Field experimental studies on super-tall buildings, super-long piles & super-thick raft in Shanghai

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Abstract: This paper not only presents the valuable field experimental data, but also demonstrates the analytical results on settlement, earth pressure, loads on pile group, loads on mega columns and stress in raft, especially, the influence of structure stiffness on stress in raft, the contribution of number of storeys of structure stiffness to foundation and its contribution limit. Meanwhile, in order to provide a new reform for the design of piled raft, a real theoretical and practical method is also given. Besides, some suggestions on settlement prediction and loads on pile group are proposed in this paper.

Key words: field test; super-tall building; super-long pile; super-thick raft; foundation

CLC number: U452 **Document code:** A **Article ID:** 1000－4548(2008)03－0406－08

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上海的超高层超长桩超厚筏基础的现场测试研究

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摘 要：提供了宝贵的现场试验数据，论述了沉降、土压力、桩的荷载、巨型柱荷载和筏基的应力的分析结果，特别是结构刚度对筏基应力的影响和对基础的贡献层数以及刚度贡献的有限性。提出了一个实用的方法，以利于桩筏基础设计的新改革。此外，还提出一些预估沉降和群桩荷载的建议。

关键词：现场试验；超高层；超长桩；超厚筏；基础

0 Introduction

It is the first time in Shanghai to carry out such a field test to provide the information on the frame-tube structure/super-long pile/super-thick raft interaction in soft soils.

Changfeng Market is of 60-storey, 238 m in height, with rafts 4.5 m～6.25 m in thickness and bored piles ϕ850 mm drilled into silty sand layer with medium and coarse sands (i.e. 9-2 soil layer in Shanghai) to a depth of 72.5 m with a pile-spacing of 2.66 m. The total number of piles in the main building is 416.

This building is composed of a 60-storey building and a 10-storey podium. Both have 4-storey basement. The external walls of the basement employ the diaphragm walls of 800 mm and 1000 mm in thickness. The depth of embedment is in the range of 18.95 m～24 m below the ground surface. The total area of the foundation pit is about 25890 m^2. The environment around this building is comparatively complex.

The plan of the piles of the main building and the layout of instruments are shown in Fig. 1.

The major physico-mechanical properties of soil layers are shown in Table 1. The average groundwater level is about 0.5 m below the ground surface.

1 Settlements

1.1 Total settlement

To record the settlement of the building with time, the settlement reference points S-1 ～ S-20 were embedded in columns and walls at the ground floor, their locations are shown in Fig.1 by use of triangle symbols.

Unfortunately, the measurement of settlement for the building started from 30th Oct. 2004, because the basements of four floors and the fourth floor on the

Received date: 2007－05－17

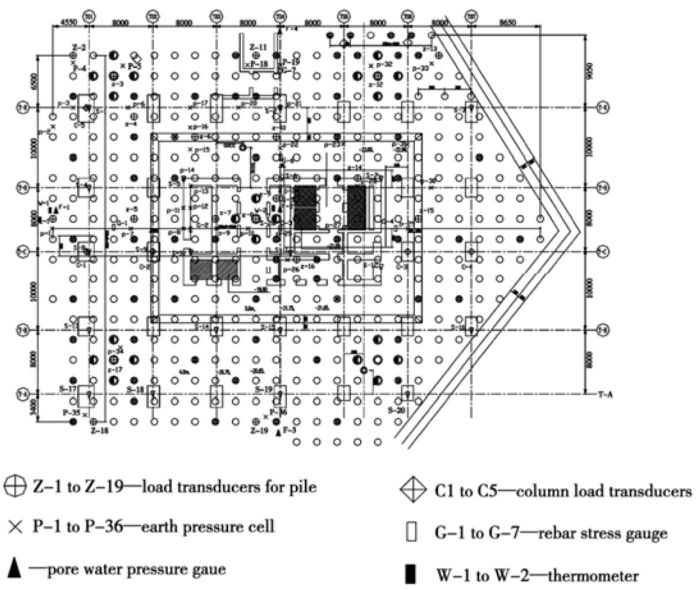

Fig. 1 The plan of the piles of the main building and the layout of instruments

Table 1 The major physico-mechanical properties of soil layers

No.	Name of soil layer	Depth/m	$Es_{0.1\text{-}0.2}$ /MPa	w /%	γ /(kN·m^{-3})	E_0	c_{cu} /kPa	φ_{cu} /(°)	c' /kPa	φ' /(°)
1	fill	1.80								
2	clay	2.50	4.60	32.9	18.3	0.94	16	21.8	1	32.5
3	Very soft silty caly	7.10	3.52	41.4	17.4	1.17	11	23.2	0	34.0
4	very soft clay	15.00	2.21	50.8	16.6	1.43	10	14.0	2	29.5
5-1-1	clay	22.30	3.69	39.2	17.5	1.14	17	16.7	1	29.7
5-1-2	silty clay	28.00	4.75	34.9	17.8	1.02	21	23.7	0	31.0
5-3-1	silty clay with clayey silt	42.00	5.39	34.1	17.9	1.00	13	29.4	0	35.5
7-2	silty fine sand	44.70	15.81	26.3	19.1	0.74				
8-1	clay	52.30	6.02	35.4	18.0	1.02				
8-2	silty clay with silty sand	58.00	5.19	32.5	18.2	0.94				
9-1	silty fine sand	67.30	15.29	26.7	19.0	0.76				
9-1	with silty clay	70.40	8.33	23.8	20.0	0.65				
9-1	silty fine sand	76.50								
9-2	medium coarse sand with gravel	92.50	21.10	20.1	19.8	0.60				
10	silty clay	97.50	12.92	25.7	19.1	0.74				
11	fine sand	106.4	14.99	26.3	19.4	0.74				

ground had been completed. The relationship between settlement versus number of floors for typical reference point S-5 is shown in Fig. 2. At the completion of the 60th floor the measured maximum settlement of S-12 is 58 mm. In fact, the settlement caused by rafts 4 m～6.25 m in thickness, the basements of four floors and four floors on the ground should be taken into account. Based on engineering experience in Shanghai, the normal rate of settlement for concrete structure is equal or less than 1 mm per floor, the settlement is about 10 mm during that construction period. Thus, the real maximum settlement would reach to 68 mm.

1.2 Differential settlement

Differential settlement is an important standard for checking the quality of engineering. In this building the maximum differential settlement at the completion of 22-storey is 4 mm while the maximum differential settlement at the completion of 60-storey, 7 mm. So, it can satisfy the design requirements.

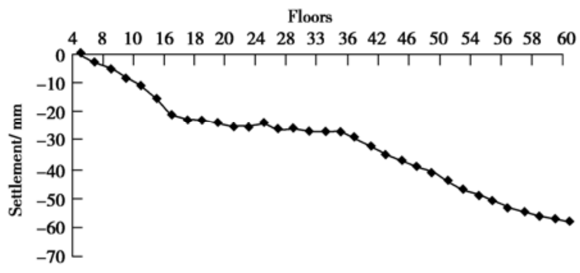

Fig. 2 Measured settlement versus number of floors for S-5

1.3 Comment on settlement

At the completion of structure of this building the maximum and average settlements are 68.0 mm and 55.4 mm, respectively, while those of the 88-storey Jinmao Building are 72.0 mm and 59.1 mm, respectively, as shown in the Table 2. Furthermore, through comparison of the ratio S_a/B_e between these two buildings shown in the same table, the former has a larger value than the latter. Now, this building is still in a good condition because the value of tilt and differential settlement are within the allowable limit. Anyway, for the safety the settlement observation should be lasted for one or two years.

1.4 Relationship between the average settlement S_a and the equivalent width B_e

In the 1980's, our research group "Superstructure and Foundation Interaction" in Tongji University had investigated the relationship between the average settlement S_a(cm) and the equivalent width B_e(m) at the completion of structure. An empirical formula, based on the statistical analysis, had been presented in order to predict the settlement as follows[1,2]:

$$S_a \approx 0.0012B_e \text{ when } Z \geq 50 \sim 60 \text{ m} \quad , \tag{1}$$

where Z is the pile length(m).

$B_e = \sqrt{A}$, A is the area of foundation(m^2).

Since the 1990's, the super-tall buildings have been developed rapidly, especially, in the recent years, it is necessary to make the similarly statistic analysis, shown in Table 2.

From Table 2 another empirical formula can be expressed as

$$S_a = \alpha\, B_e \quad , \tag{2}$$

where $\alpha \leq 0.001$。

Comparing Eq. (1) with Eq. (2), the hint shows that the former is available to the normal tall buildings, in which the number of storeys is ≤ 30, while the latter, available to the super-tall buildings and also shows that the control of settlement is strict for the super-tall buildings.

2 Earth pressures

In order to measure the contact pressure beneath the bottom of raft (foundation pressure), 36 earth pressure cells, P-1~P-36 were installed at different locations, shown by × symbols in Fig.1. The earth pressure started to measure on August 2nd 2004. The typical earth pressure of P-29 versus the number of floors is shown in Fig.3.

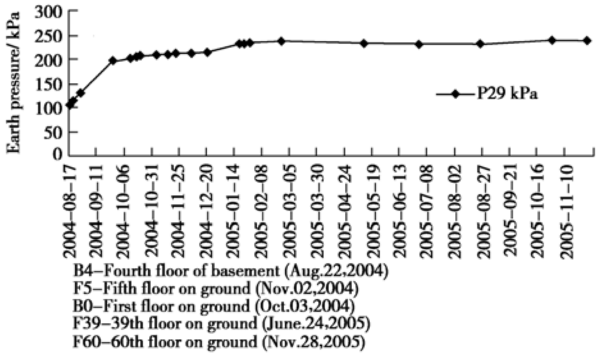

Fig. 3 Earth pressure versus number of floors

From the data shown in Fig. 3 it can be seen that there are three evident characteristics at three construction stages as follows:

1st construction stage (B4~B0): During the construction period of B4 the C30 concrete of rafts 4 m～6.25 m in thickness had been poured. The curve of the earth pressure versus the number of floors is just a straight line. Now, let's take the P-29 as the typical point to analyze. The average earth pressure of 35 kPa at that time of completion of B4, corresponding to the foundation pressure of 169 kPa, rapidly increases to 188.5 kPa at that time of completion of B0, corresponding to the foundation pressure of 206 kPa. Meanwhile, the bearing capacity of soil for the average pit depth of 20 m is higher than that of foundation pressure. That means the measured earth pressure of 188.5 kPa is supported by soil only. Later, the water pumping starts to be ceased, the buoyancy will play an important role to share the construction load.

2nd construction stage (B0~F10): This construction period of F10 can be considered as the overburden pressure stage (self weight of average pit depth of 20 m). The earth pressure increases with the number of floors

Table 2 Average settlement at the completion of structure S_a vs equivalent width B_e

Name of Buildings	Height/m	Number of floors	Length of pile/m	Area of foundation A/m^2	Equivalent width B_e/m	Foundation pressure/kPa	S_a/S_{max}	S_a/B_e0.1%
Changfeng Market	238.0	60	72.5	2875	53.62	700	55.4/68	1.033
Jinmao Building	420.5	88	83.0	3519	59.32	852	59.1/72	0.996
Henglong Plaza	288.0	66	81.5	3196	56.53	1172	54.3/58	0.961
Shimao Garden	169.0	53	58.0	2700	51.96		33.1/44	0.637
New Century	258.0	58	60.0	5500	74.16		36/45	0.485

slowly, i.e., the average earth pressure of 188.5 kPa increases to 213 kPa, the increase of pressure is merely 24.5 kPa. At that time the water buoyancy has played its role. Consequently, a new problem to distinguish the load-sharing between soil and water buoyancy has arisen.

3rd construction stage (F10 ～ F60): This construction period between F10 ～ F60 can be considered as the net foundation pressure stage. The average measured earth pressure basically keeps constant. From the practical point of view the average earth pressure can be also taken as 213 kPa, although earth pressure of P-29 is 240 kPa.

As mentioned above, before and after water pumping the measured earth pressure is the same, it is difficult to distinguish the load-sharing between buoyancy and saturated soil indeed! According to the accumulated data obtained by our research group “Superstructure and Foundation Interaction” the water buoyancy can play the role of 85%～95% depending on the permeability of soil. If that is so, for this average pit depth of 20 m the water buoyancy is about 190 kPa, then, the real earth pressure is about 23 kPa. In such a condition it is suggested that for deep excavation engineering the full buoyancy should be considered only and the sharing of soil should be ignored in practice.

These characteristics can provide a useful basis for evaluating the load carried by pile groups versus the number of floors.

3 Loads on pile group

To study the load distribution on top of pile group 19 load transducers, Z-1~Z-19 for pile were installed on the top of piles at different location, shown by symbols in Fig. 1.

Unfortunately, all the transducers were inoperative. In this case the load carried by pile groups can be expressed in the simple form as

$$P_{pile} = P_{total} - P_{soil} \quad , \tag{3}$$

Where P_{pile} is the load carried by pile groups; P_{total} is the total load; P_{soil} is the load carried by soil (raft) and equal to the average earth pressure multiplied the area of rafts minus the area occupied by the pile groups.

Then, the ratio of load of pile groups to the total load, η versus number of floors is easily shown in Fig. 5.

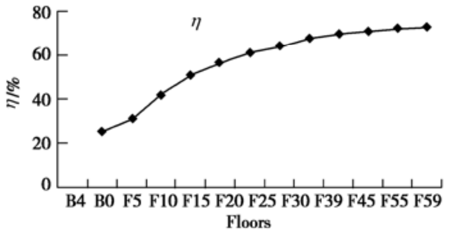

Fig. 4 Ratio of load of pile groups to total load η vs number of floors

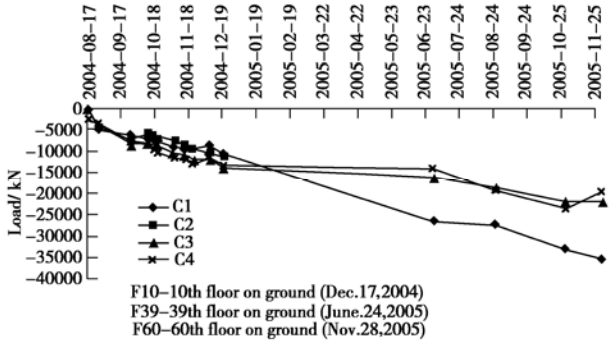

Fig. 5 Load on mega columns vs time and number of floors

Evidently, from Fig. 4 it can be seen that the ratio of pile load to the total load, η is about 67% during the completion of 39th floor and that η is 72% at the completion of this building of 60 storeys.

4 Loads on mega columns

To our knowledge, the measured data on mega columns have not yet been reported up to now. For example, in the 88-storey Jinmao Building[7] there are 8 mega columns with 1.5 m×5.0 m designed at the four sides of raft foundation to support 100,000 kN each column. In Frankfurt[4] the 300 m-high Commercial Bank Tower has 6 mega columns, which take 59% of the tower loads. However, these two buildings had not carried out the mega column tests.

In engineering practice the mega columns are always used in the design for the super-tall building. To get the special information for checking the real load on the mega columns in Changfeng Market 5 strain gauges, C1～ C5 were attached to 5 typical columns, shown by symbols in Fig.1, among them one gauge was destroyed.

The measured loads on mega columns vs time and number of floors and summary of measured loads on mega columns are shown in Fig. 5 and Table 3, respectively.

The designed loads on mega columns of 2.0 m ×

2.4 m and 1.5 m × 2.4 m are about 70000 kN and 60000 kN, respectively. Now, the measured loads are less than the designed loads. That is, the factor of safety is high enough. Thus, these data may be valuable to designers for reference.

Table 3 Summary of measured loads on mega columns

No. of mega column	Section of mega column/m^2	Measured loads on mega column at completion of F10/kN	Measured loads on mega column at completion of F60/kN
C1	2.0×2.4	10725	35526
C2	1.5×2.4	11333	
C3	1.5×2.4	13945	21985
C4	1.5×2.4	13293	19744

5 Steel stresses in rafts

The main concern in the design of the thick raft foundation is how great the stresses are in the raft. In order to measure the steel stresses along the longitudinal and transverse directions in the raft foundation, 28 rebar stress gauges were attached to the top and bottom reinforcing steel at 7 locations, shown by symbols □ in Fig. 1. At each location, 2 rebar stress gauges were arranged perpendicular to each other at the top reinforcing steel, G121, G122～G721, G722. and similarly the other 2 rebar stress gauges at the bottom, G111, G112～G711, G712, respectively.

5.1 Three construction stages

Based on the characteristics of stress change, shown in Table 4 and Fig. 6, this section is divided into three stages to analyze as follows:

1st construction stage (from the beginning of pour of concrete to the end, Aug. 2～Aug. 17, 2004): The measured stresses are taken as the examples, shown in Table 4 for macro-analysis.

Change of compression stress. For example, the compression stresses of G121 and G122 decrease from −15.05 and −13.62 MPa to −8.64 and −5.66 MPa，respectively.

Change of tensile stress. For example, the tensile stresses of G311 and G312 increase from 3.68 and 9.27 MPa to 8.62 and 12.74 MPa，respectively.

Thus, it can be seen that whatever the change of compression or tensile stresses is, it can reflect the normal change of stress. However, some data are irregular, as shown in Table 4 because of pours of three thicknesses at different time and different chemical reaction in concrete.

2nd construction stage (after 10 days at the end of pour of concrete to F10 construction stage, corresponding to the overburden pressure stage, Aug. 27～Dec. 20, 2004): Take G1(G111, G121, G121 and G122) as a typical example to analyze the change of stress, as shown in Fig 6.

From Fig 6 it can be seen that the tensile stresses of G111 and G112 at the bottom, from Aug.17 to Dec. 20, 2004, corresponding to the completion of F10, basically increase with equal stress slowly up to 16.02 MPa and 17.94 MPa，respectively. Nevertheless, the stress change of G121 and G122 at the top is different from that at the bottom. First, the compression stresses increase at the same rate; later, the compression stresses decrease and become the tensile stresses; finally, the tensile stresses

Table 4 Change of reinforcing steel stresses of G1~G7

No.	Measured time	Stresses of G1~G7/MPa						
		G1	G2	G3	G4	G5	G6	G7
11	Aug.9, 2004	−1.81	5.57	3.68	4.98	−6.07	3.78	4.96
	Aug.17, 2004	−1.17	5.27	8.62	3.66	−9.17	5.10	−11.97
12	Aug.9, 2004	7.65	3.96	9.27	−9.10	4.91	3.43	3.25
	Aug.17, 2004	4.30	1.38	12.74	−11.46	4.38	2.54	2.73
21	Aug.9, 2004	−15.05	−8.84	−8.54	3.19	−3.39	0.88	−5.49
	Aug.17, 2004	−8.64	−5.05	−6.47	0.08	−5.40	−1.51	−10.09
22	Aug.9, 2004	−13.62	−15.3	−13.37	−4.59	1.03	−1.76	−11.03
	Aug.17, 2004	−5.66	−9.99	−7.85	−9.30	6.00	−3.05	−8.72

Note: No. 11 and 12 denote rebar stress gauges at the bottom, No. 21 and 22, at the top. Symbol “－” denotes compression stress.

increase slowly up to 3.47 MPa and 3.58 MPa, respectively. It should be emphasized that there is a turning point of compression and tensile stresses between 5F and 7F at the top. Why? It is the influence of contribution of structure stiffness to foundation and it is also a long time for geotechnical circle to find such an important evidence.

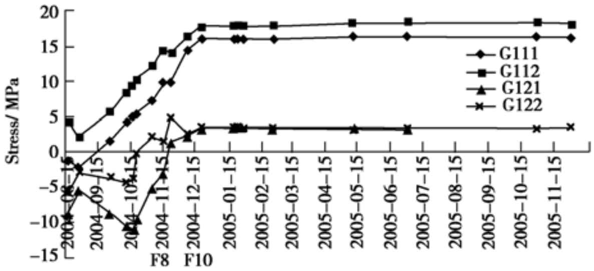

Fig. 6 Change of reinforcing steel stress of G1 vs number of floors or time

3rd construction stage (from F10 to F60 construction stage, corresponding to the net foundation pressure stage, Dec. 20, 2004～Dec. 1, 2005): From Fig. 6 it can be seen that the characteristic of tensile stresses change of G111 and G112 at the bottom and G121 and G122 at the top is the same, that is, the stresses of G111 and G121 at the bottom basically keep the constant, 16.3 MPa and 18.3 MPa, while the stresses of G121 and G122 at the top also basically keep the constant, 3.63 MPa。

From Fig. 6 it can also be seen that the contribution of structure stiffness to the foundation is limited.

These characteristics of stress change in raft mentioned above provide a good condition to reform the design of raft foundation, especially, the piled raft or piled box foundation.

5.2　Suggestion

In the 1970's, the measured data of deep embedded box foundation and the theoretical analysis of the superstructure-box-soil interaction[7] showed that after the stress resulting from temperature had been corrected, the stress in the foundation was very small and the value of stress was about 10 MPa. The steel stress was the maximum value when the construction load reached the overburden pressure of soil. i.e., at that time when it was 4~5 storeys. Later, with the increase in the construction load as well as the number of storeys, the increase or decrease in steel stress was slight. It means that the structural stiffness significantly influences the steel stress in the foundation.

In the mid-1980's the measured results obtained from Hubei Foreign Trade Centre[3] also showed that when the construction was from the 5th storey (June～July, 1984) to the 18 storey, the steel stress gradually deceased. However, at the completion of construction (May～June, 1985), the steel stresses also approached the same values as that at the 5th storey, corresponding to the overburden pressure stage. Zhangwu Building and Xiaofang Building with piled box foundation in Shanghai[1-2] also had such a similar test situation. The basic data are listed in Table 5 in order to compare with piled raft foundation.

Table 5 Summary of basic test data of 6 engineering cases

Cases	Number of storeys of superstructure	Number of storeys of basement	Height/m	Embedment of raft/m	Foundation and thickness/m	Pile type and length/m	NCSSF	Stress in box/raft/MPa
Hubei Foreign	22	1	82.80	5.0	Piled box	RC pipe pile	6	10.5
Trade Centre	Frame-shear wall				1.5	ϕ500,22		
Zhangwu	16	1	56.5	4.5	Piled box	26×0.5×0.5		15.0
Building	Frame-shear wall				0.68			
Xiaofang	30	1	101.0	4.5	Piled box	54×0.5×0.5		14.2
Building	Shear wall				0.60			
Maohai	26	1	94.5	7.6	Piled raft	Steel pipe pile	6	21.7
Building	Frame-tube				2.3	ϕ609,60		
Post-telecom	36	2	143.3	13.6	Piled raft	Bored pile	10	42.7
Building	Tube in tube				2.5	ϕ600,60		
Changfeng	60	4	238.0	20.6	Piled raft	Bored pile	14	36.2
Market	Frame-tube				4.5~6.25	ϕ850,72.5		

Note: NCSSF is the abbreviation of number of contribution of structure stiffness to foundation.

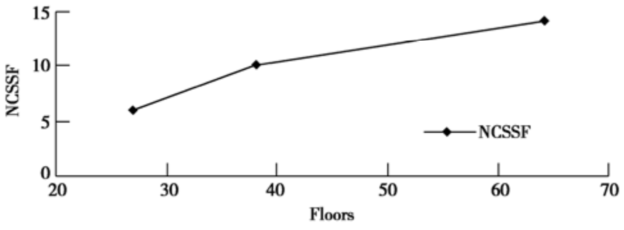

Fig. 7 Number of storeys of structure including basement versus NCSSF

Now the valuable data of the field tests on Maohai Building[1-2] and Changfeng Market in Shanghai and Post-telecom Building with piled raft foundation in Shen-xi Province[5] are summarized in Table 5 and Fig. 7.

In this good condition the following equation is suggested to design the piled raft (or box) foundation:

$$([K_B]+[K_r]+[K_{ps}])\{U_B\}=\{S_B\}+\{P_r\} \qquad (4)$$

where $[K_B]$ and $\{S_B\}$ are the condensed equivalent stiffness matrix and corresponding equivalent load vector at the boundary of n-storey structure, including substructure (basement) in which n is number of storeys of structure's contribution to foundation, shown in Fig. 7. $[K_r]$ is the stiffness matrix of raft; $[K_{ps}]$ is the stiffness matrix of pile-soil system; $\{U_B\}$ is the boundary displacement vector; $\{P_r\}$ is the nodal force vector of raft itself.

Solving Eq. (4) for $\{U_B\}$, the settlement, the moment in the raft, the load on pile and other results can be obtained using back-substitution.

It should be noted that the number of structure's contribution, n shown in Fig. 7 is determined by the interpolation or trial error method.

For safety, the number of structure's contribution at left and right sides in Eq. (4) are taken as $n-1$ and $n+1$ in raft design, respectively.

Furthermore, the stress in rafts can be calculated using the theory of structure-foundation interaction or the ordinary method according to the overburden pressure (soil) stage, or these two methods both are used and compared each other to get the reasonable value for raft design.

6 Concluding remarks

According to the analytical results mentioned above, five preliminary important conclusions can be drawn as follows:

(1) Settlements

Based on the comparison and statistic methods, an approximate empirical formula is expressed as

$$S_a=\alpha B_e ,$$

where $\alpha \leq 0.001$.

This formula is very useful to predict the settlement for super-tall buildings. For example, Zhao X H., Gong J. and Zhang B. L. [6] predicted that the maximum settlement of Shanghai World Financial Center (SWFC) of 101-storey, using comparison and analytical methods, will be more than 82 mm in the 88-storey Jinmao Building. Now, Eq. (2) can also be used to predict the settlement at the completion of SWFC of 101-storey. Since the foundation area A = 6200 m^2 in SWFC, $B_e=\sqrt{A}=\sqrt{6200}$ = 78.74 m, then, the average settlement at the completion of 101-storey $S_a \leq 78.74$ mm. It is the safety control value and the tilt control value is more important.

(2) Earth pressures

There are three evident characteristics of earth pressure at three construction stages, which can provide a useful basis for evaluating the load carried by pile groups. It is suggested that for deep excavation engineering the full buoyancy should be considered only and the sharing of soil should be ignored in practice.

The overburden pressure stage is not only an important characteristic for evaluating the load carried by pile groups, but also a useful basis for evaluating the contribution of structure stiffness to the foundation referring to 6.2.

(3) Loads on pile groups

For deep excavation engineering in Shanghai as well as the similar soil condition including water level, the loads carried by pile groups, P_p is equal to the total load, P_t minus water buoyancy. That is

$$P_p=P_t-p_w\times A_n , \qquad (5)$$

where p_w is the water buoyancy; A_n is the net area of foundation, and equals to the area of foundation minus the area occupied by pile groups.

Thus, it is easy to design the piled raft or piled box foundation.

(4) Loads on mega columns

The measured load data on mega columns may be valuable for design reference.

(5) Steel stresses in rafts

In the 1980's our research group "Superstructure and Foundation Interaction"[1,2] had theoretically and experimentally shown the contribution of structure stiffness to foundation. However, due to only one engineering case in Shanghai, the contribution of storeys could not be determined for given number of storeys of a tall building. Now, this dream will come true! The methods to determine the contribution number of storeys and to calculate the stress in piled raft or piled box foundation have been presented in this paper.

Finally, for the box foundation and piled box foundation or the piled raft foundation there is a common characteristic, the steel stress was the maximum value when the construction load reached the overburden pressure stage. This valuable conclusion based on the field tests of 30 years can help the designer make a creative decision in the design of the piled raft or piled box foundation.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the National Natural Science Foundation of China (Grant No. 50578121) and Shanghai No. 2 Construction Company for this project.

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