Pile-soil Stress Ratio of Pile-supported and Geogird-reinforced Composite Foundation*

LONG Jun(龙军)**, ZHAO Minghua(赵明华), ZHANG Ling(张玲), ZHANG Genbao (张根宝)

(Institute of Geotechnical Engineering, Hunan University, Changsha Hunan 410082, China)

Abstract: The load and deformation of the pile-capped horizontal reinforced cushion of the pile-supported and geogrid-reinforced composite foundation were discussed to obtain the deformation and the tension stress of the reinforced material. Treating the pile and the soil as linear elastic object, and considering the static equilibrium and the compatibility of deformation as well as the influence of the reinforced material, the calculation method of the pile-soil stress ratios in different depths of the reinforced material was deducted. This method takes the following influence factors into account: differential settlement between pile and soil, horizontal reinforced cushion, pile distance, diameter of the pile cap and so on. Finally, to validate the proposed method, a case study was illustrated, which shows that the calculated value is close to the observed value. The pile-soil stress ratio and the bearing capacity of the composite foundation will be higher after setting up the horizontal reinforced mattress. This method is feasible for calculating the pile-soil stress ratio of the pile-supported and geogird-reinforced composite foundation.

Key words: road engineering; pile-supported and geogird-reinforced composite foundation; compatibility of deformation; pile-soil stress ratio; differential settlement

0 Introduction

Pile-supported and geogrid-reinforced composite foundation is a new technology used in foundation treatment. It comprises of horizontal reinforced geogrid and vertical columns as shown in figure 1. (1) Embankment: compressed embankment soil to get rid of the fracture of pavement; (2) Reinforced geogrid: improve the bearing capacity of foundation, reduce the un-uniform and excessive settlement and benefit the horizontal drainage of soft foundation; (3) Improved region: vertical piles squeeze the periphery soft soil to get better bearing capacity and smaller settlement value; (4) Substratum soil: provide the end resistance of rigid piles.

Many engineering practice cases[1-6] suggested that this foundation-treating is capable of solving problems like insufficient bearing capacity, intolerable settlement and unstable foundation. But it should be noticeable that the engineering practice has preceded much than its design theory, such as the issue of the determination of pile-soil stress ratio. Currently numerous investigators

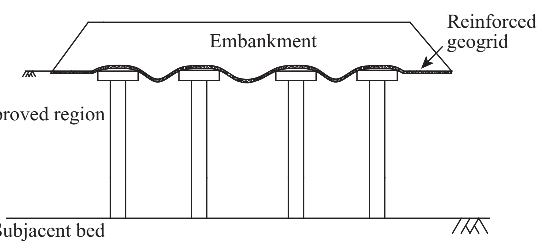

Fig. 1 Composition of the pile-supported and geogrid- reinforced composite foundation

devote into this issue on the basis of their different assumptions. Rao, et al. simplified the deformed shape of the horizontal geogrid to be a parabola and used the obtained practice data σ_s to determine the pile-soil ratio[7]. Chen, et al. improved the traditional soil arch effect analysis method in the HEWLETT limit state space based on the equilibrium of embankment soil body in the equivalent treating zone of single pile, and derived the computing formula of load bearing ratio for pile[8]. Zheng, et al. idealized a circular arc to simulate the deformation of reinforcement and idealized a completely plastic constitute model for the pile, analyzed the pile-soil stress ratio mechanically[9]. Yang, et al. took the constraint effect

Manuscript received July 30, 2011

* Supported by Chinese National Programs for High Technology Research and Development(No. 2006AA11Z104)

** *E-mail address*: mhzhaohd@21cn.com

of horizontal reinforcement and the shearing forces on the pile-soil interface into account, used the limit equilibrium conditions to get the bearing capacity of two-directional composite foundation[10]. In References [11] and [12], the similarity criterion of composite foundation model test was obtained by dimensional analyzing approach, the model test was designed in accordance with similarity theory to obtain a number of distribution data of pile-soil stress, incorporating with the load transferring properties of foundation, a simplified calculation model was constructed, together with practice-convenient designating method for composite foundation.

In this study, the deformation of horizontal reinforcement was analyzed, and the influence of reinforced cushion on pile-soil stress ratio was discussed. On the basis of elastic theory, in line with static equilibrium and deformation compatibility, a computational method of pile-soil stress ratio for pile-supported and geogrid-reinforced composite foundation was derived.

1 Establishment of calculation model

1.1 Basic assumptions

The interaction among the components of pile-supported and geogrid-reinforced composite foundation is complex. For simplicity, some assumptions should be given as below:

(1) Due to the minor deformation, rigid pile and soil are idealized to be linear elastic material.

(2) The settlements along pile cap are identical, and the loading is distributed to pile and the top of soil beneath pile cap according to elastic theory, i. e.:

$$\sigma_{p} = \delta_1 \sigma_{sp} = \frac{E_p d^2}{E_p d^2 + E_s (D^2 - d^2)} \sigma_{sp},$$

$$\sigma_{s}' = \delta_2 \sigma_{sp} = \frac{E_s (D^2 - d^2)}{E_p d^2 + E_s (D^2 - d^2)} \sigma_{sp},$$

where, σ_{sp} is the stress of the top of pile cap; δ_1 and δ_2 are stress distribution coefficients of pile and soil under pile cap respectively; E_p and E_s denote elastic modules of pile and soil; d is the diameter of pile; and D is the diameter of pile cap.

(3) The stiffness of pile is much larger than that of soil, the vertical deformation of inter-pile soil induced by loads is symmetric about the plane of $r = L/2$, while the transversal displacements of both pile and soil are ignored, where, L is the inter-pile interval.

(4) The settlement on the horizontal plane at the depth of $z = l_0$ is uniform, above this plane there is relative vertical displacement between soil beneath pile cap and soil between two neighbor pile caps.

1.2 Model establishment

The deformation of composite foundation resulted from the embankment loads is presented in figure 2.

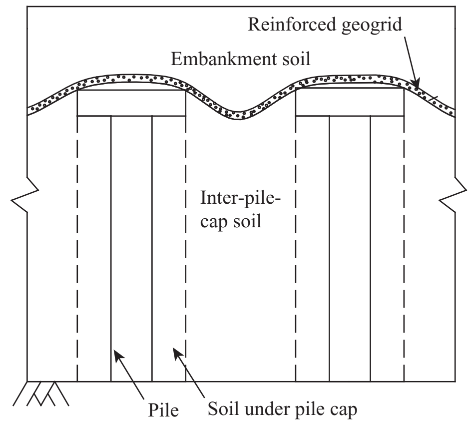

Fig. 2 Deformation of pile-supported and geogrid-reinforced composite foundation

Due to the action of upper loads, the geogrid between pile caps deforms downwards to the shape of catenary line. When the differential settlement between pile and soil is adequately small, the catenary can be replaced by parabola[13] with the curve equation as:

$$y = \frac{4s}{b_n} x^2, \tag{1}$$

$$\sin\theta = \frac{4s}{\sqrt{16s^2 + b_n^2}}, \tag{2}$$

where, s is the pile-soil differential settlement; b_n is the clearance interval of two pile caps; θ is the angle from horizontal level to the tension direction of geogrid.

Thus, the corresponding length of deformed curved S is:

$$S = 2\int_0^{\frac{1}{2}\cdot b_n} \sqrt{1 + (\frac{dy}{dx})^2}\, dx =$$

$$\frac{8s}{b_n^2}\left[\begin{array}{l} \frac{1}{2}(\frac{b_n^2}{8s}\ln(\frac{b_n}{2} + \sqrt{\frac{b_n^2}{4} + (\frac{b_n^2}{8s})^2}) - \\ \frac{1}{2}(\frac{b_n^2}{8s}\ln\frac{b_n^2}{8s} + \frac{b_n^2}{4}\sqrt{\frac{b_n^2}{4} + (\frac{b_n^2}{8s})^2} \end{array}\right], \tag{3}$$

The strain of geogrid is:

$$\varepsilon_{\mathrm{r}} = \frac{S + D}{D + b_{\mathrm{n}}}. \tag{4}$$

The settlement of inter-pile soil is assumed to be uniform for simplicity, as shown in figure 3. The height of shading section s' is the average settlement value. In accordance with the fact that the area embraced by axis x, two dotted lines and the parabola equals to the shading area, we have:

$$s' = \frac{sb_{\mathrm{n}}/3}{b_{\mathrm{n}}} = \frac{s}{3}, s'' = s - s' = \frac{2s}{3}. \tag{5}$$

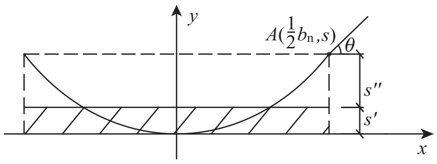

Fig. 3 Deformation of reinforcement

Thus, the differential settlement between inter-pile-cap soil and pile is $2/3s$, the schematic diagram of deformed model can be simplified to that illustrated in figure 4.

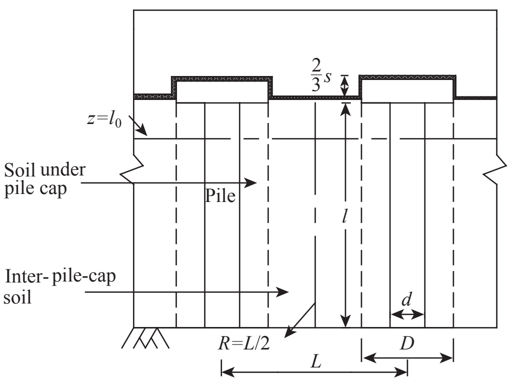

Fig. 4 Calculating model of the pile-supported and geogrid-reinforced composite foundation

2 Calculation of pile-soil stress ratio

2.1 Mechanical analysis of soil

According to the fourth assumption, a typical cylindrical soil element with inter radius of d, outer radius of D and height of dz is extracted from the region between the plane of $z = l_0$ and pile cap, as shown in figure 5. Its equilibrium equation is:

$$\sigma_z(z)A_{\mathrm{s}}' - (\sigma_z(z) + \mathrm{d}\sigma_z)A'_{\mathrm{s}} - \tau\pi d\mathrm{d}z + \tau'\pi D\mathrm{d}z = 0, \tag{6}$$

where, A_{s}' is the area of soil under pile cap which can be computed by the formula $A_{\mathrm{s}}' = 0.25\ \pi(D^2 - d^2)$; σ_z is the vertical stress of the element; and τ is the surrounding friction of pile which can be obtained by Berrum formula:

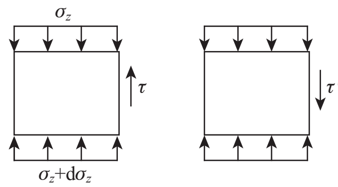

Fig. 5 Analysis of soil element under pile cap

$$\tau = k_0 \tan\varphi\sigma_z(z), \tag{7}$$

where, τ' is the inter-element vertical shearing stress abiding by Mohr-Coulomb criterion:

$$\tau' = \sigma_\rho \tan\varphi + c, \tag{8}$$

where, k_0 is the static lateral earth pressure coefficient; φ is the internal friction angle of soil; c is soil cohesion; σ_ρ is the horizontal stress of soil element on the plane of $r = D$.

As mentioned in assumption (3), $\sigma_\rho = \sigma_\varphi = \mu\sigma_z/(1-\mu)$, we have:

$$\tau' = \frac{\mu_{\mathrm{s}}}{1-\mu_{\mathrm{s}}}\sigma_z(z)\tan\varphi + c, \tag{9}$$

where, μ_{s} is Poisson's ratio of soil.

Substitute equation (7) and equation (9) into equation (6), add the stress boundary condition of soil beneath pile cap: $\sigma_z|_{z=0} = -\sigma_{\mathrm{s}}' = -\delta_2\sigma_{\mathrm{sp}}$, we can solve the differential equation to get:

$$\sigma_z = \left(\frac{E_2}{E_1} - \delta_2\sigma_{\mathrm{sp}}\right)\mathrm{e}^{E_1 z} - \frac{E_2}{E_1} \tag{10}$$

where, $$E_1 = \frac{4\left(\frac{\mu_{\mathrm{s}}}{1-\mu_{\mathrm{s}}}\tan\varphi D - K_0\tan\varphi d\right)}{D^2 - d^2};$$

$$E_2 = \frac{4cD}{D^2 - d^2}.$$

The mechanical analysis of a soil element between two pile caps above the plane of $z = l_0$ with inner radius of D, outer radius of $L/2$ and height of dz is conducted as presented in figure 6. It is known that there is no shearing stress on the symmetric plane of $r = L/2$. Similar to the above analytical process, we have:

$$\sigma_z''(z) = \frac{E_4}{E_1}1(1 - \mathrm{e}^{E_1 z}) + E_5 z - \sigma_{\mathrm{s}}, \tag{11}$$

$$\varepsilon_z'' = E_3\sigma_z'',$$

where, σ_{s} is the stress on the top of soil between pile caps, and other parameters as below:

$$E_3 = \frac{1}{E_{\mathrm{s}}}\frac{1 - \mu_{\mathrm{s}} - 2\mu_{\mathrm{s}}}{1 - \mu_{\mathrm{s}}^2};$$

$$E_4 = \frac{\mu_s}{1-\mu_s}\frac{4D\tan\varphi}{L^2-D^2}\left(\frac{E_2}{E_1}-\delta_2\sigma_{sp}\right);$$

$$E_5 = \frac{\mu_s}{1-\mu_s}\frac{4D\tan\varphi}{L^2-D^2}\frac{E_2}{E_1}-\frac{4cD}{L^2-D^2}.$$

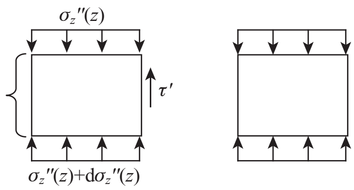

Fig. 6 Analysis of soil element between pile caps

Then the settlement of inter-pile-cap soil above the plane of $z = l_0$ is:

$$u_1' = \int_0^{l_0} \varepsilon_z''\mathrm{d}z. \tag{12}$$

In assumption (4), it has been presumed that there is no relative displacement between soil under pile cap and inter-pile-cap soil at the plane of $z = l_0$. So we have:

$$\sigma_z(l_0) = \sigma_z''(l_0) = \sigma. \tag{13}$$

The value of l_0 can be determined by solving equation (13). We can regard the soil under the plane of $z = l_0$ as an integrity and choose an element with inter radius of d, outer radius of L and height of dz to analyze, as shownn in figure 7.

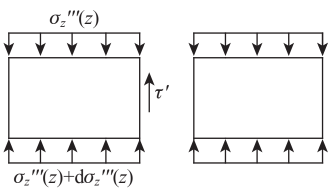

Fig. 7 Analysis of soil element

Through analogical handling technique, we obtain:

$$\sigma_z'''(z) = \frac{E_6}{E_1}(\mathrm{e}^{E_1 z}-1)+E_7 z-\sigma, \tag{14}$$

$$\varepsilon_z''' = \frac{1}{E_3}\sigma_z''',$$

where, σ_z''' is the vertical stress of soil element under the plane of $z = l_0$; other parameter is:

$$E_6 = -\frac{4\cdot K_0\cdot\tan\varphi \mathrm{d}\left(\frac{E_2}{E_1}-\delta_2\sigma_{sp}\right)}{L^2-d^2};$$

$$E_7 = \frac{4K_0\tan\varphi d\frac{E_2}{E_1}}{L^2-d^2}.$$

Then we integral the strain in the range of $l - l_0$ and l and get the settlement of soil below the plane of $z = l_0$:

$$u_1'' = \int_{l-l_0}^{l} \varepsilon_z'''\mathrm{d}z, \tag{15}$$

where, l is the length of pile.

Adding two compartment of settlement in equation (12) and equation (15) yields the total settlement of soil between two pile caps along the pile:

$$u_1 = u_1' + u_1''. \tag{16}$$

2.2 Mechanical analysis of pile

The schematic diagram of stress analysis of pile element is given in figure 8.

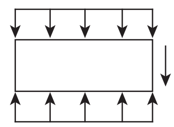

Fig. 8 Analysis of pile element

Using similar technique in section 2.1, we have:

$$\begin{cases}\sigma_z'(z) = E_8(\mathrm{e}^{E_1 z}-1)+E_9 z-\delta_1\sigma_{sp}, \\ \varepsilon_z' = E_{10}\sigma_z',\end{cases} \tag{17}$$

where, $$E_8 = \frac{4K_0\tan\varphi}{d}\left(\frac{E_2}{E_1}-\frac{\delta_2\sigma_{sp}}{E_1}\right);$$

$$E_9 = -\frac{4K_0\tan\varphi}{d}\frac{E_2}{E_1};$$

$$E_{10} = \frac{1}{E_p}\frac{1-\mu_p-2\mu_p^2}{1-\mu_p},$$

and μ_p is Poisson's ratio of pile. By integration, the compression quantity of pile can be solved:

$$u_0' = \int_0^l \varepsilon_z'\mathrm{d}z. \tag{18}$$

Conducting the integral static force analysis on the pile as illustrated in figure 9, we get the equilibrium equation:

$$ku_0''A_p - \int_0^l \tau\pi d\mathrm{d}z - \delta_1\sigma_{sp}A_p = 0, \tag{19}$$

Solving equation (19) yields:

$$u_0'' = \frac{1}{k}\delta_1\sigma_{sp} + \frac{1}{k}\frac{4K_0\tan\varphi}{d}\left[\left(\frac{E_2}{E_1}-\frac{\delta_2\sigma_{sp}}{E_1}\right)(e^{E_1 l}-1)-\frac{E_2}{E_1}l\right], \tag{20}$$

where, k is the coefficient of foundation reaction for soft soil.

Considering that the pile stiffness is much larger than that of soil, we can see approximately the summation of pile compression and pile displacement as the settlement of pile cap, i. e.:

$$u_0 = u_0' + u_0''. \tag{21}$$

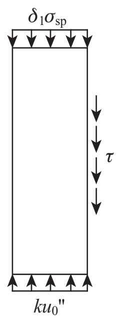

Fig. 9 Static force analysis of pile

As mentioned in equation(5), we can rewrite the relative settlement between pile cap and inter-pile-cap soil as below:

$$u_1 - u_0 = \frac{2s}{3}. \tag{22}$$

2.3 Calculation of pile-soil stress ratio

According to the *Technical Code for Building Pile Foundations*, the vertical limit bearing capacity of pile is Q_u, we can define $\sigma_p = \lambda Q_u / A_p$, where, λ denotes the serviceable degree of the bearing capacity of pile which can be measured through in-situ tests. From assumption (2), we can write:

$$\sigma_{sp} = \frac{\sigma_p}{\delta_1}, \sigma_s = \frac{\sigma_{sp}}{n}. \tag{23}$$

Substituting equation (16), equation (21) and equation(23) into equation (22) generates the value of n, which is the stress ratio of pile cap and inter-pile-cap soil beneath the geogrid under reinforcement. The force analysis of the geogrid covering the pile cap and soil is presented in figure (10) and figure (11) respectively.

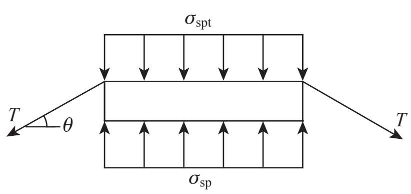

Fig. 10 Analysis of reinforcement above pile cap

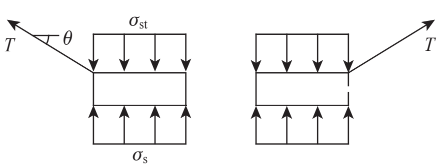

Fig. 11 Analysis of reinforcement between pile caps

$$\sigma_{sp} \frac{\pi D^2}{4} - \sigma_{spt} \frac{\pi D^2}{4} - T\pi D \sin\theta = 0, \tag{24}$$

$$\sigma_{st} A_s - \sigma_s A_s - T\pi D \sin\theta - T\pi(L - D)\sin\theta = 0, \tag{25}$$

Combining equation(24) and equation (25), we solve for stress of both pile and soil:

$$\sigma_{spt} = \sigma_{sp} - \frac{4T\sin\theta}{D},$$

$$\sigma_{st} = \sigma_s + \frac{4TL\sin\theta}{L^2 - D^2}. \tag{26}$$

Then the stress ratio of pile cap and inter-pile-cap soil above reinforcement is:

$$n' = \frac{\sigma_{spt}}{\sigma_{st}}. \tag{27}$$

It can be found obviously that $n' < n$. The inclusion of horizontal reinforcement transfers the loads sustained by soil to the pile and increases the bearing capacity of composite foundation.

3 Case study

A test area of composite foundation locates on the Pearl River Delta Plain. Prestressed pipe piles of PHC-A400-95 are used, equipped with concrete caps on the top of piles. All is covered by geogrid of CATT60. The diameter of pile is 40 cm, the interval of piles is 2.4 m and pile length is 12 m. Other parameters can be referred to Reference[14]. Knowing that $d = 0.4$ m, $b_n = 1.27$ m, $k_0 = 0.625$, $\varphi = 20°$, $c = 30$ kPa, Poisson's ratios: pile of 0.25 and soil of 0.4, elastic modulus: soil of 5 MPa, pile of 4×10^4 MPa, relative settlement of pile cap and inter-pile-cap soil is 21 mm. Values of all the parameters seen in equations above are calculated and listed in table 1.

Tab.1 Calculated values of parameters

E_1 (m^{-1})	E_2 (kN/m^3)	E_3 ($kN^{-1} \cdot m^2$)	E_4 (kN/m^3)	E_5 (kN/m^3)
0.625	132.05	9.33(10^{-5})	77.44	21.45
E_6 (kN/m^3)	E_7 (kN/m^3)	E_8 (kN/m^2)	E_9 (kN/m^3)	E_{10} ($kN^{-1} \cdot m^2$)
13.72	17.45	768.07	−384.53	8.33(10^{-6})

Both calculated values and measured values for pile-soil stress ratio can be found in table 2.

The inclusion of horizontal reinforcement makes it possible to increase pile-soil stress ratio for piled embankment. It is a good paraphrase of the design thought that "to elaborate completely the bearing capacity of soil, and pile should be responsible for the complement". An apparent growth of pile-soil stress ratio can be observed from the ground below reinforcement to that above it.

Tab. 2 Comparison between calculated and measured values

	Pile top soil stress(kPa)	Inter-pile-cap soil stress(kPa)	Pile-soil stress ratio	Measured pile-soil stress ratio
Above reinforcement	174.25	12.82	13.59	14.05
Below reinforcement	192.07	9.41	20.41	22.43

4 Conclusions

(1) Regarding both pile and soil as elastic material, the incorporation of static equilibrium condition and deformation compatibility solved the pile-soil stress ratio for pile-supported and geogrid-reinforced composite foundation. The application possibility is verified by good agreement of calculated results and in-situ measured values.

(2) Loads transferring from soil to pile developed by horizontal reinforcement increased pile-soil stress ratio together with the bearing capacity for composite foundation.

References

[1] ALZAMORA D, WAYNE M H, HAN J. Performance of SRW, Supported by Geogrids and Jet Grout Columns [C] //Proceedings of ASCE Specialty Conference on Performance Confirmation of Constructed Geotechnical Facilities. Reston, VA, US: American Society of Civil Engineering, 2000: 456-466.

[2] HAN J, AKINS K. Case Studies of Geogrid-Reinforced and Pile-Supported Earth Structures on Weak Foundation Soils [C] //Proceedings of International Deep Foundation Congress. Orlando: [s. n.], 2002: 668-679.

[3] CHEN Hongyou, LI Bin. The Application of Composite Pile-supported Foundation of Synthetic Geotechnical Material to Soft Foundation Treatment in Xiangtan-Shaoyang Freeway [J]. Central South Highway Engineering, 2002, 27 (1): 40-41. (in Chinese)

[4] ZHAO Minghua, YANG Minghui, WU Yazhong, et al. Study on Capacity Mechanism and Model Test of Geogrid Mattress and Gravel Pile Composite Foundation [J]. Journal of Highway and Transportation Research and Development, 2005, 22 (11): 6-9, 29. (in Chinese)

[5] STEWART M E, FILZ G M. Influence of Clay Compressibility on Geosynthetic Loads in Bridging Layers for Column-supported Embankments [C] // Proceedings of Contemporary Issues in Foundation Engineering. New York: ASCE, 2005: 11-25.

[6] WHYTE D. The Overriding Aspects of the Design of Geosynthetic-reinforced Pile Supported Embankments [C] // Proceedings of Contemporary Issues in Foundation Engineering. New York: ASCE Publications, 2005: 29-41.

[7] RAO Weiguo, ZHAO Chenggang. The Behavior of Pile-net Composite Foundation [J]. China Civil Engineering Journal [J], 2002, 35 (2): 74-80. (in Chinese)

[8] CHEN Yunmin, JIA Ning, CHEN Renpeng. Soil Arch Analysis of Pile-supported Embankments [J]. China Journal of Highway and Transport, 2004, 17 (4): 1-6. (in Chinese)

[9] ZHENG Junjie, CHEN Baoguo, ABUSHARAR S W. Pile-soil Stress Ratio of Two-directed Reinforcement Composite Foundations [J]. Journal of Huazhong University of Science and Technology, 2007, 35 (7): 110-113. (in Chinese)

[10] YANG Yu, CHEN Changfu, ZHAO Minghua. Bearing Capacity of Two-dimensional Reinforced Composite Foundation [J]. Journal of Highway and Transportation Research and Development, 2008, 25 (6): 35-39. (in Chinese)

[11] CHEN Yanping, ZHAO Minghua, CHEN Changfu. Similarity Model Test of Geocell Reinforced Gravel Mattress and Gravel Pile Composite Foundation [J]. China Journal of Highway and Transport, 2006, 19 (1): 17-22. (in Chinese)

[12] ZHAO Minghua, ZHANG Ling, JIANG Desong. Design Calculation Method for Soft Foundation Treatment by Geocell Mattress and Stone Column [J]. Journal of Highway and Transportation Research and Development, 2008, 25 (4): 47-51. (in Chinese)

[13] CARLSSON B. Reinforced Soil. Principles for Calculation [M]. Sweden: Terratema AB, Linöping, 1987.

[14] LIAN Feng, Gong xiaonan, LUO Yong. Experiment Study of Pile-soil Stress Ratio of Pile-net Composite Foundation [J]. Bulletin of Science and Technology, 2008, 24 (5): 690. (in Chinese)

(Selected from Journal of Highway and Transportation Research and Development, vol. 27, no. 10, pp. 29-34, 2010.)