium equation based on Biot consolidation theory and continuity equation for saturated soil are:

$$\begin{bmatrix} k_e & k_{ep} \\ k_{ep}{}^T & -\beta(\Delta t)\ k_p \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta p \end{bmatrix} = \begin{bmatrix} \Delta R \\ \Delta Rw \end{bmatrix} \qquad (1)$$

Here k_e is the total stiffness matrix for node displacement

$$[k_{ep}] = \sum 2\pi \int_{-1}^{1}\int_{-1}^{1} \left([B]^T\{M\}[N']\right)\left([N']\{r\}^e\right)|J|\,d\xi\,d\eta \qquad (2)$$

k_{ep} is the total stiffness matrix for node pore pressure

$$[k_{ep}] = \sum 2\pi \int_{-1}^{1}\int_{-1}^{1} \left([B]^T\{M\}[N']\right)\left([N']\{r\}^e\right)|J|\,d\xi\,d\eta \qquad (3)$$

k_p is element matrix of seepage discharge

$$[k_p] = \frac{2\pi}{\gamma_w} \int_{-1}^{1}\int_{-1}^{1} \left(\{N_{,r}N_{,z}\}^T[kq]\{N_{,r}\ N_{,z}\}\right)\left([N']\{r\}^e\right)|J|\,d\xi\,d\eta \qquad (4)$$

β is time difference coefficient, and its value is determined by assumptive variation form for k_p at certain time; ΔRw is node pore pressure vector for element at the time t, and $(\Delta\delta)$, (Δp) are increasing vectors of node displacement and pore pressure at certain calculation time respectively.

$$(\Delta Rw)^e = \Delta t[K_p]^e\{p_t\}^e \qquad (5)$$

Tangent modulus E_t and Poisson ratio μ_t for soft soil are used as elastic modulus and Poisson ratio in elastic stiffness matrix. They can be represented by Duncan-Chang nonlinear model. Membrane element is used to represent the geonet. In order to describe the nonlinear relationship of relative displacement and shear stress on the interface between column and soil, Goodman interfacial element is used:

$$\{F\} = \begin{bmatrix} k_s & 0 \\ 0 & k_n \end{bmatrix} \{\delta\} \qquad (6)$$

2.2 *Calculation parameters*

The parameters used in calculation by FEM are listed as following.

For crushed stone column, its resilient modulus is 300Mpa, and Poisson ratio is 0.3.

For sand cushion on the top of soft soil, its resilient modulus is 20Mpa, Poisson ratio is 0.35, and the permeability coefficient is 0.1m/d.

For soft soil, the parameters in Duncan-Chang model are C=10.0kPa, $\phi=17^0$, K=9.0, n=0.1, Rf=0.31, H=0.14, F=0.0, D=2.0, Kur=12.0, m=0.1.

For geonet, its tensile stiffness is E_g=3.0MN/m.

For the interface between column and soil, the parameters in Goodman interfacial model are K_1=34.0, n=0.5, R_f=0.5, C=10.0kPa, $\phi=17°$, $K_n=1.0\times10^5$ MPa/m.

3 MECHANISM OF GEOSYNTHETICS IMPROVING STONE-COLUMN

3.1 *The infiltration action of needle-punched geotextile*

To reveal the infiltration characteristics of geotextile between soft soil and stone column, modeling experiment was carried out in one steel barrel filled with mud, which is 1.3m deep with 1.0m diameter. In the center of barrel, there is a crushed stone column wrapped with a layer of geonet and needle punched geotextile. The diameter of the column is 16cm. Above the mud, there is a insulating layer, which is composed of geonet and needle-punched geotextile covered with a crushed stone cushion to drainage horizontally (see figure 1).

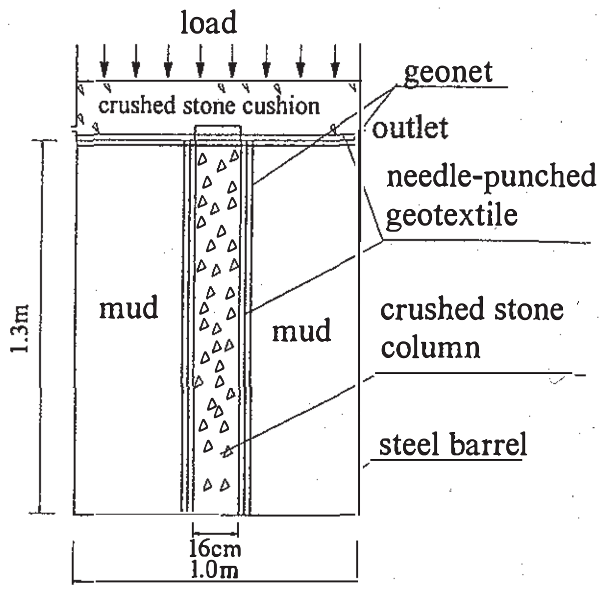
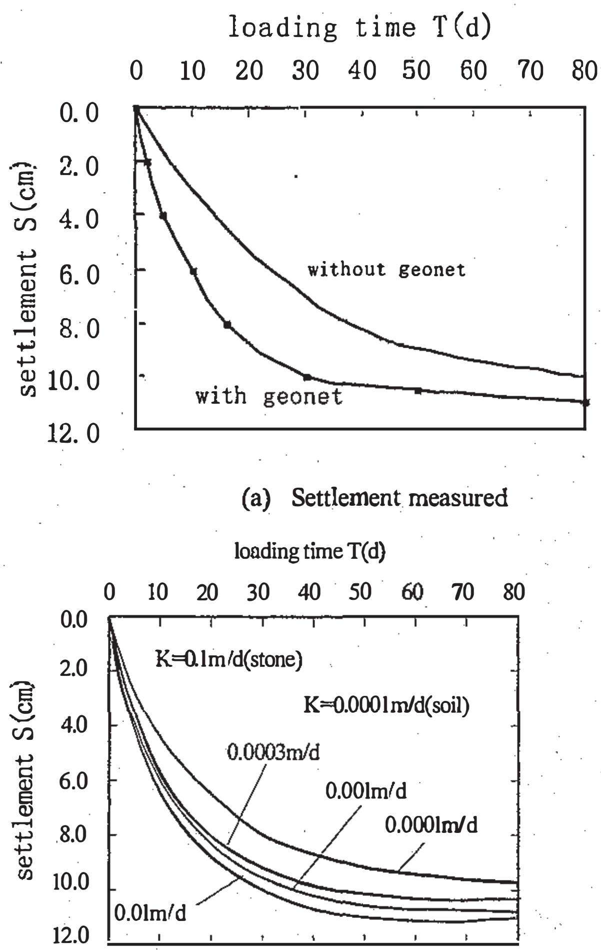


Figure 1. Model tested.



(b) Settlement calculated

Figure 2. The settlement curves of improved ground for field trial.

The results of test show that there existed a filtration layer between the column and the mud, whose permeability coefficient is between those ones of the column and the mud and its value is about 0.001m/d. The permeability coefficients of column and mud are 0.1m/d and 0.0001m/d respectively. To prove this, we used FEM to calculate and analyze the influence of the permeability coefficient of the filtration layer on the consolidation and settlement of mud during the range of 0.005~10m/d. The results have proved the existence of the filtration layer again. The results of laboratory testing and calculation indicate that the columns with and without needle-punched geotextile have different speed of consolidation and settlement (see figure 2). The needle-punched geotextile around the column improves the draining of stone column, and accelerates the speed of consolidation and settlement of the mud ground.

3.2 *Analysis of settlement of crushed stone-column improved ground*

3.2.1 *The settlement of improved ground*

The improved ground in field trial is mainly composed by following components: the soft soil is 4.82m thick; under it, there is a 0.8m thick sand layer; above the soft soil, the sand and stone cushion is 0.6m thick; the fill is 6m high. The average length of crushed stone-column is 2.4m, its radius is 0.2m, and the spacing of columns is d=1.5m (see figure 3). The loading stages of the fill is: 2.0m during 1^{st} to 6^{th} days, 2.0m during 12^{th} to 24^{th} days, 2.0m during 36^{th} to 46^{th} days.

The agreement between the results of field test and FEM calculation is satisfactory, and the error is less than 10% (figure 4). It indicates that the application of needle-punched geotextile can accelerate the speed of consolidation and settlement of soft soil.

3.2.2 *The influex nce of columns' spacing on consolidation and settlement of improved ground*

In order to verify the validity of columns' spacing for the consolidation and settlement of improved ground,

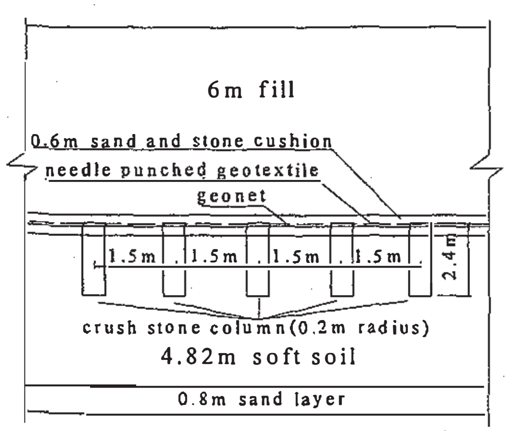


Figure 3. The structure in the field.

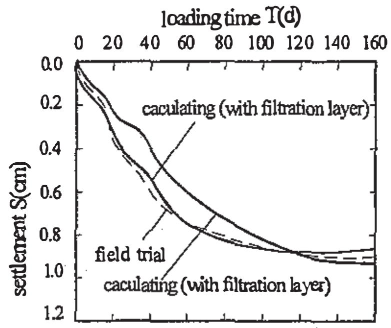


Figure 4. The settlement curves of improved ground for field trial.

we have conducted model testing with two kinds of columns' spacing (d=0.5m, 1.0m) in laboratory, and calculated and analyzed for some cases of effective radius (R=1.05m, d/2=0.8,0.5,0.4,0.3,0.25 m).

The model testing is conducted in a laboratory testing trench which is 3.72m long, 1.5m wide, and 1.5m deep. There are 21 pieces of stone-columns which are 1.2m long with 0.16m diameter. In the trench, there filled with mud 0.9m deep, and crushed stone cushion 0.3m thick. There is a layer of geonet between the cushion and the mud. 0.1MPa pressure is loaded on the top of the cushion. It took 138 days to finish the test.

In order to apply the laboratory testing results to trial section in field, the replacement rate W is used to replace the spacing d to analyze the effect of spacing. There is good agreement between the results of testing and calculation (Figure 5). The relations between the total settlement S_∞ and W or R regressed by using hyperbolic equation are:

$$\lg(S_\infty)=A_1+B_1W \quad (r=0.964) \qquad (7)$$

$$1.0/S_\infty=A_2+B_2/R \quad (r=0.996) \qquad (8)$$

Where: $A_1=3.46$, $B_1=-10.40$; $A_2=-0.0225$, $B_2=0.0296$.

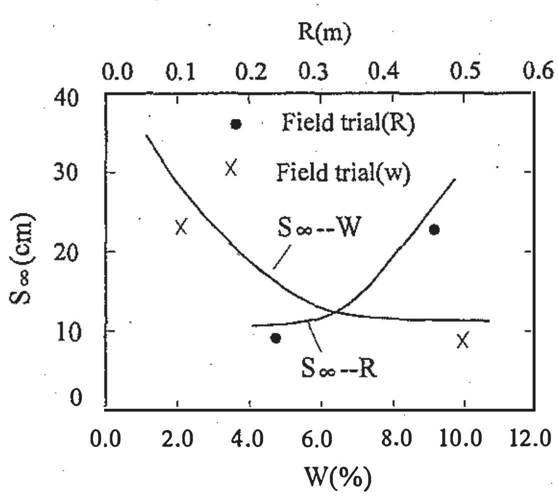


Figure 5. The relation curves of total settlement S∞ and replacement rate W or effective radius R.

The curves of S_∞-W and S_∞-R trend to level gently since W=0.7 or R=0.3. In fact, according to the definition of replacement rate, these two values are the same. If the equality criterion of replacement rate was used, the W of improved ground in field should be W=0.7 in order to ensure the stone-column to act well. As the radius of stone column in-site r=0.2m, so the spacing of columns is about d=1.5m. This is agreed with that one used in field.

The calculating results of shear forces on the wall of column (Figure 6) and pore pressures also show that decreasing the spacing of columns can accelerate the speed of consolidation and settlement of soft soil and weaken the pressure on the surface of soft soil ground. It means that the application of geonet reinforced stone-column can improve the capacity of soft soil ground.

3.2.3 *Reinforcement of geonet for 1 crushed stone column*

The limit bearing capacity of geonet reinforced stone-column is deduced by using limit state equilibrium theory (Zhou et al. 1997). Results show that the failure plane of bulging is located at the depth approximately equal to 1 to 3 times the radius of the crushed stone-column near the top of column to the nonlinear distribution of lateral pressure and axial force on column. Using the geonet can increase the bearing capacity of stone column significantly, shown as Figure 7, in which T is the tensile strength of geonet, r is the radius of column, C_t is the cohesion of soft soil, p_s and p_t are the limit pressures acted on the tops of column and soft soil respectively, h is the bulging length of

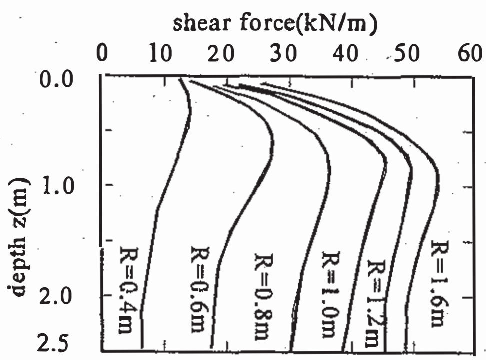


Figure 6. Distribution of shear stress on the wall of column.

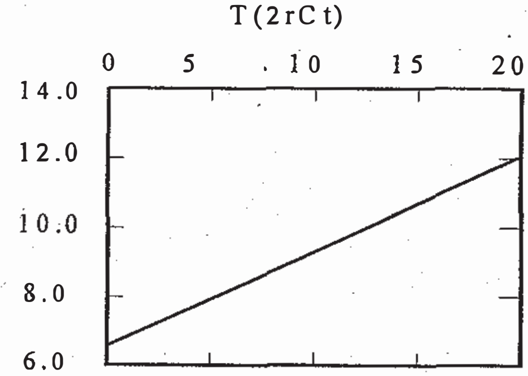


Figure 7. The relation curve of p_s/p_t and $T/(2rC_t)$.

column, and h_1 is the spacing between the top of column and the location at which the maximum shear stress is acted on the wall of column.

4 CONCLUSIONS

1. The results of laboratory test and calculation by FEM show that using needle punched geotextile around the stone column can improve the filtrating function of stone column.
2. Using geonet with more rigid tensile stiffness to wrap up the stone-column can increase its bearing capacity to resist bulging.
3. The results of calculation and measurement in field trial indicate that this kind of soft soil ground treatment method is valid and reasonable.

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