LOWLAND TECHNOLOGY INTERNATIONAL Vol. 13, No. 2, 1-8, December 2011
International Association of Lowland Technology (IALT), ISSN 1344-9656

A CASE STUDY OF THE BEHAVIOR OF SOIL-NAIL SUPPORTED DEEP MIXED WALL IN THE SOFT DEPOSIT OF SHANGHAI

L. Ma [1], S.L. Shen [2], Y.J. Du [3] and W.J. Sun [4]

ABSTRACT: This paper presents a case study of an excavation retained by soil-nail supported deep mixed (DM) wall (DMSNW) in soft deposit of Shanghai, China. The soft deposit in Shanghai is Quaternary sediment with silt content over 50% and clay content of about 40%. The strength of this deposit is very low and the sensitivity is very high. In order to retain the excavation in the soft deposit, soil-nail supported DM wall is generally adopted when the excavation depth is less than 6 m. This paper presents an investigation on the interaction mechanism between nail and surrounding soil through a field case. A two-dimension finite element method (2D-FEM) was conducted. The effectiveness of 2D-FEM is verified via comparing calculated DM wall displacement with the field measured value. Based on the FEM result, the importance of four key design factors, e.g. nail length, nail spacing, thickness of DM wall, and stiffness of DM wall, are discussed. The results indicate that FEM analysis is an efficient way to predict the displacement and internal force of nails. Finally, a design chart is proposed for the soil-nail supported DM wall used in excavation practice.

Keywords: Nail supported DM wall, excavation, FEM, lateral displacement, influence factors.

INTRODUCTION

In recent years, soil nailing is increasingly used to stabilize slopes and support excavations. The technique of soil-nail supported deep mixed (DM) wall is widely applied in Shanghai, China due to its low cost. However, the interaction mechanism between nail and surrounding soil is still not well understood due to the complex of soil-grout along nails. Therefore, to obtain a cost-effective design of nail supported DM wall, it is desirable to investigate the stress transferring mechanism between the nail and the surrounding soil during excavation.

The objectives of the paper are *i*) to verify the effectiveness of 2D-FEM on the analysis of displacement through a field excavation case retained by soil-nail supported DM wall in the soft deposit of Shanghai, *ii*) to investigate the stress transferring mechanism between nail and surrounding soil during excavation, *iii*) to evaluate the importance of four key design factors on the behavior of DMSNW during excavation, e.g. nail length, nail spacing, thickness of DM wall, and stiffness of DM wall.

BRIEF REVIEW OF LITERATURES

Laboratory investigations on the interaction mechanism between nail and soil have been conducted in the past three decades, e.g. Bruce and Jewell (1987), Schlosser et al. (1992), Shen et al. (1981), Sun et al. (2004) and so on. Results from these laboratory tests have been successfully employed in the design of soil-nail. Based on the research of soil-nail during the past three decades, various design methods were developed. The available design methods with different definitions of safety factors and assumptions of failure surface were used in the engineering practice (Stocker et al. 1979; Shen et al. 1981; Schlosser 1983; Bridle 1989; Chen et al. 1994; Zhou and Yin 2008). Limit equilibrium methods incorporated with tension force were first introduced by Stocker et al. (1979) based on the assumption of a bilinear sliding surface. After this, Shen et al. (1981)

[1] PhD student, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University and State Key Laboratory of Ocean Engineering, Shanghai 200240, maleigeotechnical@situ.edu.cn, CHINA
[2] Professor, ditto, slshen@sjtu.edu.cn, CHINA
[3] Professor, Institute of Geotechnical Engineering, Southeast University, Nanjing 210096, duyanjun@seu.edu.cn, CHINA
[4] PHD student, Graduate Research Assistant Via Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061, sunwj@vt.edu, USA
Note: Discussion on this paper is open until June 2012

developed this method by considering a parabolic sliding surface. Both methods analyzed only the tension resistance and pull-out capacity of the inclusions. Later, Schlosser (1983) proposed a more general solution, including the influence of both lateral friction and passive normal soil reaction. Based on this method, both tension and shearing resistance of soil nail were considered. Then, Bridle (1989) computed the tensile and shear forces in soil-nails by assuming that the moment required to maintain the equilibrium of the wall should be equal to the moment resistance provided by the nails. With the assumption proposed by Bridle (1989), a moment limit equilibrium method was developed by Chen et al. (1994), which set nails as a component of the resisting moment. A new mathematical model for the soil-nail interaction was proposed by Zhou and Yin (2008). There were also a great number of researches reported in this field in recent years, e.g. Schaefer et al. (1997), Halim and Tang (1996), Christian et al. (1994), and Low and Tang (1997). Although the FEM analyses is used as an easy way for soil nail analysis recently (Cheuk et al. 2005; Fan and Luo 2008; Su et al. 2010; Zhou et al. 2009; Zhou et al. 2009), the simulation and analysis of the soil nailing DM retain wall is still not enough.

PROJECT OVERVIEW AND GEOTECHNICAL CONDITION

The excavation was conducted at Orient Art Center in Shanghai. The soft deposit at the excavated site is a deltaic deposit of Yangtze River. The elevation of the ground surface varied from 4.1 to 4.7 m. Groundwater level was 0.3 to 0.6 m under ground surface. The excavation lasted for 153 days. The depth of excavation

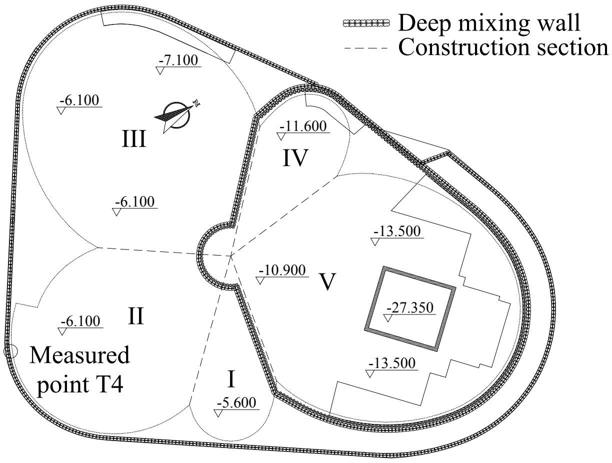

Fig. 1 Plan view of the excavated area and layout of instrumentation

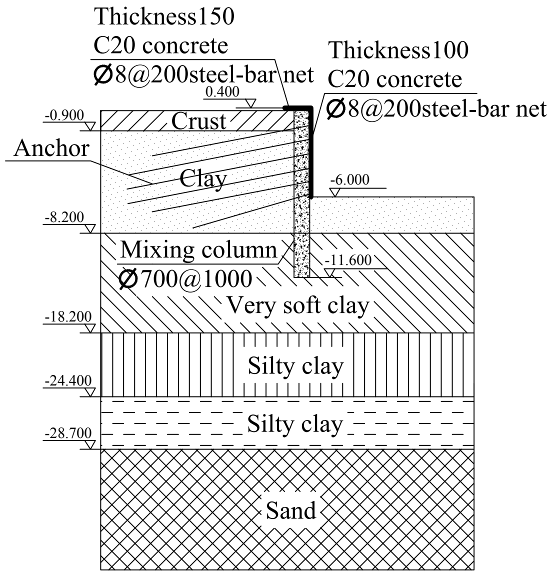

Fig. 2 Profile view of the excavated section II

was from 5.6 m to 29.2 m. The excavated area was 15,300 m^2, and the volume of excavated soil was 1.6×10^5 m^3. The soil-nail supported DM wall includes 6 rows of soil-nails with the length of 9 to 15 m and spacing at 1×1 m. The DM wall is about 6 m in height. The DM column is 700 mm in diameter with center to center spacing at 500 mm. There are five excavation sections separated in the foundation pit, and excavated depths of section I-V are 5.6 m, 6.0 m, 6.1 m, 11.6 m, and 10.9 m, respectively. The maximum depth of staged constructed pit is 27.35 m in section V. Fig. 1 shows the plan view of the excavated area; and Fig. 2 shows the profile view of measured point T4 in excavated section II. In this paper, the analysis of the performance of low pit retained by the soil-nailing supported deep mixed wall in excavated section II is presented.

Fig. 3 plots the geotechnical profile and soil properties in the middle of section III. As shown in Fig. 3, the soil profile at this construction site is as follows: at the top, there is a crust layer with the average thickness of about 3.02 m. The crust is consisted of clay, gravel, and smashed bricks, etc. Below the crust layer, there is a clay layer with an average thickness of 5.63 m. The soil of this layer is high compressible and in a plastic state. This layer is mainly consisted of silty clay with little mucky clay. Under this layer, there is a very soft clay layer with the average thickness of 9.48 m. The next lower two layers are silty clay, of which average thickness are 6.64 m and 3.64 m, respectively. Overlain this layer is a silty soil containing a little clay, and the thickness is 4.55 m. The soil is in a saturated state. Next layer is saturated sand soil with an average thickness of 6.03 m. The excavation was till this layer. The next two layers are sand and silty fine sand.

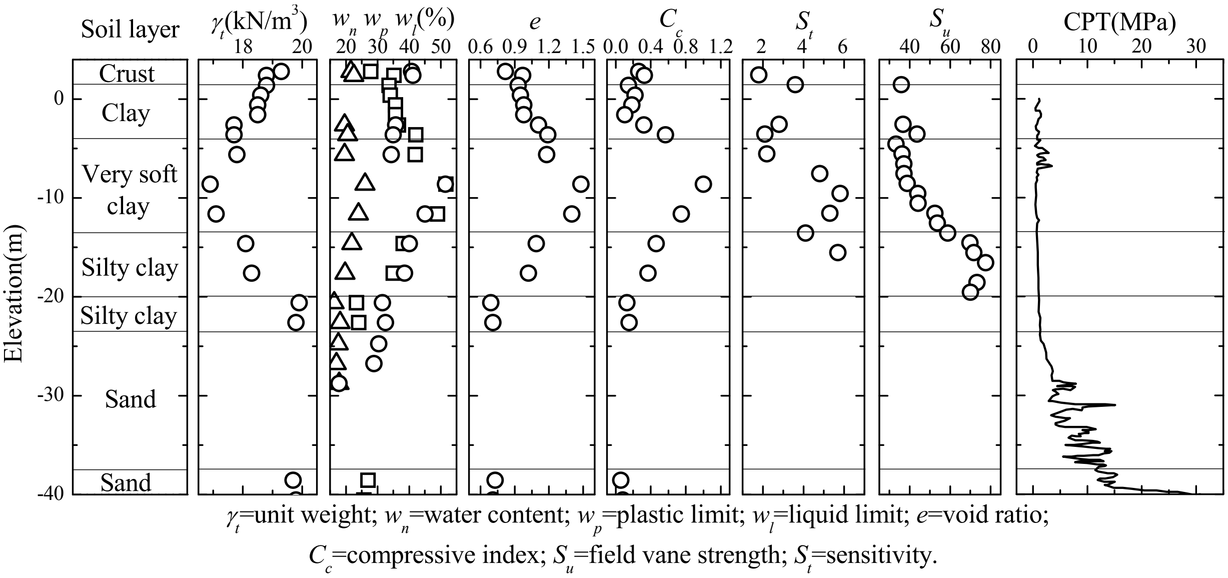

Fig. 3 Geotechnical profile and soil properties in the field

ANALYSIS METHOD

Finite Element Model

In this study, the two-dimensional finite element model (FEM) using Plaxis ver 8.0 program was established to study the performance of soil nailing (Brinkgreve 1994; Brinkgreve 2004). Fig. 4 shows the model; and the dimensions of the model were 60 m long and 40 m wide. The horizontal displacement is fixed at left and right boundary. Both horizontal and vertical displacements are fixed as zero at bottom boundary. The top and bottom boundaries were set as drained; and both left and right boundaries were set as undrained condition.

Stiffness matching procedure

In order to simulate soil nailing in 2D, the stiffness matching procedure was used. The approach used in 2D-Plaxis is to make the stiffness of soil nailing to be the same for both 3D and 2D plane strain models. Therefore, under same construction procedure and field condition, the assumption of same stiffness for both 3D and 2D plane strain models results in same field performance of soil nails. As shown in Fig. 5, the area replacement of soil nailing in a row is transformed from 3D to 2D models. The assumption equations are list as following:

$$E\frac{\pi d^2}{4} = Eab \tag{1}$$

$$\tau \times \pi d = \alpha \times \tau \times 2(a+b) \tag{2}$$

$$\alpha = \frac{\pi d}{2(a+b)} \tag{3}$$

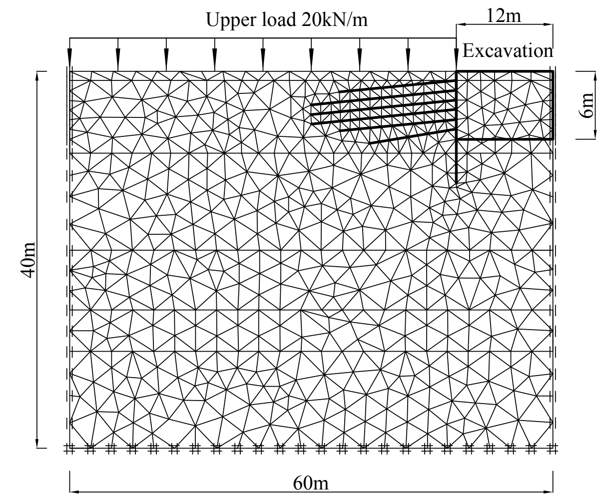

Fig. 4 The finite element model

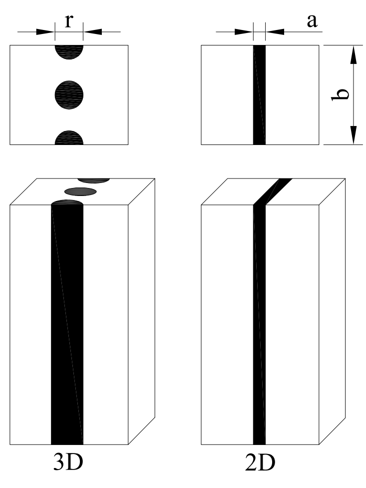

Fig. 5 The stiffness matching procedure for nails from 3D to 2D

where E is elastic modulus of soil nailing, d is diameter of soil nailing, a and b are equivalent lengths of soil nailing in 2D plain strain model, τ is the average bond strength between soil and nail elements, α is the adjustment factor of section area between 3D and 2D simulation. For this case, the diameter of soil nailing was 50 cm, and the value of α is equal to 0.2. In this study, the diameter and spacing of soil nailing are required as input parameters in the 2D-Plaxis simulation.

Element Type and Simulation Method

Soils were simulated using triangle elements with 15 nodes. Nails were simulated with bar elements that can only bear horizontal force (Song and Chen 1996; Yang 2004). When soils are distorted, the force is transferred from soils to soil-nails through cohesion and friction at the contact interface between nail and soil. Since the DM wall can bear both horizontal forces and bend moment, it was simulated by beam elements. The contact interface elements were also used to simulate the contact between the DM wall and the soil.

Constitutive Relation and Soil Parameters

In this study, classic Mohr-Coulomb model was used for soils. Table 1 shows the soil parameters used for the FEM analysis (Huang and Gao 2005). Soil-nails were simulated by the elastic model, and EA is 1.0×10^5 kN. The mixed soil-cement DM wall is 1200 mm thick With the EA of 1.2×10^5 kN and the Poisson's ratio of 0.25.

Simulation of Excavation Procedure

The excavated depth in excavation section II of this foundation pit is 6 m; and it was excavated using 6 steps after installing DM wall. The first row of soil-nails was installed after the excavation depth reached 1 m; and then the next row of soil-nails was installed as the excavated depth reached 2 m, and so on. The excavation and installation of the supporting system were finished when the pit reached 6 m of excavated depth. All of the soil nails were installed with excavation.

RESULTS AND DISCUSSION

Lateral Displacement

Fig. 6 shows the lateral displacement of point T4 (see Fig. 1). As shown in Fig. 6, the lateral displacement in T4 is increasing with depth at beginning, and decreasing at lower depth. The maximum lateral displacement occurred close to the excavation face, at the depth of about 5.5 m. From Fig. 6, it can be also seen that FEM simulates the variation of lateral displacement very well. The numerical lateral displacement is very close to the field measurement especially for DM wall below the bottom of the foundation pit, whereas the calculated value is larger than measurement for DM wall above the excavation face. Analysis results show that the influence of the fourth soil layer is considerable since it is a thick soil layer with low strength.

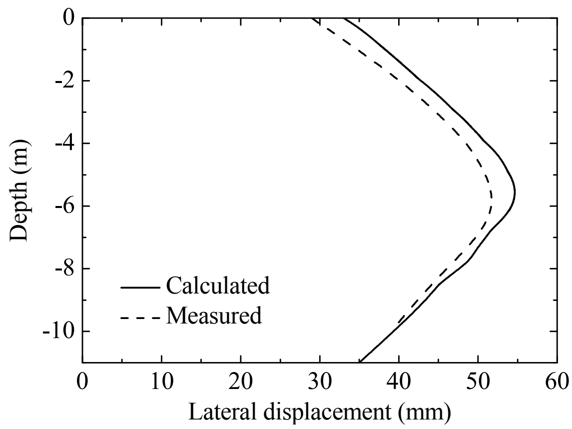

Fig. 6 Calculated and measured lateral displacement at point

Table 1 Soil properties used in the FEM simulation

Soil layer	Thickness	Unit weight	Cohesion	Angle of internal friction	Young's modulus	Poisson's ratio
	H (m)	γ (kN/m$^{3)}$	c (kPa)	φ (°)	E (kPa)	ν
Crust	1.5	18.9	20	30	8000	0.3
Clay	7.1	18.4	25	31	7000	0.35
Very soft clay	10	16.6	28	23	5500	0.35
Silty clay	6.2	18	30	24	14000	0.35
Silty clay	4.3	19.5	28	25	22000	0.35
Sand	14	19	7	35	27000	0.3

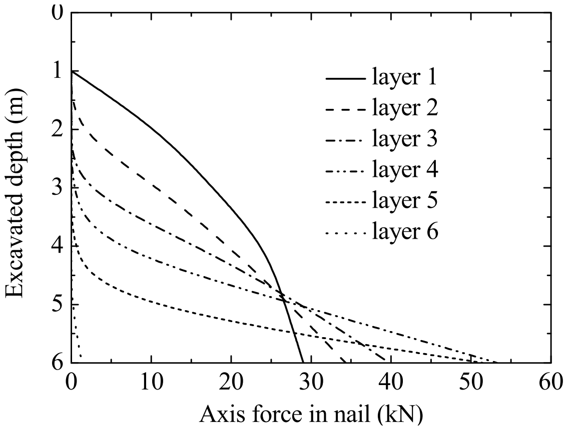

Fig. 7 Axial forces in nails

Tensile Forces in Nails

Fig. 7 shows the variation of axis forces in nails. The force was calculated by multiplying the stress with a 1.0 m spacing (Song and Chen 1996). After first layer of soil-nail was installed, underlying soil was excavated. The nail then began to bear force and restricted displacement of soil. This observation is also found for the following row of soil-nails. After installation of soil-nails, the displacement of DM wall after this stage becomes very small.

From Fig. 6 and Fig. 7, it is also found the internal force in soil-nail is related to its location and wall displacement. The forces on the top and bottom nails are small, whereas the forces are large at other locations. The axis force of the soil-nail installed at the last layer (layer 6) is very small and can even be ignored. The reason is mainly because that the last layer soil-nail was set when the excavation almost reached to the bottom and there was no soil excavated under this layer of the nail.

The aforementioned phenomenon is consistent with that reported by Yang and Song (2004). It is concluded that the bearing force of the soil-nails and restrict displacement of soil were mobilized during the pit excavation.

INFLUENCE FACTORS

To investigate the behavior of nail-supported retaining wall, a parametric study was conducted to study the influence of nail length, nail spacing, and the thickness and stiffness of DM wall on the lateral displacement of DM wall. All the other material properties remain the same values as those aforementioned except for the pointed out parameter. The results are presented and discussed as follows.

Effect of nail stiffness and spacing

Fig. 8 shows the influence of the stiffness of nail on the lateral displacement. When the stiffness of nail increased by twice and 5 times, the lateral displacement decreases 3.2 mm and 5.4 mm, respectively. However, when the stiffness increased by 10 times, the lateral displacement decreases only 6.2 mm. When the stiffness of nail is decreased by more than 0.5 times, the lateral displacement increased sharply. Fig. 9 shows the relation between nail stiffness and maximum lateral displacement. With increase in nail stiffness, the lateral displacement of foundation pit decreased. However, when the stiffness is greater than two times of its original value, there is no significant decrease of the lateral displacement along the DM wall. Thus, the relationship between the stiffness of nail and the maximum lateral displacement could be separated into two stages as shown in Fig. 9. The intersection between two tangent lines from beginning and end of the maximum displacement-stiffness corresponds to the stiffness of the nail of 1.5×10^5 kN. This value represents the critical stiffness of nail.

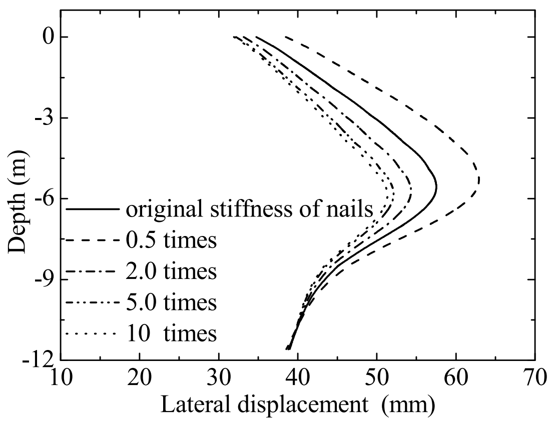

Fig. 8 Effect of stiffness of nail on lateral displacement

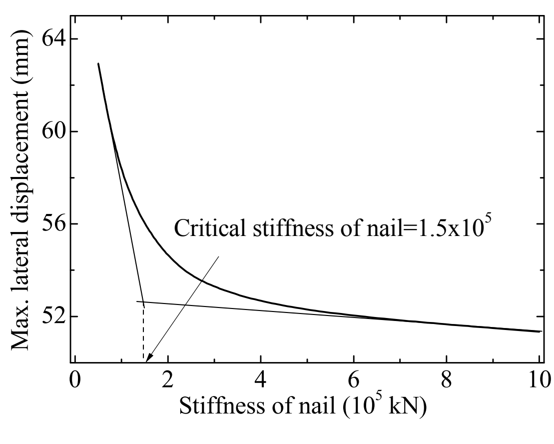

Fig. 9 Stiffness of nail vs. maximum lateral displacement

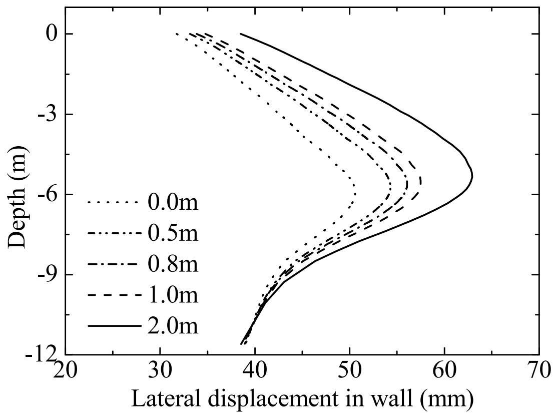

Fig. 10 Lateral displacement vs. depth for different horizontal nail spacing

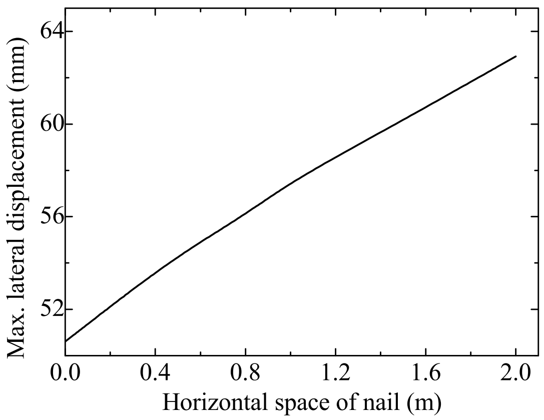

Fig. 11 Variation of maximum lateral displacement with horizontal nail spacing

Fig. 10 shows the effect of the horizontal nail spacing on the lateral displacement. Fig. 11 shows the variation of maximum lateral displacement with the horizontal nail spacing. It can be seen that the maximum lateral displacement linearly changes with the horizontal nail spacing. When the spacing is zero, which means that the whole vertical DM wall surface was supported by nails, the maximum lateral displace is lowest (50.6 mm).

Effect of nail angle and length

Fig. 12 shows the effect of insertion angle of soil nailing on the lateral displacement. As shown in figure, the angle has less impact on lateral displacement when it is between 5° to 20°. The maximum difference of ground lateral movement is 7 cm in 6 m depth. Fig. 13 shows the variation of maximum lateral displacement with the angle. When the angle is smaller than 20°, there is no significant variation in maximum lateral displacement linearly increases with the angle of soil nailing. Thus, the optimum angle of the nail ranges from 5° to 20°.

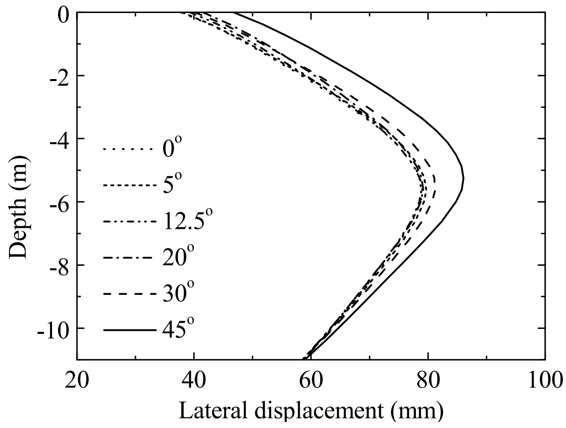

Fig. 12 Lateral displacement vs. depth for different angles of soil nail to the horizontal direction

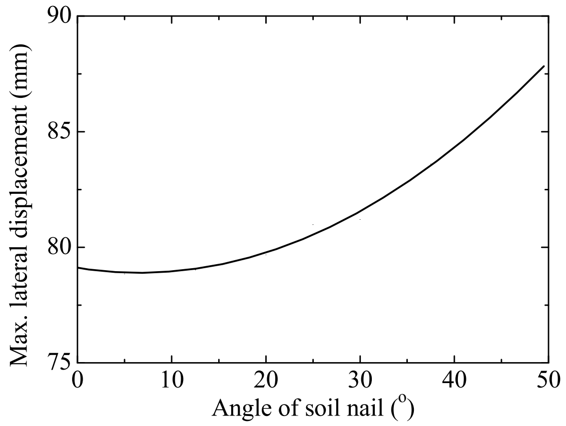

Fig. 13 Angle of soil nailing vs. maximum lateral displacement

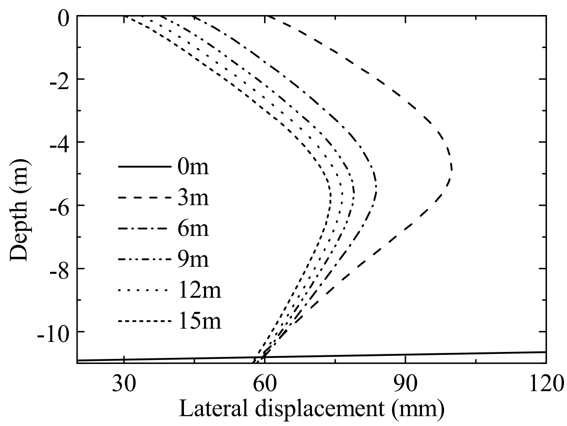

Fig. 14 Lateral displacement vs. depth for different lengths of soil nailing

Fig. 14 shows the lateral displacement along DM wall for different lengths of soil nails. Lengthening soil nail could decrease lateral displacement along DM wall. Fig. 15 shows the relation between maximum lateral displacement and length of soil nails. When soil nail is less than 6 m, the maximum lateral displacement of surround soil dramatically decreases with the increase of soil nailing length. The greatest lateral displacement is about 85 mm at the depth of 5 m when the length of nailing is 6 m. However, when the length is greater than 6 m, the maximum lateral displacement gently decreases with the increase of soil nailing length. Therefore, the optimum length of nailing is 6 m for this case.

Stiffness of DM wall

As shown in Fig. 16, the stiffness of DM wall increases, the maximum lateral displacement decreases sharply, whereas the lateral displacement slightly increases both on the top and at the bottom. It is because that the DM wall deforms as a whole with the increase of the stiffness, which leads to the decrease of maximum displacement and increase of lateral displacement at top and bottom. It is evident that the increase of the stiffness of deep mixing wall reduces total ground movement. It is concluded that application of DM wall with two times of its original stiffness is the optimum choice in this case.

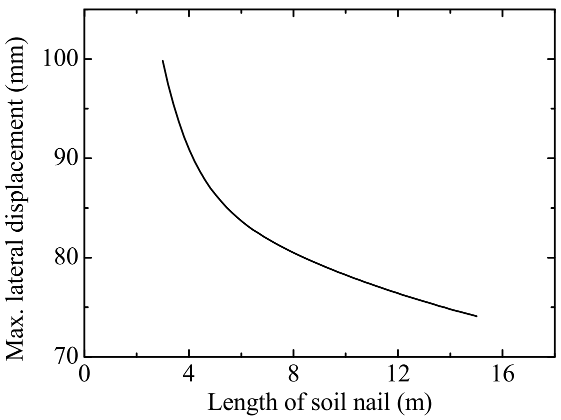

Fig. 15 Length of soil nailing vs. maximum lateral displacement

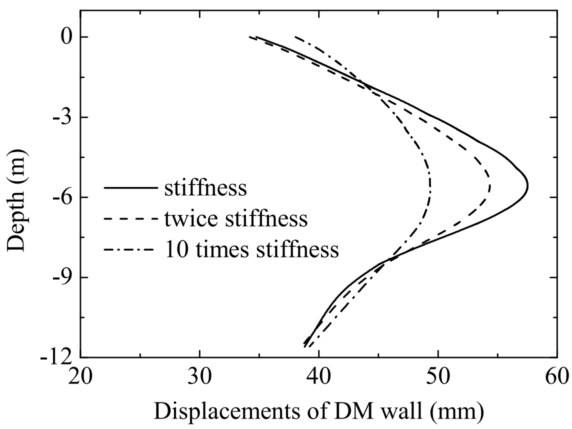

Fig. 16 Effect of stiffness of DM wall on lateral displacement

CONCLUSIONS

A case history of a 6 m deep excavation retained by soil-nail supported DM wall in Shanghai soft clays is presented. Based on the FEM analysis results and field investigation, the following conclusions can be drawn:

1) Soil-nail supported deep mixed wall is an efficient approach to retain the excavation in soft clayey deposit when the excavation depth is less than 6 m.

2) FEM results are in good agreement with the field measurements. FEM results show that the internal force in nails depends on the locations of nail. The forces in nails at the top and bottom layers are small. Axis force of each nail layer is mobilized during the excavation of the soil layer below it. The axis force increased with the increase of the depth of excavation except for the soil-nail at the bottom.

3) The simulated lateral displacement of DM wall relates to the properties of both soil nail and DM wall. In this case, the stiffness of soil nail should be greater than 1.5×10^5 kN. The choosing of spacing between soil nails is based on the requirements of ground settlement. The angle of nail to horizontal direction should be limited between 5° and 20°. The length of nail should be greater than 6 m. Finally, the stiffness of DM wall is one of the most important factors that affect the displacement of DM wall. Double the stiffness of Deep mixing wall would be the optimum choice in this case.

ACKNOWLEDGEMENTS

The research work described herein was funded by the National Nature Science Foundation of China under Grant No. 41072209 and the Science and Technology Commission of Shanghai Municipality (Grant No. 08201201600). This research work is also financially supported by the Shanghai Leading Academic Discipline Project (Project Number: B208) and is also supported by the Innovative Self-selected Project of the State Key Laboratory of Ocean Engineering (Grant No. GKZD010051). Financial support is also sponsored by the research project of the Institute of Lowland Technology, Saga University, Japan with grant No. 2007C01. These financial supports are gratefully acknowledged.

REFERENCES

Bridle, R.J. (1989). Soil nailing-Analysis and design. Ground Eng.. 22(6):52–56.

Brinkgreve, R.B.J. (1994). Geomaterial models and numerical analysis of softening. Ph.D. dissertation, Delft University of Technology, Delft, the Netherlands.

Brinkgreve, R.B.J. (2004). PLAXIS-2D user's manual and scientific manual. Version 8 [computer program]. A.A. Balkema, Rotterdam, the Netherlands.

Bruce, D. A. and Jewell, R. A. (1987). Soil Nailing: Application and Practice-Part 1, Part 2. Ground Engineering. 20(1):21-33.

Chen, L.K., Zhang, Z.M. and Yang, F.Y. (1994). Practical technique for geotechnical reinforcement. Earthquake Press, Beijing. (in Chinese)

Cheuk, C.Y., Ng, C.W.W. and Sun, H.W. (2005). Numerical experiments of soil nails in loose fill slopes subjected to rainfall infiltration effects. Computers and Geotechnics. 32:290-303.

Christian, J.T., Ladd, C.C. and Baecher, G.B. (1994). Reliability applied to slope stability analysis. Journal of Geotechnical Engineering. 120(12):2180–2207.

Fan, C.C. and Luo, J.H. (2008). Numerical study on the optimum layout of soil-nailed slopes. Computers and Geotechnics. 35:585-599.

Halim, I.S. and Tang, W.H. (1996). Reliability of undrained clay slope considering geologic anomaly. Proc., 6th Int. Conf. on Application of Statistics and Probability in Soil and Structural Engineering, L. Esteval and S. E. Ruiz, eds., Mexico City, Mexico. 776–783.

Huang, S.M. and Gao, D.Z. (2005). Foundation and underground engineering in soft ground (Second Edition). China Building Industry Press, Beijing.

Low, B.K. and Tang, W.H. (1997). Reliability analysis of reinforced embankments on soft ground. Canadian Geotechnical Journal. 34(5):672-685.

Schaefer, V.R., Abramson, L.W., Drumheller, J.C., Hussin, J.D. and Sharp, K.D. (1997). Ground improvement, ground reinforcement, ground treatment: Developments 1987–1997, ASCE, New York.

Schlosser, F. (1983). Analogies et differences dans le comportement et le calcul des ouvrages de soutennement en terre armee et par clouage du sol. Annates de 71 L'Institut Technique de Batiment et des Travaux Publiques. 148:26-38.

Schlosser, F., Unterreiner, P. and Plumelle, C. (1992). French Research Program CLOUTERRE on soil nailing. Geosynthetics in Foundation Reinforcement and Erosion Control System, Geotechnical Special Publication. ASCE. 76:739-750.

Shen, C.K., Bang, S. and Herrmann, L.R. (1981). Ground movement analysis of earth support systems. Journal of Geotechnical Engineering Division, ASCE. 107(12):1609-1624.

Song, E.X. and Chen, Z.Y. (1996). Soil nailing supported and finite element analysis. Engineering Investigation. 2:1-5. (in Chinese)

Stocker, M.F., Korber, G.W., Gassler, G. and Gudehus, G. (1979). Soil nailing. Proc. Intl. Conf. on Soil Reinforcement, Presses de L'Ecole Nationale des Ponts et Chaussees, Paris, France. 2:469-474.

Su, L.J., Yin, J.H. and Zhou, W.H. (2010). Influences of overburden pressure and soil dilation on soil nail pull-out resistance. Computers and Geotechnics. 37:555-564.

Sun, T.C., Zhang, M.J. and Yang, Q. (2004). Modeling study on composite soil nailing for deep excavation. Chinese Journal of Rock Mechanics and Engineering. 23(15):2585-2592.

Yang, G.H. (2004). Practical calculation method of retaining structures for deep excavations and its application. Beijing: Geological Press. (in Chinese)

Yang, J. and Song, E.X. (2004). Analysis of an underground excavation and recommendation. Industry Architecture (Supp.):333-336. (in Chinese)

Zhou, W.H. and Yin, J.H. (2008). A simple mathematical model for soil nail and soil interaction analysis. Computers and Geotechnics. 35:479-488.

Zhou, Y.D., Cheuk, C.Y. and Tham, L.G. (2009). An embedded bond-slip model for finite element modelling of soil–nail interaction. Computers and Geotechnics. 36:1090-1097.

Zhou, Y.D., Cheuk, C.Y. and Tham, L.G. (2009). Numerical modelling of soil nails in loose fill slope under surcharge loading. Computers and Geotechnics. 36:837-850.