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THE EFFECTS OF SITE FACTORS ON THE BEHAVIOR OF RIGID-PILE COMPOSITE GROUND AND RAFT FOUNDATION SYSTEM

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Abstract: *This paper adopts the finite element method (FEM) to calculate an example of a 25-storey frame-tube structure by considering the interaction of superstructure, foundation and ground. The analysis of the effects of site factors on the stress and displacement of the raft foundation is carried out. The main site factors include: constraint effect of the surrounding ground soil, influence of neighboring buildings, and effect of the construction defect of cushion. The study shows that 1) the geometry size of ground soil has relatively great influence on the stress and displacement of the raft foundation, the influence sphere is about 2~3 times the geometry size of the raft; 2) neighboring buildings have a more significant effect on the stress and displacement of adjacent edge of the raft, this effect gradually disappears with the increase of building spacing; 3) the construction defects of cushion have limited effect on the stress and displacement of the raft.*

Key words: *Interaction, Overall finite element model, Site factors, Raft stress, Raft displacement*

1. INTRODUCTION

Rigid pile composite ground is a new type of ground treatment method. It can increase the bearing capacity and diminish the displacement of ground, and it has been used in tall building structures in recent years [4] [7].

In the design process of raft foundation, different site factors, such as constraint effect of surrounding ground soil, neighboring buildings, construction quality of cushion, etc. will have effects on the stress and displacement of the raft. By studying these factors, the influence degree and characteristics can be made definite to guide engineering practice, which is of great theoretical and practical meaning. This paper adopts the overall FEA method of ground-raft-superstructure to analyze the effect of the above factors on the stress and displacement of rigid pile composite ground and raft foundation system.

2. OVERALL FINITE ELEMENT MODEL

The interaction of superstructure-raft foundation-ground makes overall finite element model necessary. In the past, the substructure method is always used during the design process to reduce computation, and the calculation is always limited to elastic analysis. The overall model and elastoplastic analysis are more accurate, which is good for study of the characteristics of interaction. This paper uses FEA software ADINA to establish the overall finite element model and conducts elastoplastic analysis [6].

2.1. Material constitutive model

Superstructure, concrete pile and concrete of raft foundation are considered to be in linear elastic condition under vertical loads. So the linear elastic constitutive model is used to represent the concrete constitution of beams, columns, shear walls, slabs and raft foundation. Parameters of concrete linear elastic model are based on current Chinese code (GB50010, Code for Design of Concrete Foundation) [2].

The major researching object of this paper is the interaction of rigid pile composite ground and raft foundation. The accurate simulation of mechanical properties of soil is a key factor. The Druker-Prager elastic-plastic model (DP model) which is suitable for granular materials is used to represent ground soil [5].

2.2. Selection of element

Two nodes Hamiltonian beam element with constant cross-section is used to simulate beams and columns, which carry axial force, bending and torsion. Shell element is use to simulate slabs and shear walls. TRUSS element which has less DOFs and can only carry axial force is used to simulate rigid pile. 3-D solid element (Q8) [9] is used to simulate raft and ground, which have large volume and carry great shear force.

2.3. Treatment of contact problem

There are two kinds of contact problems in this paper; the first one is the contact of raft and cushion, the second is the contact of different layers of ground. The Contact Pair option is used to simulate the interaction. The surface of contact for the first contact problem is defined as Not Tied, which doesn't consider the bond force of the interface except the friction; the surface of contact for the second contact problem is defined as Tied, which makes the different layer of ground completely close contact without sliding and disengagement.

The interaction is set as follows: the contact relationships in normal direction of cushion and raft foundation, backfill soil and sidewall, cushion and ground soil are all defined as Hard Contact, i.e. the pressure in normal direction can transfer completely in the interface; Interface Element is used to simulate the friction.

2.4. Transformational program ETA and rapid modeling program DFTA

This paper presents a transformational program (ETA) and a rapid modeling program (DFTA), both of them are developed based on DELPHI language to simplify the modeling process. The ETABS model can be transformed into command flow of ADINA with ETA. ETA can automatically complete the modeling of ADINA with one button. The material properties and geometric parameters which will be used to export the command flow of ADINA are needed in DFTA. DFTA can automatically complete the modeling of ADINA. The overall finite model in ADINA is established through the above process, as shown in Figure 1.

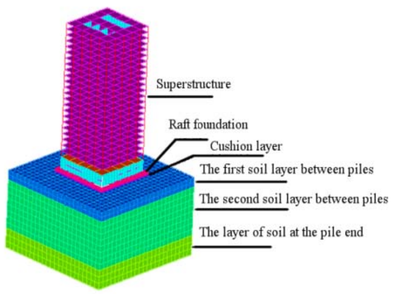


Figure 1. Finite element model

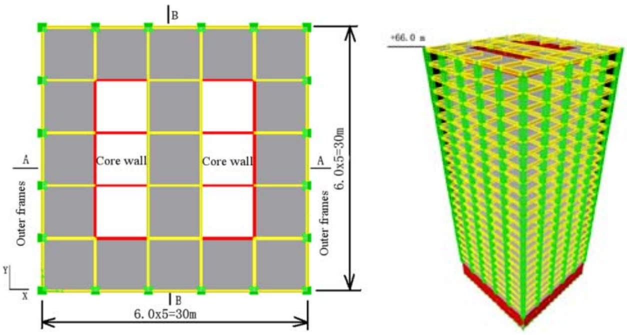


Figure 2. Geometric dimensions of superstructure

3. EFFECTS ANALYSIS OF SITE FACTORS ON RAFT FOUNDATION

3.1. Calculation model

The frame-tube system which is often used in tall building structures is adopted as the superstructure of the calculation examples, as shown in Figure 2. The structure is a 25-storey tall building structure with a 2-storey basement. The column spacing of the outer frame is 6m, and all storey height is 3m. The modeling of foundation and ground are finished in ADINA. The raft foundation is 1.6m thick with a 2m outrigger on each side. Rigid-pile composite ground is used as ground treatment. A uniform distribution of piles is adopted. The diameter of a pile is 400mm, the length is 30m and the pile spacing is 2m. The ground is divided into 4 layers, which are the cushion layer, the first layer of soil between piles, the second layer of soil between piles and the layer of soil at pile end. The plane dimension of the ground is 2 times that of the superstructure, and the total thickness is 40.3m. The displacement boundary conditions of the model are: four side planes of the ground soil are constrained only on normal direction while the bottom surface is fixed. The structural parameters of the overall model are shown in

Table 1; the parameters of ground soil are shown in Table 2; load determination is shown in Table 3.

Table 1 Parameters of structural components

Component	Section (mm)	Concrete strength	E (N/m^2)	ν	Weight (N/m^3)	Element
Frame beam	300×650	C35	3.15×10^{10}	0.2	25000	Beam
Frame column	1000×1000	C40	3.25×10^{10}	0.2	25000	Beam
Tube shear wall	300	C40	3.25×10^{10}	0.2	25000	Shell
Floor	100	C35	3.15×10^{10}	0.2	25000	Shell
Concrete pile	400	C25	2.8×10^{10}	0.2	25000	Truss
Basement roof	250	C35	3.15×10^{10}	0.2	25000	Shell
Sidewall	300	C40	3.25×10^{10}	0.2	25000	Shell
Raft	1600	C40	3.25×10^{10}	0.2	25000	Q8

Table 2 Parameters of ground soil

Layers of soil	Thickness (m)	Cohesion (N/m^2)	Internal friction angle	E (N/m^2)	ν	Weight (N/m^3)	Element
Cushion	0.3	0	40°	4×10^7	0.2	20000	Q8
The first layer of soil	5	2×10^4	20°	1×10^7	0.25	20000	Q8
The second layer of soil	25	2×10^4	20°	2×10^7	0.25	20000	Q8
The soil at pile end	10	2×10^4	20°	7×10^7	0.25	20000	Q8

Note: The dilation angles in all examples are 0. Generally, it's a conservative method.

Table 3 Load determination

Load	Basement	The first and second storey	Other storey
Dead load (kN/m^2)	3	3	3
Live load (kN/m^2)	4	3.5	3
Line load on outer frame (kN/m)	——	10	7

Note: The stress and displacement of raft foundation are mainly influenced by vertical load. So lateral earthquake and wind load are not considered in this paper.

3.2. Basic assumptions

(1) The original stress and displacement caused by piling are not considered;
(2) Concrete beams, columns, shear walls of superstructure and concrete piles are all treated as linear elastic body;
(3) Ground soil is continuous elastoplastic body and simulated by DP model;
(4) Piles keep close contact with surrounding soil, i.e. there are no sliding or disengagement between them in the process deformation;

(5) Drainage consolidation and stress history are not considered.

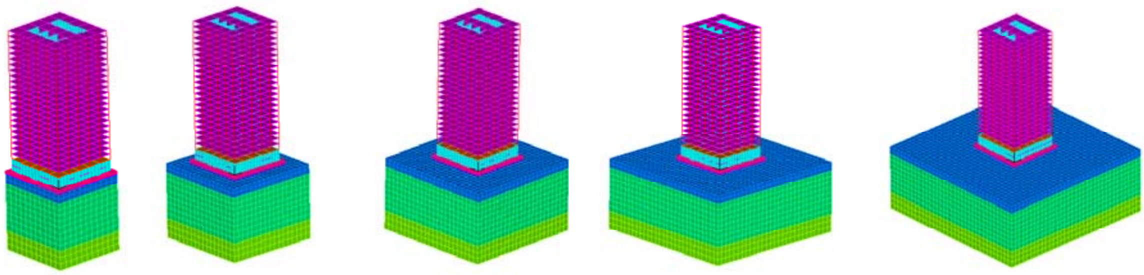
3.3. Examples design

This paper focuses on the effect of different site factors on the stress and displacement of rigid-pile composite ground and raft foundation system. In view of these factors, different calculation examples are designed as follows:

(1) 5 models of ground soil with different geometric dimensions are established, i.e. the soil model with 1 time, 1.5 times, 2 times, 2.5 times and 3 times the raft dimension, as shown in Figure 3.;

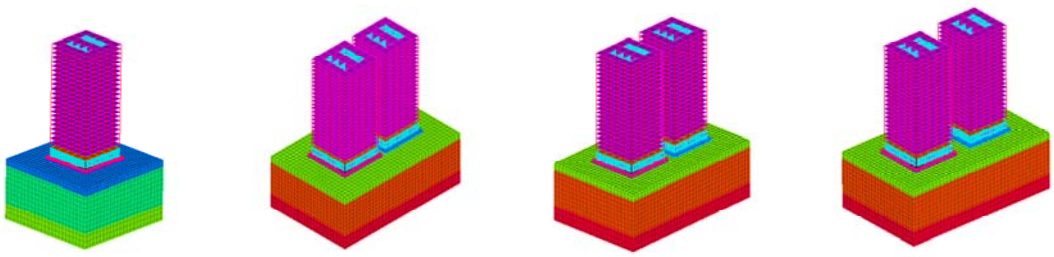
(2) The finite element models of a single building and two exact same buildings with the spacing of 7m, 10m, 15m are established as shown in Figure 4.;

(3) The finite element models with deformation modulus of cushion as 40MPa, 20MPa and 10MPa are established.



(a) 1b (b) 1.5b (c) 2b (d) 2.5b (e) 3b

Figure 3. Finite element models of ground soil with different geometric dimensions



(a) A single building (b) Spacing of 7m (c) Spacing of 10m (d) Spacing of 15m

Figure 4. Finite element models with different neighboring building spacing

3.4. Results and analysis

3.4.1. Stress

From Figure 5.-Figure 7., we can conclude that the geometric dimension of ground soil has a great effect on the stress of the raft. With the increase of the modeling size, the maximum shear stress which controls the thickness of the raft tends to increase. In contrast, the tensile stress which controls the reinforcement of the raft decreases. The constraint range of the surrounding soil is approximately 2 to 3 times the geometric size of the raft foundation.

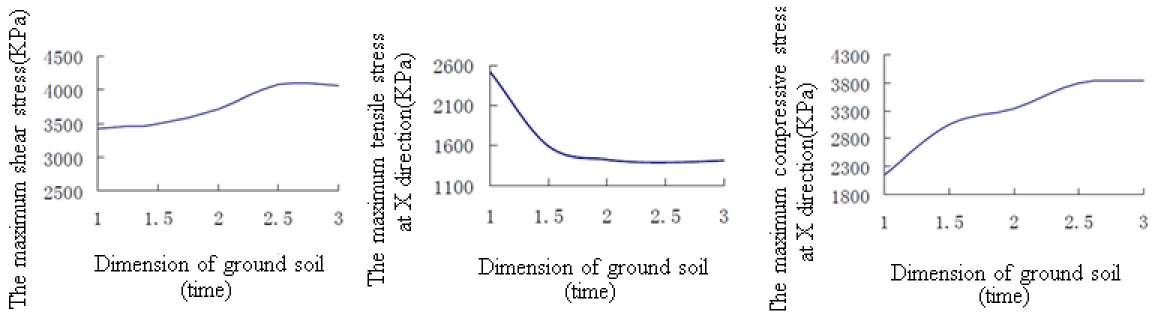
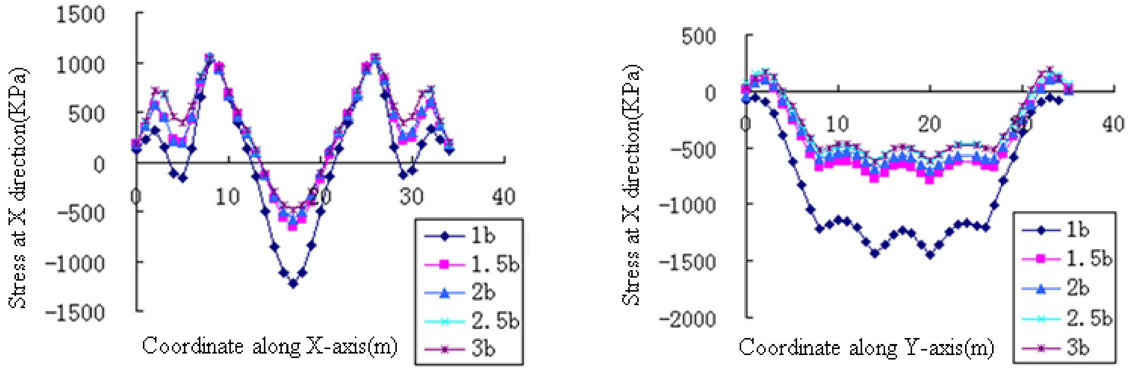
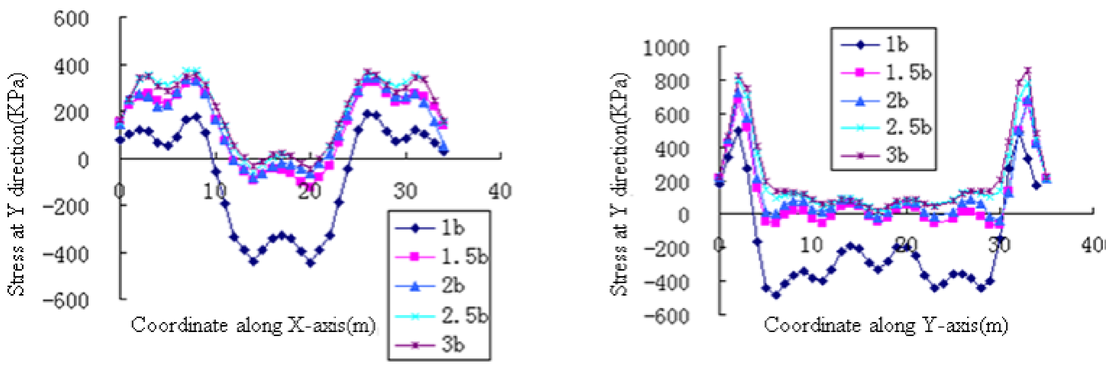


Figure 5. The relationship of maximum stress of raft and geometric dimensions of ground soil



(a) A-A axis (b) B-B axis

Figure 6. The relationship of raft stress at X direction and geometric dimensions of ground soil



(a) A-A axis (b) B-B axis

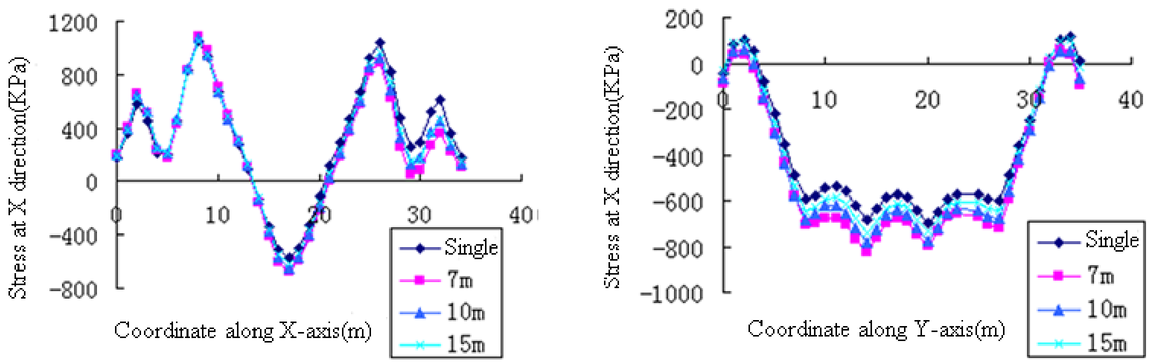
Figure 7. The relationship of raft stress at Y direction and geometric dimensions of ground soil

Table 4, Figure 8. and Figure 9. show that neighboring buildings have a relatively big effect on the tensile stress along the central axis of the two buildings, and little effect on the shear stress of the raft. The edges of the raft are obvious influenced but this effect gradually disappears with the increase of the building spacing. It is suggested that the reinforcement of the edges be strengthened when designing the raft if the neighboring buildings are close.

Conclusions can be drawn based on Table 5, Figure 10. and Figure 11. that cushion defects have little effect on the tensile stress and reduce the shear stress of the raft; The uniformly distribution function of cushion on the stress of piles and soil has been weakened. However, taking into account the extremeness of the cushion quality assumed in this section and the great stiffness of thick raft, the effect of cushion quality on the stress of the raft is limited. The redundancy increased in the design process can guarantee the safety of the superstructure.

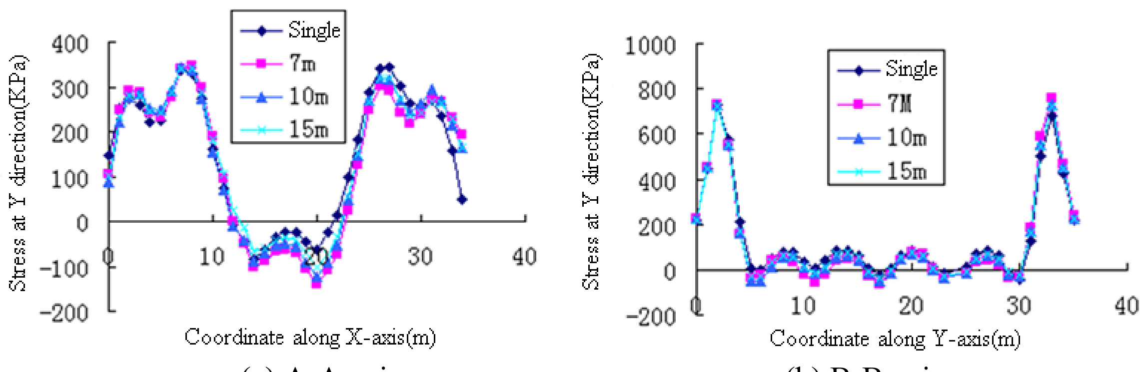
Table 4 Comparison of maximum raft stress in conditions of different spacing

Stress (KPa)	Single building	7m	10m	15m
Maximum equivalent stress	7360	7525	7425	7477
Maximum shear stress	3703	3809	3703	3750
Maximum compression stress at X direction	3337	3466	3423	3388
Maximum tensile stress at X direction	1423	1614	1557	1499
Maximum compression stress at Y direction	3357	3420	3385	3377
Maximum tensile stress at Y direction	1139	1145	1158	1188



(a) A-A axis (b) B-B axis

Figure 8. The relationship of raft stress at X direction and neighboring building spacing



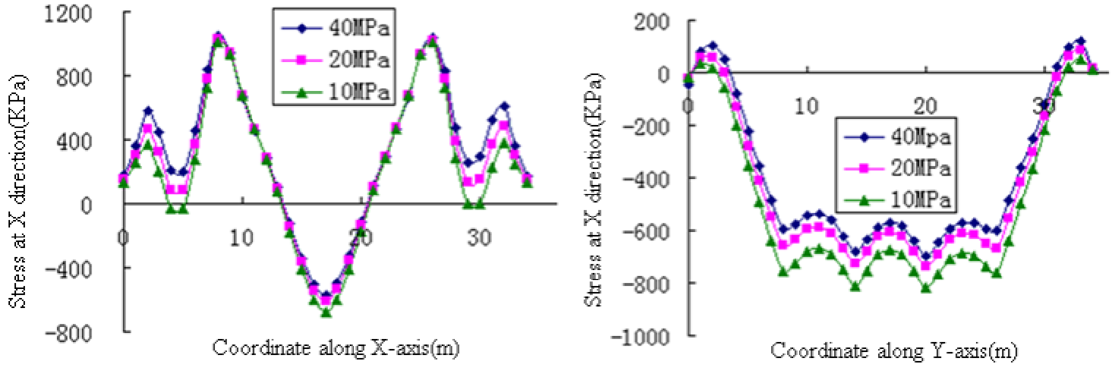
(a) A-A axis (b) B-B axis

Figure 9. The relationship of raft stress at Y direction and neighboring building spacing

Table 5 Comparison of raft stress in conditions of different cushion quality

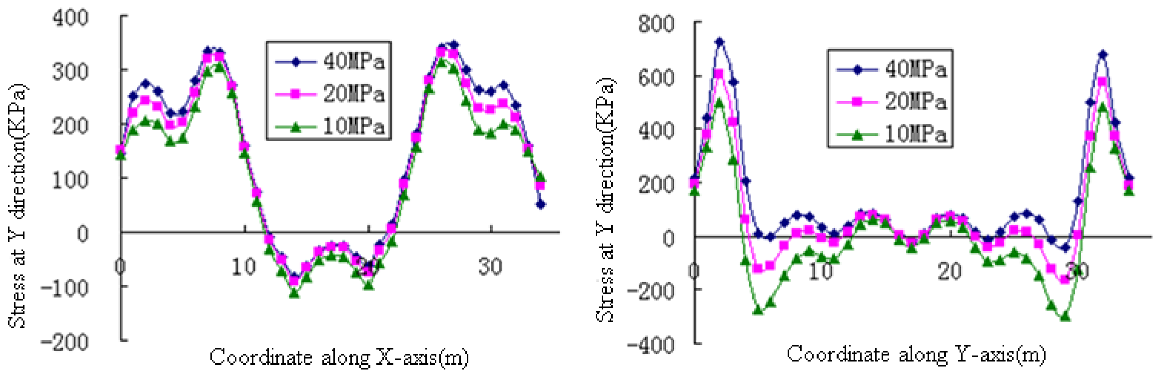
Deformation modulus of cushion	40MPa	20MPa	10MPa
Maximum equivalent stress (KPa)	7360	6707	5892
Maximum shear stress (KPa)	3703	3374	2970
Maximum compression stress at X direction (KPa)	3337	2865	2394

Maximum tensile stress at X direction (KPa)	1423	1474	1571
Maximum compression stress at Y direction (KPa)	3357	2876	2395
Maximum tensile stress at Y direction (KPa)	1139	912	729



(a) A-A axis (b) B-B axis

Figure 10. The relationship of raft stress at X direction and cushion quality



(a) A-A axis (b) B-B axis

Figure 11. The relationship of raft stress at Y direction and cushion quality

3.4.2. Displacement

From Figure 12. and Figure 13., we can conclude that with the increase of the modeling size, the maximum displacement tends to reduce rapidly at first and then increase slowly. When the geometric size of the ground soil is about 2 to 3 times the raft foundation, the displacement of the raft tends to be stable, that is, the constraint range of the surrounding soil is approximately 2 to 3 times the geometric size of the raft.

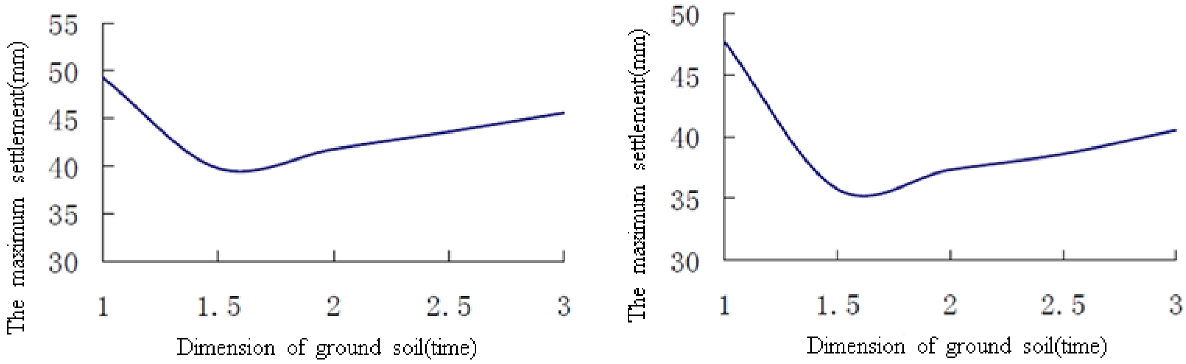
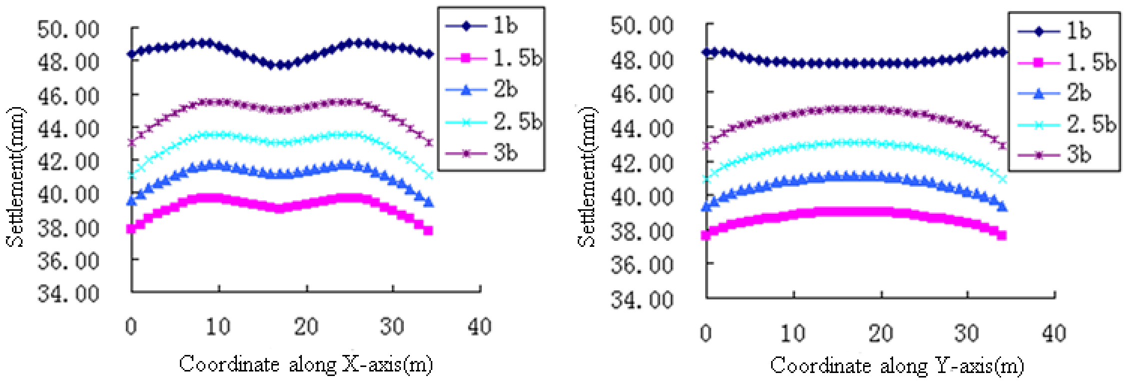


Figure 12. The relationship of raft displacement and geometric dimensions of ground soil

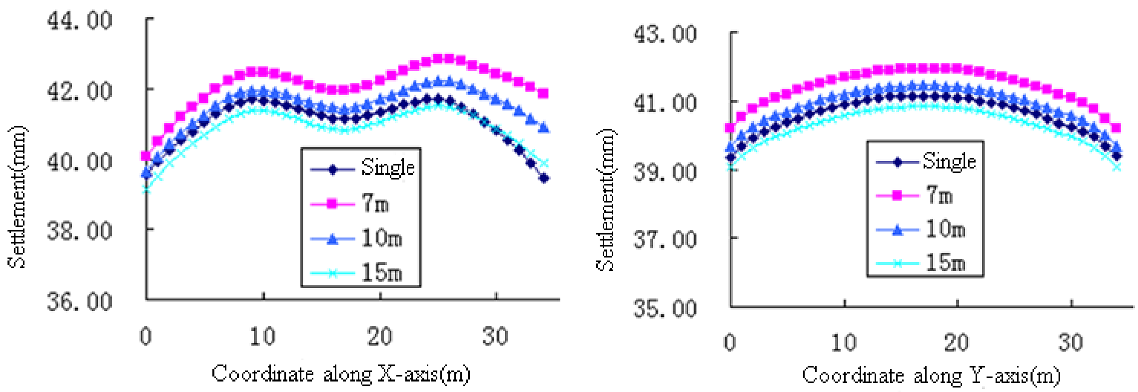


(a) A-A axis (b) B-B axis

Figure 13. Effect of different soil dimensions on local displacement of the raft

Table 6 Comparison of raft displacement in conditions of different building spacing

Settlement (mm)	Single building	7m	10m	15m
Maximum settlement	41.75	42.91	42.31	41.58
Minimum settlement	37.32	37.93	37.48	36.90



(a) A-A axis (b) B-B axis

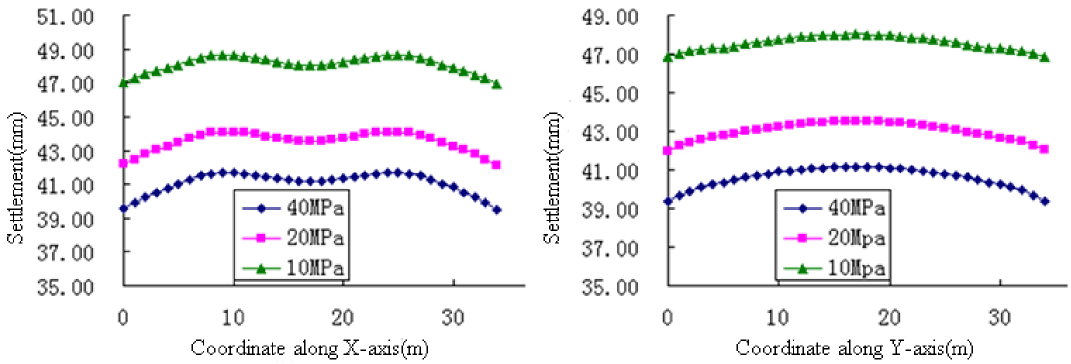
Figure 14. The effect of different building spacing on local displacement of the raft

Table 6 and Figure 14. show that neighboring buildings have some but not big effect on the displacement of the raft. Neighboring buildings only have an obvious influence on the adjacent edges of the raft, and this effect gradually disappears with the increase of the building spacing. It is suggested that the displacement limits should be set relatively strict if two buildings are very close to each other.

Conclusions can be drawn based on the Table 7 and Figure 15. that cushion quality has little effect on the displacement of the raft, because the raft is of great stiffness. The redundancy increased in the design process can guarantee the safety of the superstructure.

Table 7 Comparison of raft displacement in conditions of different cushion quality

Displacement of cushion	40MPa	20MPa	10MPa
Maximum settlement (mm)	41.75	44.15	48.71
Minimum settlement (mm)	37.32	40.31	45.54



(a) A-A axis (b) B-B axis

Figure 15. The effect of cushion quality on local displacement of the raft

4. CONCLUSION

(1) This paper proposes the overall finite element analysis method of the rigid pile composite ground-raft foundation-superstructure system, and develops the transformation software (ETA and DFTA) of superstructure and underground parts, which realizes the rapid modeling of complicate projects.

(2) The effect of site factors on the stress of the raft are summarized as follows:
The geometric dimension of the ground soil has a great influence on the stress of the raft. The constraint range of the surrounding soil is about 2 to 3 times the geometric size of the raft. Neighboring buildings and cushion quality have some but not much effects on the stress of the raft.

(3) The effects of site factors on the displacement of the raft are summarized as follows:
The geometric dimension of ground soil has a great effect on the displacement of the raft. When ignoring surrounding soil, the maximum displacement obtained is larger and the settlement control is a little more conservative. Neighboring buildings play a certain role in increasing the displacement of the raft. Cushion quality has little effect on the displacement of the raft.

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