Study on Settlement Time Property of Composite Foundation

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***Abstract*: In order to provide the basis for design and construction of CFG pile, as well as to promote the foundation treatment, settlement time property of composite foundation is studied by means of 3-D numerical simulation methods considering Biot consolidation theory. The results prove that: ① 3-D numerical simulation considering Biot consolidation theory can well study settlement time property of composite foundation; ② increasing pile length, pile diameter, permeability of soil and surcharge preloading, and reducing pile space and compressibility of soil, is advantageous to dissipation of excess pore water pressure and shortens consolidation time and the effect of increasing permeability of soil is the most remarkable; ③ increasing pile length, pile diameter and surcharge preloading, and reducing pile space and compressibility of soil, is helpful for controlling settlement deformation and the effect of increasing pile length is the most remarkable; ④ design ideas of sparse-density pile are brought out and the main factors for settlement are surcharge preloading and pile length.**

Keywords: Composite foundation; Settlement; Time property; 3-D numerical simulation

I. INTRODUCTIONS

With the rapid development of the national economy, national infrastructure is in the ascendant. CFG pile composite foundation technology is used in course of ground treatment of the railway industry, such as the Beijing-Tianjin inter-city lines, Wuhan-Guangzhou passenger line, the Beijing-Shanghai High Speed Railway, and can better improve ground bearing capacity, and reduce distortion and save construction costs. Post-construction settlement of the high-speed railway subgrade requirements for 15mm [1], which is much higher than the original roadbed design standards.

At this stage, simulation of composite foundation, especially pile-slab composite foundation, is mainly simplified to two-dimensional plane strain problem [2][3], while elastic-plastic theory is mainly used in analysis of settlement property by 3-D model [4][5], considering consolidation theory less. Further, because of the complexity of CFG pile-slab composite foundation, many parameters affect the settlement calculation, and the theory is not mature and far behind the needs of engineering practice.

For the reasons, the thorough research on settlement time property of CFG pile-slab composite foundation in typical sections has been done by numerical simulation methods.

II. MODELING AND VALIDATION

A. Modeling

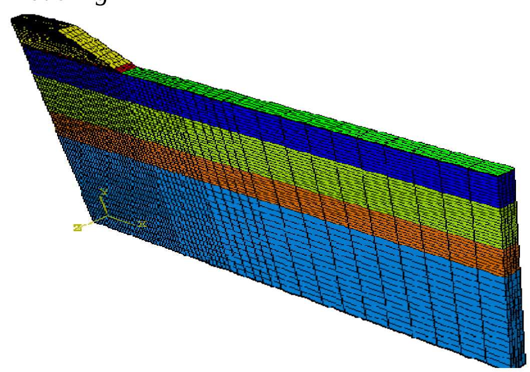

Fig.1 3-D FEM

3-D liquid-solid coupled numerical models of Biot consolidation theory have been established. Elements with eight-node hexahedron reduced integral elements, soil and cushion with C3D8RP, others such as raft, pile and fillings with C3D8R. The model has a total of 25518 elements and 47584 nodes. Meshing diagram is as shown in Figure 1 **.**

B. Constitution and Calculation

Constitution model of soil is by elastic-plastic model of 3-D Biot consolidation theory and structures (piles, concrete board, etc.) by linear elastic model. Specific parameters are as shown in Table 1 and Table 2.

Table.1 Division and parameters of soil

Layer name	**Unit Weight γ**	**Water Content W**	**Void Ratio e**	**Cohesion Cu**	**Internal friction angle φu**	**Poisson's ratio μ**	**Modulus of elasticity E**	**Coefficient of permeability k**	**Friction coefficient of pile and soil**
	kg/m^3	%		kPa	°		MPa	*10^{-6}mm/s	
Layer 1	1910	26.42	0.85	43.6	23.5	0.31	18.4	0.95	0.28
Layer 2	2010	23.69	0.69	78.1	27.1	0.26	28.8	0.86	0.34
Layer 3	2100	/	/	/	/	0.26	150	/	/
Layer 4	2310	/	/	/	/	0.13	500	/	/

C. Boundary Conditions and Initial Conditions

Boundary conditions are: top with free x, y and z direction and permeable; left and right with fixed x and impervious; front and back with fixed z and impervious; bottom with fixed x, y and z, impervious.

Initial conditions are: firstly, the upper load part of the model is killed and the static analysis is done only considering the part below the surface, and then its result is used in the formal model as initial stress. Assume that consolidation of foundation soil has been completed at the beginning of calculating, which can offset the initial deformation, so that the deformation is induced by additional stress of the upper fillings, that is settlement deformation.

Table.2 Physical and mechanical parameters

Materials	**Unit weight γ**	**Poisson's ratio μ**	**Modulus of elasticity E**	**Coefficient of permeability k**
	kg/m^3		MPa	mm/s
graded broken stone	2100	0.15	100	/
AB fill	2100	0.15	60	/
Embankment fill	2000	0.15	45	/
ballast mattress	2100	0.15	120	0.1
Reinforced concrete slab	2400	0.10	30000	/
CFG pile	2300	0.10	20000	/

D. Model Validation

Basic working conditions: pile diameter of 0.4m, pile length of 13.0m, pile space of 2.0m; two soil layers of reinforced zone, a total of 13.0m; two underlying layers, a total of 23.0m.

Based on the basic conditions and the physical and mechanical parameters of stratum and structures, model calculation has been carried out. The final settlement curves of the model surface and slices of pile center are as shown in Figure 2 and Figure 3, and the surface settlement curves at the center of embankment with time as shown in Figure 5.

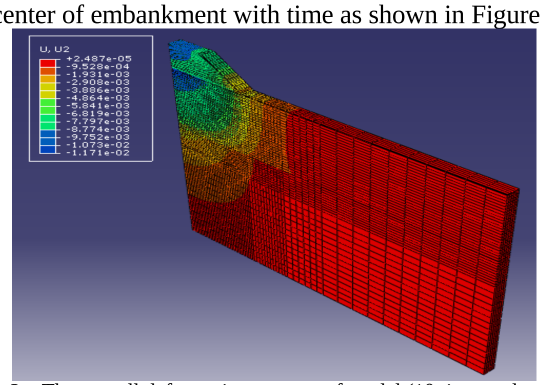

Fig.2 The overall deformation contour of model (10 times enlarged)

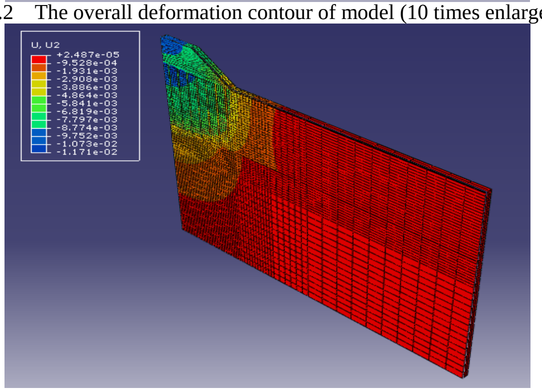

Fig.3 The slice deformation contour of model (10 times enlarged)

Figure 2 and Figure 3 show that ground surface settlement reaches maximum at the centerline; the settlement gradually reduces with increasing distance from the centerline and the deformation gradually decreases with increasing depth. Settlement gradually radiates around and decreases with roadbed center as the dot, and the surface settlement curves of composite foundation appear inverted bell-shaped.

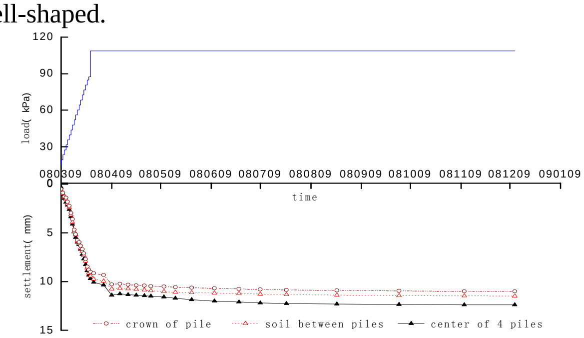

Fig.4 Settlement-time-filling curve of ground surface

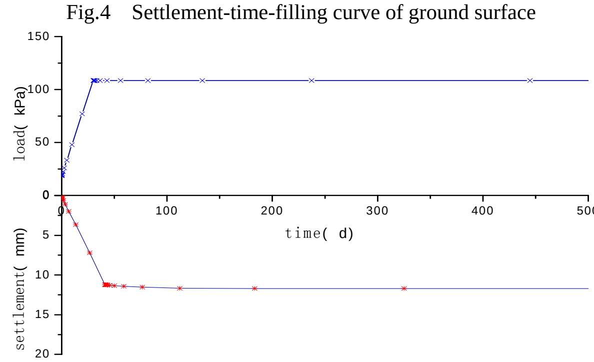

Fig.5 Surface settlement curves of subgrade center over time

Figure 4 shows that maximum settlement amount is 11.48mm within 8-month monitoring period. From Figure 5, settlement deformation gradually increases with increasing embankment filling height. The largest deformation is 11.71mm at the roadbed center surface.

Comparing Figures 4 with Figure 5, trends of the settlement deformation are basically the same and the deformation amount with the difference of 0.23mm is basically equal with the maximum error of about 2%. The results show that 3-D numerical simulation considering Biot consolidation theory can well simulate the settlement deformation of on-site basic working conditions, which is feasible in studying settlement deformation time property.

III. CALCULATION RESULTS AND ANALYSIS

The paper mainly studies the effect of parameters of soil and pile on settlement time property. In view of two layers of soft clay, the second layer is extended down to the model underside.

A. *Effect of Compressibility on Settlement Time Property*

Soil compressibility affects not only strength of composite foundation but also consolidation settlement deformation. Modulus of elasticity take respectively 10,20,30,40 and 50MPa, and the other parameters are the same with basic working conditions. The results are as shown in Figure 6.

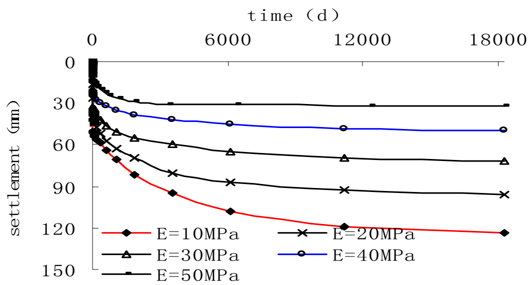

Fig.6 Surface settlement curves of subgrade center over time

Figure 6 shows that the surface settlement gradually increases with time and steady time of deformation decreases with increasing modulus of elasticity, and decline gradually increases. Corresponding ground surface settlement decreases by respectively 26.74, 24.75, 21.91 and 18.5mm for each additional 10MPa from 10MPa.

B. *Effect of Permeability on Settlement Time Property*

Soil permeability has greater impact on settlement consolidation. Permeability coefficients take respectively 10-7、10-8、10-9、10-10 and 10-11 m/s, and the other parameters are the same with basic working conditions. The results are shown in Figure 7.

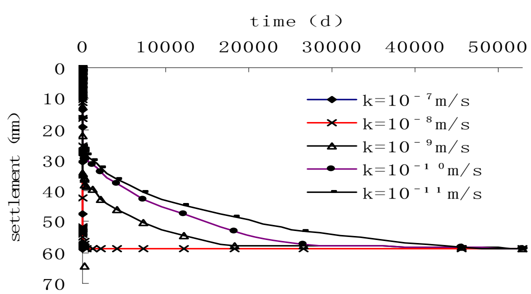

Fig.7 Surface settlement curves of subgrade center over time

Figure 7 shows that surface settlement of pile top gradually increases with time and remains unchanged with increasing coefficient of permeability. Increasing coefficient of permeability can accelerate consolidation, but does not change the amount of consolidation settlement.

C. *Effect of pile length on settlement time property*

Pile length affects not only settlement deformation of composite foundation but also time of consolidation. Pile length takes respectively 8, 10,12,14,16 and 24m, and the other parameters are the same with basic working conditions. The results are shown in Figure 8.

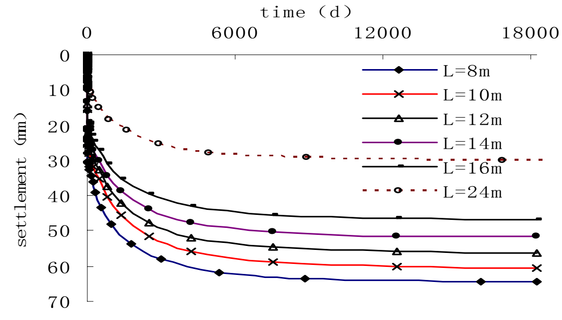

Fig.8 Surface settlement curves of subgrade center over time

Figure 8 shows that ground surface settlement increases with time and decreases with increasing pile length. Corresponding ground surface settlement decreases by respectively 3.93, 4.33, 4.52, 4.98, and 4.16mm for each additional 2m from 8m. As the pile length increases, decline firstly increases and then decreases, which shows that increasing pile length can control settlement but the effect becomes weak when pile length reaches a certain value. As the pile length increases, steady time of deformation gradually decreases and decline gradually increases. Corresponding steady time decreases by respectively 2.5, 2, 1.5, 1.5 and 0.5 years for each additional 2m from 8m.

D. *Effect of Pile Space on Settlement Time Property*

Changes of pile space can also affect settlement deformation and consolidation time of composite foundation to some extent. Pile space takes respectively 1.6, 1.8, 2.0, 2.2 and 2.4m, and the other parameters are the same with basic working conditions. The results are as shown in Figure 9.

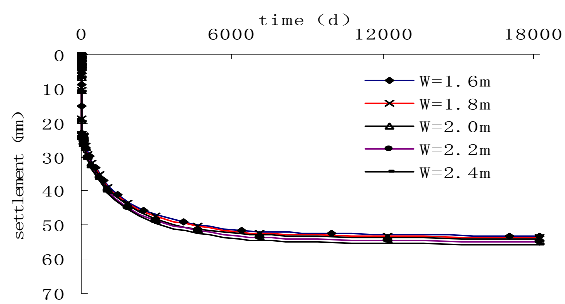

Fig.9 Surface settlement curves of subgrade center over time

Figure 9 shows that surface settlement of pile top gradually increases with time, and steady time gradually increases with increasing pile space but not significantly. Corresponding ground surface settlement increases by respectively 0.48, 0.57, 0.73 and 0.91mm with the average of about 0.67mm for each additional 0.2m from 1.6m.

E. *Effect of surcharge preloading on settlement time property*

Changing height of surcharge preloading can not only significantly affect settlement deformation of composite foundation and make it take place earlier, but also affect consolidation time. Height of surcharge preloading takes respectively 3, 4, 5, 6, and 7m, and the other parameters are the same with basic working conditions. The results are shown in Figure 10.

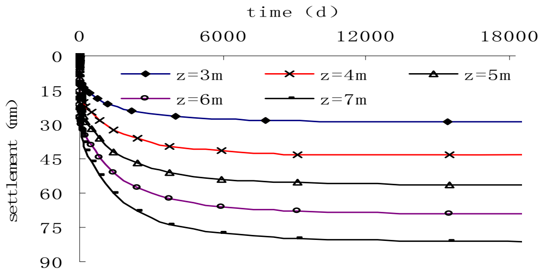

Fig.10 Surface settlement curves of subgrade center over time

Figure 10 shows that surface settlement of pile top gradually increase with time and steady time gradually increases with increasing filling height but the growth rate gradually decreases. Corresponding ground surface settlement increases by respectively 14.47, 12.71, 12.71 and 12.34mm for each additional 1m from 3m.

IV. OPTIMAL DESIGN OF COMPOSITE FOUNDATION

Through analyzing factors of settlement time property of composite foundation, shown in Table 3, design ideas of sparse-density pile are brought out based on the preceding analysis and summary, shown in Figure 11.

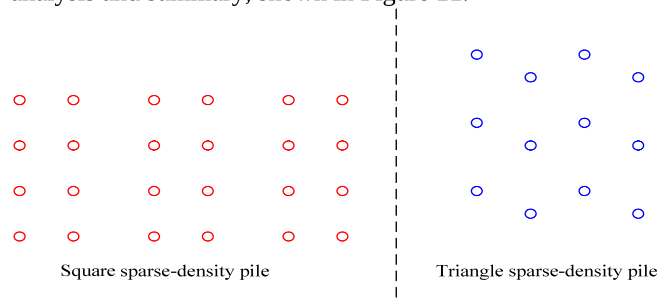

Fig.11 Layout of sparse-density pile of composite foundation

Table 3 Effect of composite foundation on settlement

	Pile length	**Pile diameter**	**Pile space**	**Modulus of elasticity**	**Coefficient of permeability**	**Surcharge preloading**
	m	m	m	MPa	*10-6mm/s	m
Range	8～24	0.2～0.6	1.6～2.4	10～50	0.01～100	3～7
Changes of settlement	34.41	3.28	2.69	91.9	/	52.23

Table 3 shows changes of soil permeability have no effect on the final settlement, modulus of elastic, surcharge preloading and pile length with the best effect but pile space and pile diameter with ordinary effect. The current pile diameter is 0.4m and 0.5m in general and pile diameter is also a certain value during controlling settlement. Numerical simulation results and analysis of significance by SPSS software show that contribution rate of effect of pile space on settlement control is 0.08 and pile length of 0.92. So, in the process of controlling settlement, pile space is a certain value, and the main factors for settlement control of composite foundation are surcharging preloading and pile length.

V. CONCLUSIONS

Through in-depth study on settlement time property of composite foundation, the following conclusions are obtained:

(1) By comparing and analyzing the basic working conditions it is verified that 3-D numerical simulation considering Biot consolidation theory can well study settlement time property;

(2) increasing pile length, pile diameter, permeability of soil and surcharge preloading， and reducing pile space and compressibility of soil, is advantageous to dissipation of excess pore water pressure and shortens consolidation time and the effect of increasing permeability of soil is the most remarkable;

(3) increasing pile length, pile diameter and surcharge preloading, and reducing pile space and compressibility of soil, is helpful for controlling settlement deformation and the effect of increasing pile length is the most remarkable;

(4) By analyzing factors and optimizing design, design ideas of sparse-density pile are brought out and the main factors for settlement are surcharge preloading and pile length.

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