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Rigidity characteristic and deformation calculation of large-area thick raft foundation

Le calcul de la rigidité et de la déformation pour fondation sur radier épais de vaste étendue

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ABSTRACT
Model Test results show that when raft thickness is 1/6 of column span, the rigidity of frame structure with raft foundation is limited rigidity; and contact pressure of foundation may distribute linearly. The simplified global analysis method with the consideration of superstructure for the contact pressure and settlement of raft under partial load and superimposition principle can be employed in the settlement of large-area thick raft foundation with multi-tall buildings.

RÉSUMÉ
L'essai sur modèle montre que si l'épaisseur de radier est de 1/6 de la travée des poteaux, la rigidité de la construction de cadres de fondation en radier est limitée et la contre-force de la fondation peut se répartir linéairement. Par la méthode simplifiée de calcul général et le principe superposé utilisés sous l'action de la charge partielle en superstructure pour calculer la contre-force et l'affaissement du radier, on peut obtenir le volume d'affaissement sur une grande surface de la fondation à radier épais sous l'action des tours multiples.

1 INTRODUCTION

With the development and utilization of the underground space, large-area frame structure with thick raft foundation under tall buildings with a bottom area of over 10,000 square meters is widely used. On such foundation, various stories of tall buildings are built and there is great difference of load and structural rigidity between tall buildings and podium. Compared with the size of large-area thick raft foundation, the ratio between raft thickness and its length is very small, and its flexibility index is quite big, so the deformation characteristic of the raft is flexible. However, under the local load of tall buildings, constrained by superstructure, it may function as rigidity to adjust settlement, thus the whole raft is a irregular flexible slab, local rigid regions at high-rise buildings locations exist on the non-uniform flexible slab. For this foundation form, existing approach cannot accurately calculate the contact pressure of the whole range of raft as well as its settlement.

To solve the above -mentioned problem, serious of indoor large-scale model tests had been done in China Academy of Building Research. The purpose of the tests is to study the internal force of raft, load dispersion range through frame structure with thick raft foundation under local vertical load, interference between tall buildings and the deformation characteristics of large-area thick raft foundation.

2 ANALYSIS OF SIMULATION TEST RESULTS

2.1 *Range of Slab's Even Transfer of Load under Local Load*

The test is to find out the characteristics and transfer range of contact pressure of slab under local vertical load. The model test took the cylinder in the middle of concrete slab with a diameter of 800mm, a wall thickness of 70mm; the size of slab was 4.5m×4.5m×0.2m (slab thickness). Subsoil was medium compressible silty clay.

When the load was increased to 600kN (the deflection of the slab corresponding to within the range of 2.5 times of slab thickness from cylinder edge was 0.75‰), the pressure within the range of 2.5 times of slab thickness from cylinder edge distributed evenly; when the load was increased to 800kN (the deflection of the slab corresponding to within the range of 2.5 times of slab thickness from cylinder edge was 1.89‰) , bending crack appeared at the circumference of cylinder. Along with the increased of load, the increment of pressure transferred to the range of 2.5 times of slab thickness from cylinder edge decreased by and by, load concentrated on the cylinder and distributed as saddle under the cylinder. When the load was increased to 1600kN, reverse circular bending crack appeared at 2.5 times of slab thickness from cylinder edge (reverse deflection of slab corresponding to 2.5 times of raft thickness from cylinder side was 1.06‰).

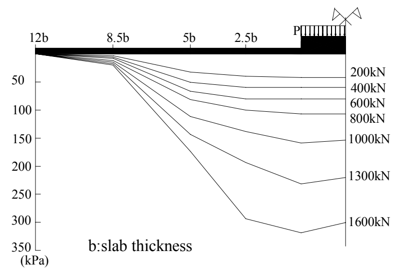
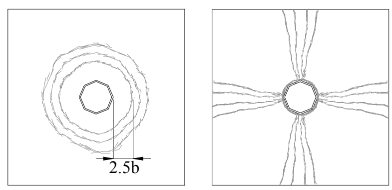


Figure 1.Contact pressure distribution along diagonal slab



Crack at raft top Crack at raft bottom

Figure 2.Crack of the raft

The test shows that when load is linear relationship with the deflection, the pressure distributes evenly within the range of 2.5 times of slab thickness from the edge of cylinder; along with the increase of load, when the slab at the circumference of cylinder fails, load can only be transferred to 2.5 times of slab thickness from the edge of cylinder; i.e., 2.5 times of slab thickness is the range that slab can transfer pressure evenly and the effective range that pressure can be transferred to after slab fails.

2.2 *Raft Thickness and Deformation Characteristics under Central Vertical Load*

Experiments have been done to illustrate raft thickness and deformation characteristics under central vertical load. The distribution of contact pressure under the slab with different length-height ratio of the slab was measured. The area of the slab was 1000mm×1000mm, with a thickness of 100mm, 125mm, 160mm, and 200mm respectively. The conditions of the measurement are listed as the following:

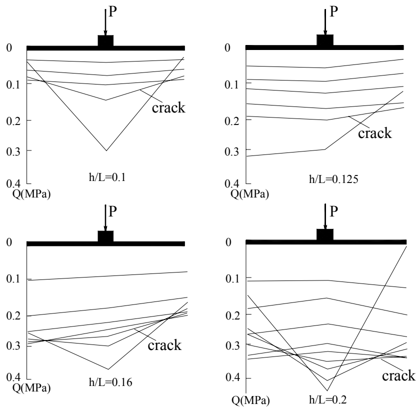


Figure 3. Distribution of pressure under the slab with different h/L ratio

The first condition - the ratio of thickness (*h*) to span (l) of the plate was 0.1 (i.e. *h/l* =0.1). When the applied load was very small, the contact pressure was distributed linearly, while the contact pressure at the middle part increased rapidly with the increase of the load. When damage occurred, the deflection at the middle was very big and the pressure increased suddenly, at the same time punching shear occurred. The contact pressure was not in linear distribution;

The second condition - *h/l*=0.125, under certain conditions it could be considered as the pressure distributed linearly. When the load increased, the pressure at the middle was larger. Finally bending shear failure occurred;

The third condition - *h/l*=1/6, in a range of very large load, the pressure was in linear distribution. Finally it was also bending shear failure. As soon as deflection occurred, punching shear took place;

The fourth condition - *h/l*=0.2, under the action of load, the pressure became smaller at the middle and larger at the sides, approaching to the case of rigid foundation. Finally, under very large load, bending shear failure also occurred.

Test shows that the distribution characteristics of contact pressure are relevant to the ratio of thickness to the span of the slab.

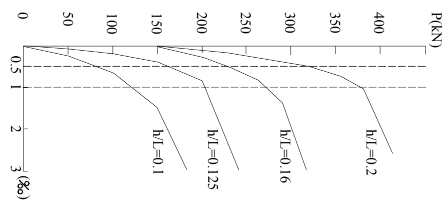


Figure 4.Relation of deflection and load at different raft h/L ratio

Fig. 4 shows that for raft with different thickness, the deflection was almost the same as cracked (about 1‰), but there was great difference between loads, the thicker raft's load bearing capacity was far more than that of thinner raft. Thus the raft thickness that can guarantee a raft deflection of no more than 1‰ and the even distribution of contact pressure (namely the thickness-span ratio of 1/6) is reasonable raft thickness.

Investigations show that most thickness-span ratios used for beam slab design in actual project are 1/6 to 1/5. Test and actual engineering measurement show that for the frame thick-raft structure at length to height ratio 1:3, with a slenderness ratio of frame column of around 3:1, its total bending does not exceed 0.5‰, the local bending mainly reflected in having of plate between columns, at the direction of long side length, it could reach to 1‰, and its rigidity is similar to that of box foundations. Therefore, the thickness-span ratio of 1/6 can be used as the basis for appraising the rigidity of raft foundation. When the actual thickness-span ratio is over 1/6, the foundation has limited rigidity, namely it is semi-rigid foundation, the contact pressure of foundation may distribute linearly, and for raft design, only local bending moment is taken into consideration without regard to total bending moment. When thickness-span ratio is less than 1/6, for raft design, total bending moment should be taken into consideration, and the method of beam slab on elastic foundation should be adopted to calculate contact pressure and internal force.

Table 1:Model Size

Test Number	No.1	No.2	No.3
Raft Foundation Area (mm×mm)	3150×1910	4290×1910	5430×2270
Main Building Area (mm×mm)	1710×1710	1710×1710	1710×1710
Column Spacing, Span and Storeys of Frame structure	5@570 2 Storeys	7@570 2 Storeys	9@570 2 Storeys

2.3 *The Pressure Diffusion of Thick Raft Foundation under Local Vertical Load*

To make out the maximum scope of contact pressure transferring through frame structure with thick raft (its thickness should not be less than 1/6 column span) under the local load of tall building, the model test was carried out in door for the circumstances when the two-storey frame structure with thick raft foundation at two ends of tall building were of single span, two spans and three spans respectively. The model size is listed in Table 1.

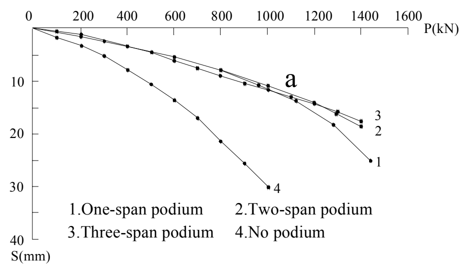


Figure 5. Curves of various model loads-maximum settlement values

When the podium at two ends of main building was one span, the contact pressure of the foundation was evenly distributed, which is indicated in Fig. 6. It shows that the two-storey frame thick raft had good load-transfer capability. The pressure could be calculated on average with the area of further adding a span when load value was not over the proportional limit value got from loading test (point a in Fig. 5).

When the podium at two ends of main building was three spans, the contact pressure was transferred to the third span and decreased to zero proportionally as shown in Fig. 6; the value of contact pressure diffused was similar to that when the podium was one span.

This test shows that the dispersion through the thick raft foundation for the tall building load is limited to a certain extent under service ability limit state.

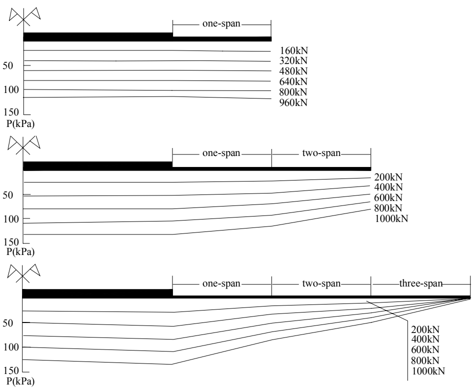


Figure 6.Curve of model test foundation pressure

Table 2:Loading path

Test Number	Loading Path	Load of Tall building A (kN)	Load of Tall building B (kN)	Remark
1	Synchronic Loading	0→800	0→800	Curve 1
2	Loading A	800→1600		Curve 2
3	Loading B		800→1600	Curve 3

2.4 *Interference between two tall buildings*

The effects of settlement and pressure of a tall building on that of the neighboring one are extremely important factors in foundation design. The effects may be reduced due to the pressure diffusion in thick raft foundation. Two abreast-tall-buildings-test was carried out for further investigation of the interaction between two tall buildings. Loading path is shown in Table 2.

Test results show that the contact pressure and settlement of foundation were related to loading path. Settlement and pressure of tall building A had light effect on that of tall building B when the space between two tall buildings was three spans.

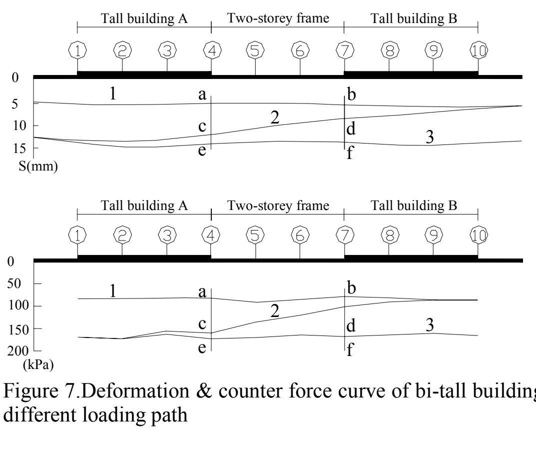


Figure 7.Deformation & counter force curve of bi-tall building test with different loading path

In Fig. 7, when the applied load to the tall building A was increased from 800kN to 1600kN, the increase of area surrounded by abdc caused by the pressure and settlement of section4--7 was almost the same as that of area cdfe when the load of tall building B was increased by 800kN. It means that the pressure and settlement of any point on the raft from any local vertical load could be calculated by superimposition principle.

When the frame in section5--6 was removed, the deflection of raft increased obviously while it did not surpass allowable value.

3 ESTABLISHMENT OF MODEL AND FEASIBILITY OF SIMPLIFIED COMPUTATION METHOD

The large-area frame structure with thick raft foundation under tall building can be simplified as an global analysis model which is shown in Fig. 8. It is characterized by simplifying the rigidity of the superstructure of tall building as rigid substitution beam by Meyerhoff method and putting such beam to the top part of the expanded basement of frame structure with thick raft foundation. Bi-tall building test also proves the range of the effects of local load on settlement and the contact pressure and the applicability of superimposition principle. With the simplified global analysis model and superimposition principle, the complicated contact pressure and settlement problem of large-area thick raft foundation can be solved approximately. The numerical analysis result of the bi-tall building test with above-mentioned method was quite close, which is shown in Fig. 9.

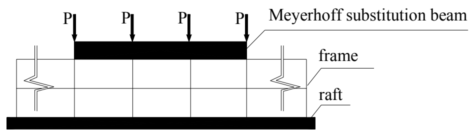
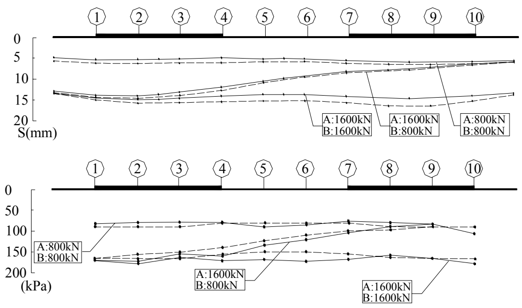


Figure 8.Simplified computation model



Solid line: test results; Dashed line: calculation results

Figure 9.Comparison of numerical calculation results & test results

4 APLICATION TO ACTUAL ENGINEERINGS

4.1 *Beijing Fujing Garden*

The main buildings of Beijing Fujing Garden are 12-storey, 19-storey, and 14-storey structures respectively. The podium was built with two storeys above ground and three storeys in basement. The buried part is about 15 meters in depth. Shown in Fig. 10, the foundation is composed of the alternating of sand, gravel, silty clay and mid-dense to dense common soil of the Quaternary Period.

In order to solve the different deformation caused by the great difference of load and structural rigidity between tall building and podium, the continuous general thick raft foundation had been adopted, aiming at using the thick raft foundation of podium to diffuse the load of tall building to decrease the additional stress under the foundation of tall building, thus to diminish the settlement of tall building and the differential settlement between tall building and podium. For the raft thickness, the thickness-span ratio should be no less than 1/6, and it should conform to the requirement of resisting punching and shearing of tube, shear wall and frame column load. The raft thickness after optimization is 1.8m and the concrete strength grade of raft is C30.

Actual measurement results show that the settlement upon the structure of tall building completed is 5mm to 7mm, and the foundation settlement is very even. According to the results of actual settlement monitoring upon the structure of tall building completed, and referring to the relevant experience in Beijing area, the final settlement of the building will not be over 20mm. Calculation shows that the 19-storey-building’s average characteristic value of load is about 380kN/m^2, owing to that general thick raft foundation had been adopted, podium may diffuse the load of tall building, the average contact pressure under tall building of 19-storey is only about 200kPa, and the foundation settlement is still at the rebound-recompressed section.

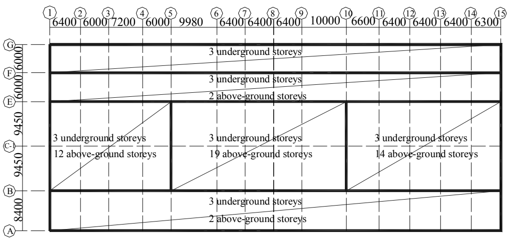


Figure 10 Foundation Plan View

4.2 *Bank of China, Beijing*

Beijing Bank of China Mansion has a floor space of about 13000m^2 with 16 storeys above ground and four storeys underground. Main building is constructed along the circumference and a courtyard with four stories of basement and an area of 4200 m^2 is enclosed in the middle. Column spacing is 6900mm, the buried depth of foundation is about 22m, and it is a foundation with from mid-dense to dense common soil of the Quaternary Period, sand, gravel and silty clay alternating with each other.

The design total load of the building is about 4,600,000kN; and load distributes unevenly with the average pressure of the tall building foundation at the circumference of about 500kPa and that of courtyard about 150kPa. Due to great difference of load and structural rigidity, settlement control becomes the key of the foundation design of this project.

To solve differential settlement and fully apply the differential settlement adjustment capability of frame thick raft, with calculation and analysis, the general thick raft foundation with variant raft thickness is adopted. The raft thickness becomes thinner by and by from the external of the first span at the edge of tall building. Thus, the rigidity of the single span podium connected with main building is capable of diffusing the load of main building so as to adjust the differential settlement between higher storeys and lower storeys. The thickness and the place of variable section of raft are shown in Fig. 11.

The results of actual measurement show that the average settlement of tall building upon completion of works is about 35mm, the settlement of cortile is about 15mm, the raft deformation between higher storeys and lower storeys is smooth, local tilting value is controlled within 1‰ and the deformation of whole foundation raft is gradient. At present, the building has been put into use for five years, and no abnormal conditions of foundation raft have been found.

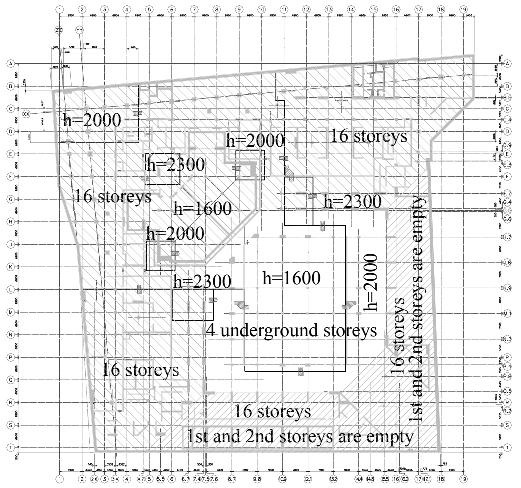


Figure 11.Foundation Plan

5 CONCLUSION

1. Under the interaction of the superstructure, thick raft (with the ratio of thickness to span of the raft more than 1/6) and foundation soil, the deformation of the entire raft is irregular and continuous. Under serviceability limit state, its settlement can be calculated based on elastic theory and superimposition method.
2. Load transferred through the raft is limited. Its range is related with frame spacing and raft thickness. Test results reveals that raft loading spreading is primarily within the range of 8m to 12m, and becomes negligible beyond range of 24m.
3. When the ratio of thickness to span of the raft $h/L > 1/6$, if the soil is uniform, rigidity of superstructure is good, load distribution is comparatively uniform, for tall building at the circumference connecting one-span podium symmetry, the contact pressure of foundation distributes linearly, raft design can only consider local flexure and its distribution rule of the internal force is as same as that of the global analysis method (with the consideration of superstructure). When the circumference of tall building exceeds one-span podium, the contact pressure under tall building still distributes linearly, and the value of contact pressure under tall building can be calculated on average with the area of further adding one span, The raft design of tall building may only consider local flexure and the raft design of podium needs to consider total flexure.
4. The simplified global analysis method in this work can be used to calculate the settlement of large-area thick raft foundation with multi-tall buildings.

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