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CONSOLIDATION MECHANISM OF GROUND IMPROVED BY A COMBINED DJM-PVD METHOD

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ABSTRACT: Dry Jet Mixed (DJM) and Prefabricated Vertical Drains (PVDs) were used in combination to enhance the performance of soft ground improvement in Huai-yan highway in China. To investigate the consolidation mechanism of ground improved by a combined DJM-PVD method, coupled two-dimensional mechanical and hydraulic numerical modeling was conducted in this study to analyze the well-instrumented ground improved by a combined DJM-PVD method in Huai-yan highway in China. The results indicate that the consolidation of the ground improved by a combined DJM-PVD method is accelerated by the drainage of PVDs, the stress concentration on DJM columns and the excess pore water pressure gradient resulting from the stress transfer between the surrounding soil and columns. It is observed that the high drainage capacity of PVDs accelerates the dissipation of the excess pore water pressure. The accelerated dissipation is explained as that upon the embankment loading, the stress concentration on the column occurs due to its higher stiffness than that of the surrounding soil, and thereby results in the reduction of the excess pore water pressure in the soil. The differential settlement develops between the soil and the column induces the transfer of stress between surrounding soil and column, which results in pore water pressure gradient in the surrounding soil and accelerates the consolidation.

Keywords: consolidation mechanism, a combined DJM-PVD method, numerical models

INTRODUCTION

Dry Jet Mixing (DJM) has become a common ground improvement technique. This technique has been increasingly used worldwide, especially in Europe, North America and Asia since its development in Sweden and Japan in 1970s (Bruce et al. 1999). The DJM method was introduced to China in the early 1980s. Because this technology can effectively reduce the settlement and increase the stability of soft ground, it rapidly spread throughout China in the 1990s, especially for highway and railway embankment applications (Liu and Hryciw 2003).

However, DJM installation in China has the following disadvantages: (1) the DJM method is relatively costly due to closely spaced columns (typical spacing from 1.1 to 1.5m used in China); (2) the improved depth is limited (less than 15m in China); and (3) the DJM columns may suddenly sink into the ground after the installation. The main reasons for these disadvantages are the introduction of high air pressure into the ground and the induced high excess pore water pressure in the soft soil during the installation. These disadvantages are associated with the DJM installation methods without the capability of releasing the residual high air pressure introduced in the ground, such as the state-of-practice methods used in China and other countries.

To overcome the current problems, a new technique was proposed to combine the DJM with prefabricated vertical drains (PVDs), designated as the combined DJM-PVD method (Liu et al. 2008). The basic concept of this combined method is to utilize the high drainage capacity of PVDs to dissipate the excess pore water pressure and release the residual air pressure induced by the installation of DJM. With the dissipation of excess pore water pressure, the soft soils surrounding the columns are consolidated. The release of the residual air pressure improves the mixing quality of the in-situ soil and the powdered reagent, consequently increasing the strength of the DJM columns, and at the same time, reduces the resistance which suppresses the installation of columns into deeper depth. As a result, wider column spacing can be adopted for practice using the DJM-PVD method, which is more cost effective than the convention DJM method.

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Liu et al. (2008) presented the practice of this new technology in a pilot highway project on very soft clay in Jiangsu, China. This paper presents the consolidation mechanism of ground improved by a combined DJM-PVD method by the numerical analysis. Based on the field tests, the numerical method was employed to analyze the consolidation mechanism of ground improved by a DJM-PVD combined method under embankment loading. The solutions were obtained using the unit cell model, which consists of the column and the tributary surrounding soil within a column zone of influence.

BRIEF DESCRIPTION OF FIELD STUDY OF A COMBINED PVD-DJM METHOD

Site Conditions

A pilot field test site was selected along the Huai-Yan highway in Jiangsu Province, China, for the verification of the combined DJM-PVD method. The highway had four lanes in round directions. The design height of the embankment at the test site was 4.0m. This site has three major soil layers, which includes the top crust layer with a thickness of 1.5 to 2.0m, the second soft clay layer with a thickness of 8.8 to 10.0m, and the third hard clay layer. The second layer has two sub-layers: the 2a layer with a thickness of 0.8 to 1.1m, and the 2b layer with the thickness of 8.0 to 8.9m. The DJM columns did not penetrate the third clay layer.

Cement, which is equivalent to Portland cement Type I, was used in this project. All the DJM columns had a diameter of 500mm, a common size used in China. The average dosage of cement was 75 to 80 kg/m for DJM columns.

The PVD board had following properties: the thickness is 4.0±0.2mm, the width of 100±2mm, and the discharge capacity is 35×10^{-6} m^3/s. The maximum tensile strength of the PVD board was greater than 13kN/m at the tensile strain of 10%.

Field Test

For better performance, drainage ditches (approximately 500 mm wide and 200 mm deep) filled with sand was first constructed along the lines of PVD locations. The PVDs were then installed with a depth of 13.0m through the drainage ditches. All the PVDs were arranged in a triangular pattern as shown in Fig. 1. The spacing of the PVDs from center to center was 2.2 m.

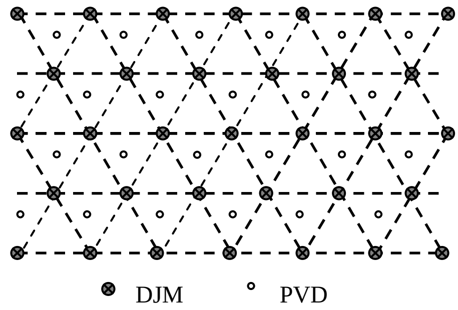

Fig. 1 Schematic plot of a combined DJM-PVD method

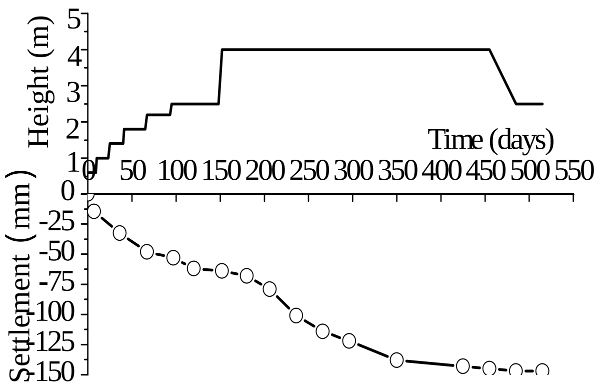

Fig. 2 Measured load and surface ground settlement versus time plot

After the installation of PVDs, DJM columns were then installed between the PVDs at the desired location to the same depth as PVDs (i.e., 13m) in a triangular pattern. The spacing of the columns was 2.2m. A drainage blanket composed of coarse sand and aggregate is placed on the top of the treated ground. The embankment construction was started after one month of DJM columns installation. The combination of the DJM columns and PVDs is expected to further accelerate the consolidation and increase the strengths of soft soils during and after the embankment or surcharge loads.

Piezometers, earth pressure cells, and settlement plates were installed under the embankment to monitor the variations of excess pore water pressures, vertical stresses, and settlements. The monitored surface ground settlement at the centerline and height of embankment are presented in Fig. 2.

NUMERICAL MODELING

The finite element (FE) analysis was preformed using a commercial software PLAXIS. 2D analysis is used in this study. The geometry of the FEM model is shown in Fig. 3. Due to the symmetry, unit cell model was used in the analysis. The DJM column at the

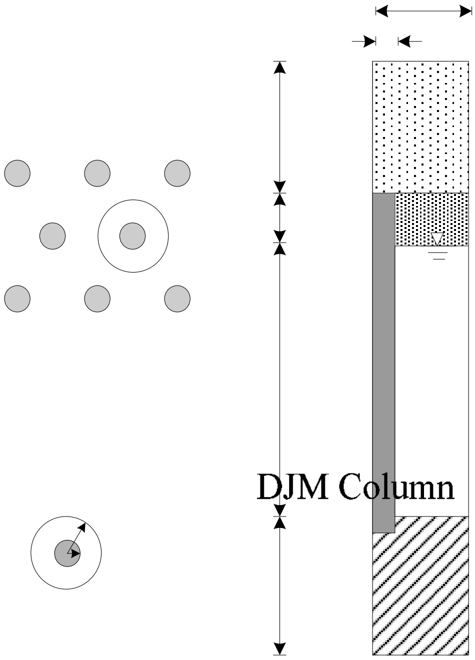

Fig. 3 Unit cell model

centerline has only half-width in the unit cell model. The Mohr-Coulomb model is used for the crust, the soft soil and the underlying firm soil and the parameters of ground soils are provided in Table 1. The elastic modulus and cohesion of soft clay layer at the top of this layer are 2.0 MPa and 10 kPa, respectively, and they increase with an increment 0.2 MPa and 1.0 kPa per linear meter depth, respectively. Linear Elastic Model is used for DJM columns. The elastic modulus of the DJM columns was estimated based on the typical relationship of $E = 100q_u$ (Porbaha, 2000). The moist density of DJM column is assumed to be the same with the surrounding soil of each layer of relevant layer. The permeability of DJM column is assumed as ten-once of the permeability of the corresponding soil. The groundwater level lies at the interface of crust layer and soft clay.

Simplified Consolidation Analysis Method for PVD Improved Ground.

From a macro point of view, vertical drains increase the mass hydraulic conductivity of subsoil in the vertical direction. Therefore, the contribution of PVD can be represented by an equivalent value of vertical hydraulic conductivity (k_{ve}) based on the equivalent average degree of consolidation (Chai et al. 2001). Chai et al. (2001) proposed an expression for the equivalent value of vertical hydraulic conductivity. In order to account for

Table 1 Subsoil and embankment fill parameters

	γ (kN/m^3)	E (MPa)	v	c (kPa)
Crust layer	18.0	10	0.30	20
Soft clay layer	16.0	*	0.35	*
Clay layer	19.0	6	0.30	15
Embankment	20.0	30	0.30	1
DJM column	***	80	0.30	400

	φ (º)	k_h (×10^{-4}m/d)	k_v (×10^{-4}m/d)
Crust layer	15	1.0	1.0
Soft clay layer	15	3.26	1.63
Clay layer	20	3.26	1.63
Embankment	35		
DJM column	0	*	*

Note: γ = Moist density; E = Elastic modulus; v = Poisson ratio; c= Cohesion; φ = Friction angle; k_h = Horizontal permeability; k_v= Vertical permeability; and * see text in details.

the effect of well resistance, Zhang et al. (2006) modified Chai's expression as following

$$k_{ve} = (1 + \frac{4H^2}{\pi} \cdot \frac{8}{(F + \pi G)D_e^2} \cdot \frac{k_h}{k_v})k_v \quad (1)$$

$$F = \ln\frac{n}{s} + \frac{k_h}{k_s}\ln(s) - \frac{3}{4} \quad (2)$$

$$G = \frac{k_h}{k_w}(\frac{H}{d_w})^2 \quad (3)$$

where, H = length of PVD; k_v = coefficient of permeability of natural soil in vertical directions; $n = d_e/d_w$(d_e = diameter of unit cell, d_e =1.05a, a = PVD distance; d_w = diameter of PVD); $s = d_s/d_w$ (d_s=diameter of smear zone); k_h, k_s and k_w =horizontal hydraulic conductivities of the natural soil , smear zone soil and PVD, respectively; and q_w = discharge capacity of PVD.

In this way, an approximate consolidation analysis method for PVD improved subsoil is constructed. The subsoil and drain parameters are listed in Table 2. With these conditions, Eq. (1) yields an equivalent vertical hydraulic conductivity of 7.9k_v.

Table 2 Subsoil and PVD parameters

H(m)	k_v(10^{-9}m/s)	d_w(m)	D_e(m)	d_s(m)
13	1.63	0.05	2.31	0.3
k_h/k_s	k_h/k_v	q_w(m^3/year)	k_w/k_h	
3	2	100	104	

Four cases were modeled. In case A, the ground was unimproved. In case B, the ground was improved by a combined DJM and PVD method. In case C and D, the ground was improved by DJM columns and PVDs along, respectively. In all cases, the improvement depth was 13 m, and the distance from center to center of DJM columns or PVD were 2.2m.

RESULTS AND DISCUSSION

Vertical Settlement

Figure 4 shows the vertical settlements on the top of DJM column and on the surface of surrounding soil in case B during and after construction of embankment loading. The measured settlement on the surface of surrounding soil is also shown in this figure. The comparison verifies the competence of the numerical modeling and the adopted parameters. Figure 4 also indicate that the settlement on the top of DJM column did not equal to that of the surrounding soil surface. The local differential settlement between the DJM column and surrounding soil develops since the construction of embankment fill.

Differential Settlement

The local differential settlement development (see Fig. 5) demonstrates that the magnitude of local differential settlement between DJM column and surrounding soil nearly reached maximum immediately after the full embankment loading, which is thought to be due to the rapid consolidation of soft clay near the top of the column. This finding is consistent with those of Stewart et al. (2005), and Bergado et al. (2005). This local differential settlement, however, was almost eliminated

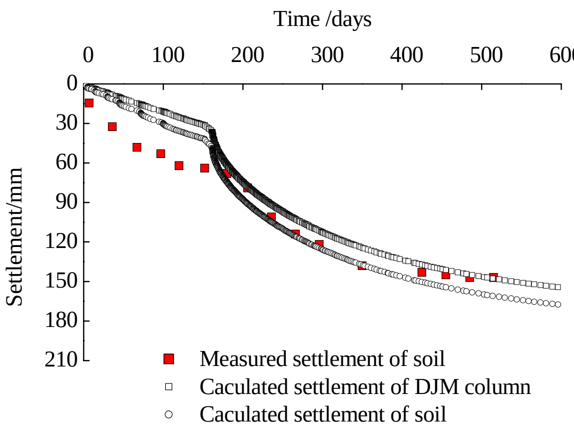

Fig. 4 Computed settlement versus measured settlement in case B

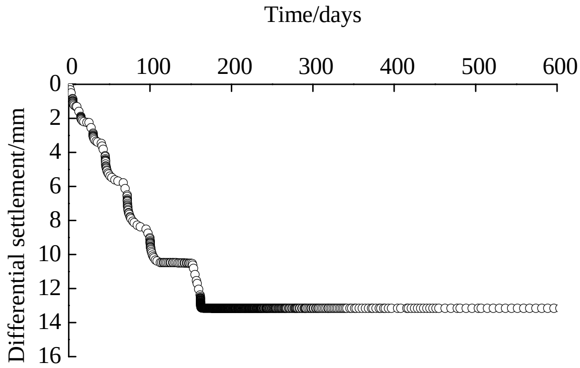

Fig. 5 Local differential settlement and time in case B

at the surface of embankment due to the combined effect of compaction as well as arching of the embankment fill.

Excess Pore Water Pressure

The average excess pore water pressure of surrounding soil at the middle of soft clay layer is shown in Table 3 and Fig. 6.

The excess pore water pressure reached maximum immediately after the fully embankment loading. The maximum excess pore water pressure was 74.3 kPa for unimproved ground, while, that was only 37.2 kPa for ground improved by combined DJM and PVD method.

Table 3 Dissipation of excess pore water pressure

Case	u_{max} (kPa)	Consolidation degree after 455days	Time for U=90% (days)
Unimproved	74.3	30.1	4620
DJM	49.5	55.1	2513
PVD	51.6	84.8	645
DJM-PVD	37.2	91.0	432

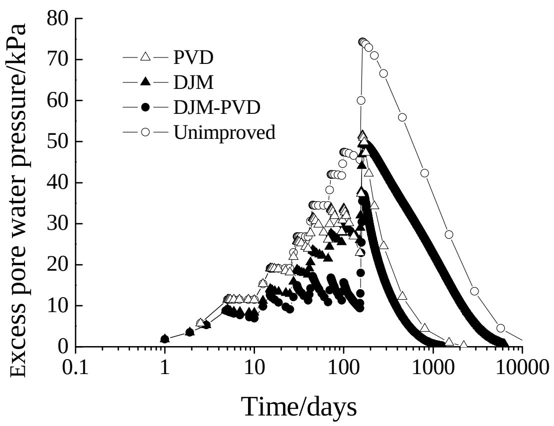

Fig. 6 Dissipation of excess pore water pressure

After 455 days, the average consolidation degree for ground improved by combined DJM and PVD method was almost three times as that for unimproved ground. It is obvious that the high drainage capacity of PVDs accelerates dissipate the excess pore water pressure. The faster dissipation can also be attributed to that the DJM column had accelerated the consolidation process due to its higher stiffness, which results in a stress concentration on the column. The stress concentration resulting in a reduction of excess pore water pressure in the soil. Consequently, it can be inferred that the consolidation process of the surrounding soil in the ground improved by DJM columns is quicker than that of ground without a DJM column (Zhen and Yin 2007).

In Fig. 7, the ordinate is the ratio of dissipated excess pore water pressures to the applied embankment loading pressure. The results indicate that the dissipation of excess pore water pressures depends on two factors, drainage and reduction of vertical stress. The dissipation of excess pore water pressures due to vertical stress reduction commences right after the moment of the load applied, which is more than 30% of the total dissipation for this special case. Obviously, the contribution of vertical stress reduction to the dissipation of excess pore water pressures does not exist in the foundation with PVD alone. This extra contribution explains why DJM columns can accelerate the rate of consolidation of soft clays. It is expected that the portion contributed by DJM columns depends on the value of stress concentration ratio. The higher the stress concentration ratio, the more dissipation of excess pore water pressures will be caused by vertical stress reduction (Han and Ye 2001).

The excess pore water pressure at different depth is shown in Fig. 8. It is noted that the zero point of time in Fig. 8 is the moment when pore water pressure reached maximum. The figure shows that the maximum excess pore water pressure increases with the depth increase.

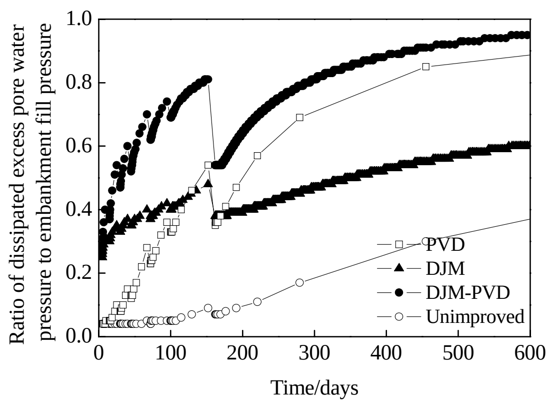

Fig. 7 Ratio of dissipated excess pore water pressure to embankment fill pressure and time

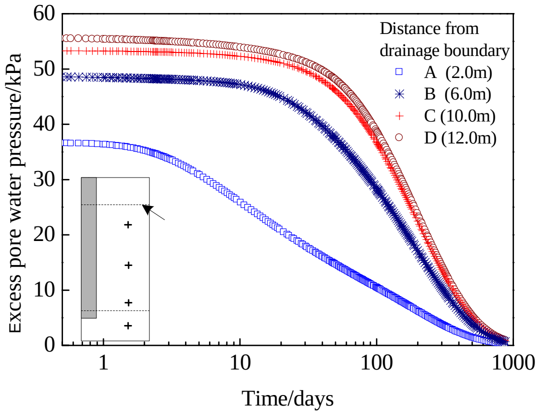

Fig. 8 Excess pore water pressure dissipation in ground improved by a combined DJM and PVD method

Near the top of the DJM column, the settlement of the surrounding soil is larger than that of DJM column. Thus local differential settlement results in the transfer of stress from surrounding soil to DJM column. Near the bottom of the DJM column, the DJM column would penetrate into the underlying layer, which induces the transfer of stress from DJM column to surrounding soil. Consequently, the maximum excess pore water pressure increase with the depth increase. On a macroscale, the transfer of stress between surrounding soil and DJM column induce excess pore water pressure gradient in the surrounding soil, which results in an upward transient seepage from the surrounding soil greater depth to the soil surface. As a result, the ground is consolidated.

CONCLUSIONS

The numerical analysis results indicate that the consolidation of the ground improved by the DJM-PVD combined method is accelerated by the drainage of PVDs, the stress concentration on column and the excess pore water pressure gradient resulting from the stress transfer between surrounding soil and column. It is observed that the high drainage capacity of PVDs accelerates the dissipation of the excess pore water pressure. The accelerated dissipation is explained as that upon the embankment loading, the stress concentration on the column occurs due to its higher stiffness than that of the surrounding soil, and thereby results in the reduction of the excess pore water pressure in the soil. The differential settlement develops between the soil and the column induces the transfer of stress between surrounding soil and column, which results in pore water pressure gradient in the surrounding soil and accelerates the consolidation.

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REFERENCES

Bergado, D.T., Noppadol P.W. and Lorenzo, G.A. (2005). Bearing and Compression Mechanism of DMM Pile Supporting Reinforced Bridge Approach Embankment on Soft and Subsiding Ground. 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan: 1149-1153.

Bruce, D. A., Bruce, M.E.C. and Dimillio, A.F. (1999). Dry mix methods: a brief overview of international practice. Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization. Balkema, Rotterdam, 15-25.

Chai, J.C. and Shen S.L. (2001). Simple Method of Modeling PVD-Improved Subsoil. Journal of Geotechnical and Geoenvironmental Engineering. 127(11): 965-972.

Han, J. and Ye, S.L. (2001). Simplified method for consolidation rate of stone column reinforced foundation. Journal of Geotechnical and Geoenvironmental Engineering, 127(7): 597-603.

Liu, S. Y., Han, J., Zhang D.W. and Hong, Z.S. (2008). A combined DJM-PVD method for soft ground improvement. Geosynthetics International, 15(1): 43-54.

Liu, S.Y. and Hryciw, R.D. (2003). Evaluation and quality control of dry jet-mixed clay soil–cement columns by standard penetration test. Transportation Research Record, No. 1849, 47-52.

Stewart, M.E., Navin, P.E. and Filz. G.M. (2005). Analysis of a column-supported test embankment at the I-95/ Route 1 interchange. ASCE GSP 126, GeoTrans 2004, 1337-1346.

Porbaha, A., Shibuya, S. and Kishida, T. (2000). State of the art in deep mixing technology: part III. Geomaterial characterization. Ground Improvement, 4(3): 91-110.

Zhang, D.W., Liu, S.Y., Hong, Z.S. and Deng, Y.F. (2006). Consolidation calculating method of ground improved by DJM-PVD combined methods. ASCE, GSP 152, Ground Modification and Seismic Mitigation, 29-36.

Zhen, F. and Yin, J.H. (2007). Responses of excess pore water pressure in soft marine clay around a soil–cement column. International Journal of Geomechanics, 7(3): 167-175.