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Effects of Site Factors on the Performance of Rigid-Pile Composite Foundation in Tall Buildings

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Abstract: Values of site factors in numerical simulation can have profound effects on the calculation accuracy. In order to fully understand the performance of rigid-pile composite foundation in tall buildings, this article set up an overall FEA model of a 25-storey frame-tube structure by considering the interaction of superstructure, foundation and ground. Thereafter, a detailed parametric study was performed by changing values of different key site factors. These parameters include: Ground soil range, distance of neighboring buildings and deformation modulus of cushion. The results show that 1) Ground soil range has a great influence on the stress and settlement of raft, the effective influence range is 2-3 times of the raft dimension; 2) Influence of neighboring buildings on the stress and settlement of the raft can be neglected; 3) With the increase of cushion modulus, the raft stress increases while the settlement decreases, an optimal cushion modulus is recommended to be 20-40MPa.

Keywords: Adina, interaction, overall FEA model, raft stress, raft settlement, rigid-pile composite foundation.

1. INTRODUCTION

Tall buildings have large loads and stiffness, so it is quite difficult and complicated to compute the performance of their foundation. Commonly, the pile foundation is used to bear the huge load. However, in places with bad geological conditions, such as karst terrain, traditional pile foundation can be inefficient because of such reasons [1-2]: 1) The thickness of the covering soil layer upon the bedrock is not enough for using friction piles; 2) The load of the end-bearing pile may lead to collapse of the sinkholes in bedrock; 3) The measure of grouting to fill sinkholes leads to the use of large amount of mortar yet fails to meet the safety criteria. Rigid-pile composite foundation is a widely used ground treatment method for its low cost and high bearing capacity [3]. It is a good choice for tall building in karst terrain. However, this technique has already been used in many tall buildings in recent years [4-6], the theory is still not perfect because the design process is mainly based on experiences of the engineers. So the research on its exact performance is of great significance.

Current researches are mostly focused on the composite foundation itself, without taking the superstructure into account [7-9]. Some studies take the interaction effect into consideration, but the superstructure is simplified into layer-model [10]. Or the materials are simulated with linear elastic models [11-14]. All these lead to inaccuracy of the analyzing results.

In order to fully study the effects of site factors on the performance of rigid-pile composite foundation in tall buildings, this paper set up an overall model of a 25-storey frame-tube structure with a 2-storey basement in the FEA software ADINA [15]. The superstructure, rigid-pile composite ground and raft foundation are all included as a system. A more accurate non-linear constitutive model of Drucker-Prager (DP) is used to simulate the ground soil [16]. To simplify the modeling process, an importing program ETA and a rapid modeling program DFTA are developed. Then a detailed parametric study is done to evaluate the influences of different site factors on the stress and settlement of the raft foundation and to present reasonable parameter values for design activities. These conclusions of the performance of rigid-pile composite foundation in tall building system can be important references for engineers.

2. CALCULATION METHOD AND BASIC ASSUMPTIONS

2.1. Method for Non-linear Problem

Whether to consider non-linearity in the overall model is very important for the simulation results. In this paper, material non-linearity is introduced by using DP constitutive model, contact non-linearity should be considered in the

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interaction between superstructure and composite ground. The general equilibrium equation of non-linear problem, which takes nodal displacement δ as the unknown can be expressed as:

$$[K(\delta)][\delta]=[R] \quad (1)$$

where $[\delta]$ is the nodal displacement matrix, $[R]$ is the nodal load matrix, and $K(\delta)$ is the total stiffness matrix. The key to solving this problem is to find an efficient way to update the changing stiffness matrix $K(\delta)$, whose value depends on the nodal displacement δ.

The Incremental Iterative Method was adopted in this article to solve the non-linear equations in the modeling process, and the increment length was adapted automatically. This method takes the advantages of the Incremental Method and the Iterative Method, which make it more efficient and effective. The iteration was done by the Modified Newton Method, which offers better convergence especially in the initial stage of solving process [17].

2.2. Basic Assumptions

In order to get better simulation results and high calculation efficiency, reasonable assumptions are put forward as follows:

(1) The original stress and displacement caused by driving piles are neglected;

(2) Concrete beams, columns, shear walls of superstructure and concrete piles remain linear elastic under static load;

(3) Ground soil is a continuous body and simulated by DP model;

(4) Piles keep in close contact with ground soil, i.e. there is no sliding or detachment between them in the deformation process;

(5) Drainage consolidation and stress history of the ground soil are neglected.

3. OVERALL NUMERICAL MODEL

3.1. Analyzed Problem

Fig. (**1**) shows the superstructure and the composite foundation system considered in this study. Fig. (**2**) shows the layout and dimensions of superstructure which is a 25-storey frame-tube building with a 2-storey basement. The column space and floor height are typical values used in practice. The 3D FEA analysis is established in ADINA. The raft has a plan dimension of 32m×32m and a thickness of 1.6m. Piles which are uniformly distributed have the configuration as follows: Pile diameter D=400mm, pile length L=30m and pile spacing d=2m. The ground is simplified into 3 layers with a total thickness of 40.3m according to common geological survey reports in karst terrain.

3.2. Boundary Conditions

The displacement boundary conditions of the model are: Four side planes of the ground soil are constrained only in normal direction while the bottom surface is fixed, as shown in Fig. (**1**).

3.3. Material Constitutive Model

The superstructure, concrete piles and raft foundation are considered to be in linear elastic condition under static loads. This is reasonable for a well-designed building. So the linear elastic constitutive model is used to simulate beams, columns, shear walls, slabs and raft foundation. Parameters of concrete linear elastic model are based on current Chinese code [18], as shown in Table **1**.

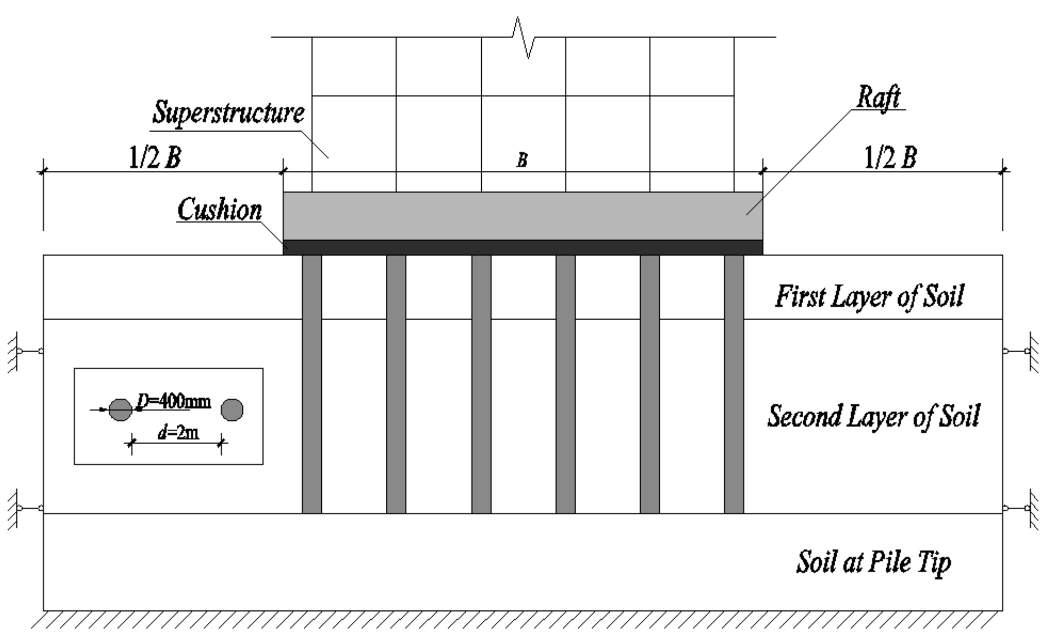

Fig. (1). Rigid-pile composite ground and raft foundation system.

The major research objective of this paper is the effects of site factors, so the accurate simulation of mechanical properties of ground soil is of great importance. The Druker-Prager elastic-plastic model which is suitable for granular materials is used to simulate ground soil [5]. Parameter values are listed in Table **2**.

3.4. Load Determination

Only static loads are considered in this article. The values of loads applied on the superstructure are based on current Chinese code [19] and listed in Table **3**.

3.5. 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 used 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) is used to simulate the raft and ground, which have large volume and carry great shear force [20].

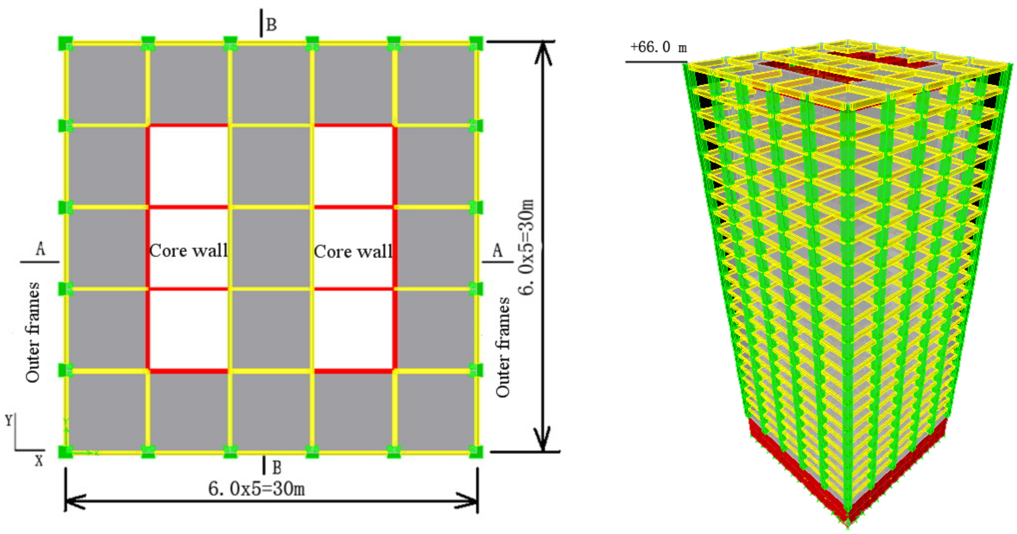

Fig. (2). Layout and dimensions of superstructure.

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)	Friction	E (N/m^2)	ν	Weight	Element
Cushion	0.3	0	40°	4×10^7	0.2	20000	Q8
First layer of soil	5	2×10^4	20°	1×10^7	0.25	20000	Q8
Second layer of soil	25	2×10^4	20°	2×10^7	0.25	20000	Q8
The soil at pile tip	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 Story	Other story
Dead load (kN/m^2)	3	3	3
Live load (kN/m^2)	4	3.5	3
Line load on frame (kN/m)	——	10	7

3.6. Contact Problems

There are two kinds of contact problems in this paper: One is the contact between raft and cushion, the other is the contact between different layers of ground soil. The 'Hard Contact' is used to simulate the interactions. The interface of the first contact problem is defined as 'Not Tied', which does not consider the bond force except for friction; the interface of the second contact problem is defined as 'Tied', which keeps different layers of ground soil in close contact without sliding and disengagement. These are the real situations in engineering practice.

The pressure in the normal direction of the interface can be transferred completely by using 'Hard Contact' to define the contact relationship. At the same time, the 'Interface Element' is used to simulate the friction.

3.7. Importing Program ETA and Rapid Modeling Program DFTA

This paper presents an importing program (ETA) and a rapid modeling program (DFTA). Both of them are developed based on DELPHI language to simplify the modeling process. In ETA, the ETABS model files can be transformed into command flow of ADINA. Then the geometric modeling, material and element definition, meshing, load applying and boundary conditions can be accomplished easily.

DFTA is developed to simplify the modeling process of the underground part of the overall model. Being offered the basic material and geometric information of the raft, cushion and soil layers, DFTA can automatically generate the command flow of ADINA, thus helps complete the overall model conveniently. The flow chart of modeling process of ETA and DFTA is shown in Fig. (**3**). The overall finite model in ADINA is shown in Fig. (**4**).

4. EFFECTS OF SITE FACTORS ON THE PERFORMANCE OF RIGID-PILE COMPOSITE FOUNDATION

The performance of rigid-pile composite foundation is decided by analyzing different parameters, which include: 1) Ground soil range; 2) Space with neighboring buildings; and 3) Deformation modulus of the cushion. To fully understand the laws of influence and offer better guidelines to engineers, detailed parametric studies are performed in this chapter.

4.1. Ground Soil Range

Ground soil is an important part in the overall numerical model. The effects of ground soil range on the performance of rigid-pile composite foundation are analyzed in this part by establishing 5 models. The ground soil range of these models is 1, 1.5, 2, 2.5 and 3 times of the raft dimension in

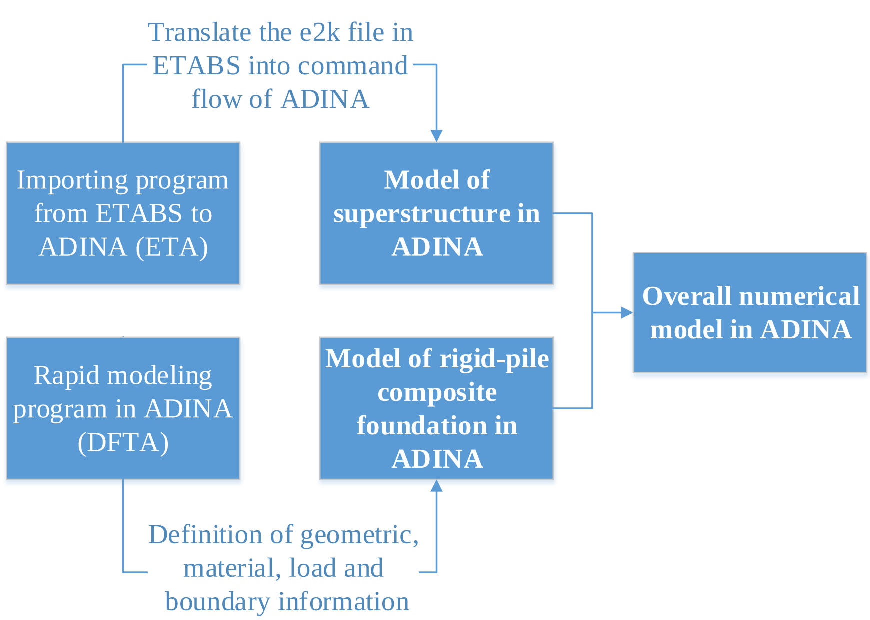

Fig. (3). Modeling process of ETA and DFTA.

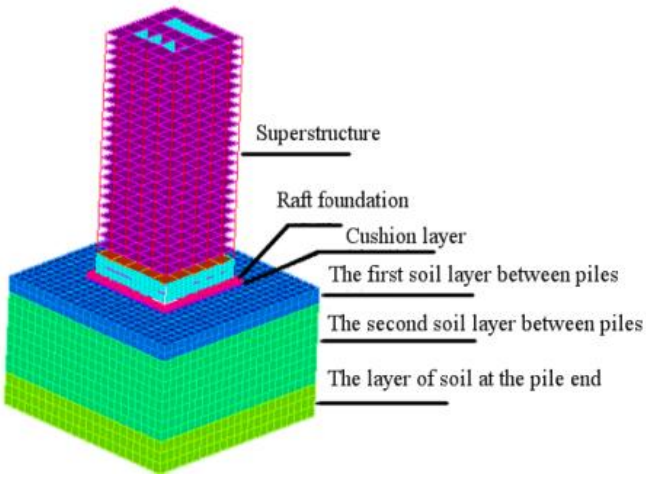

Fig. (4). Finite element model.

both length and width direction. Other parameters are the same as listed in Chapter 3. The calculation results are shown in Fig. (**5**) and Fig. (**6**).

Fig. (**5**) shows that as the ground soil range gets bigger, the maximum shear and compression stress which control the thickness of the raft increase. On contrary, the tensile stress which controls the reinforcement of the raft decreases. The stresses in the two orthotropic directions, i.e. the length and width direction get stable when the multiple of soil range to raft dimension reaches 2 to 3.

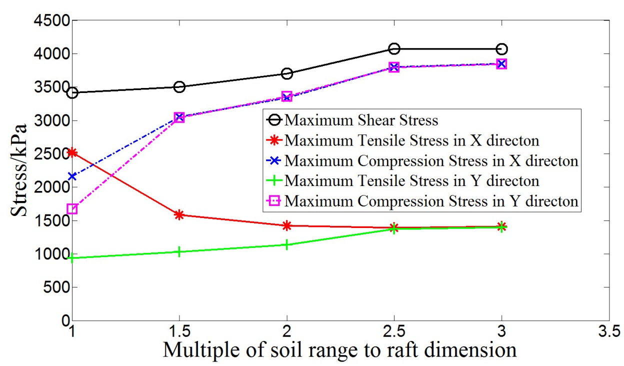

Fig. (5). Relationships between raft stress and multiple of soil range to raft dimension.

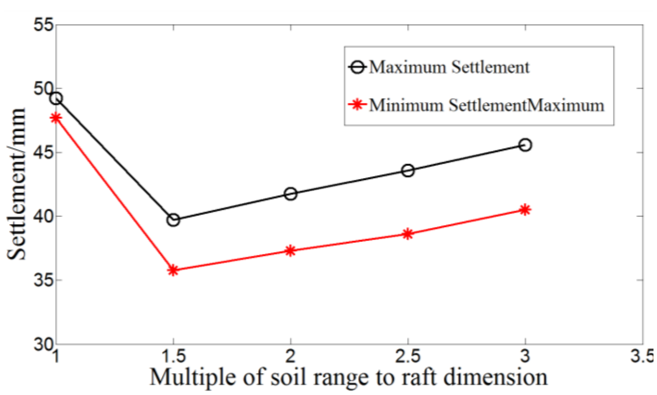

Fig. (6). Relationships between raft settlement and multiple of soil range to raft dimension.

Fig. (**6**) indicates that the settlement decreases rapidly at first and then increases slowly when the soil range reaches 2 times of the raft dimension. However the differential settlement is already stable, which means the internal force of the raft changes little even if larger soil range is considered. That is the reason why the stresses of raft get stable when the ground soil range is 2 to 3 times of the raft dimension. The pressure acting on the soil gets smaller when spreading around in the ground. It has little influence on the soil when reducing to the same quantity of the original ground stress. The spreading range of the pressure in the ground soil is 2 to 3 times of the raft dimension as the calculation results show. This is why both the stress and settlement of the raft get stable when soil range is in the corresponding range.

As a result, the ground soil range in a numerical model is recommended to be 2 to 3 times of the raft dimension in the length and width direction, so the calculation accuracy can be guaranteed while keeping a high modeling efficiency.

4.2. Neighboring Buildings

Neighboring buildings always exist in real construction sites. There should be a clear conclusion of whether or not to take their influence into account in the designing process. 4 models of a single building and two exact same buildings with various distances are established to study such effect. Considering the usual width of separating lanes and the necessary construction space, the distances are set to be 7m, 10m and 15m. Other parameters are similar to those of Chapter 3. Results are shown in Fig. (**7**) and Fig. (**8**).

Figs. (**7** and **8**) show that with the increase of distance, the raft stress and settlement increase a little at first and then get stable. The spreading angle of vertical stress in the soil varies from 20° to 30° in different types of soil. Assuming such angle to be a mean value of 30°, the depth is approximately 12m when the stress caused by a building spreads to the range of its neighboring buildings. The vertical stress at such depth is about 1/3 of the surface pressure. That is why the influence of the neighboring buildings is limited. So effects of neighboring buildings can be neglected in analyzing the performance of rigid-pile composite foundation when the distance is not so close (closer than 7m).

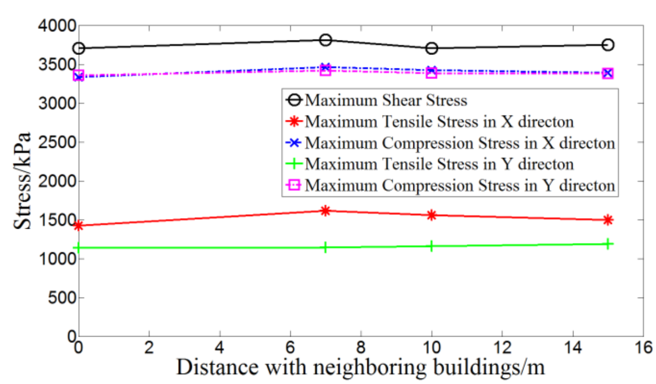

Fig. (7). Relationships between raft stress and distance with neighboring buildings.

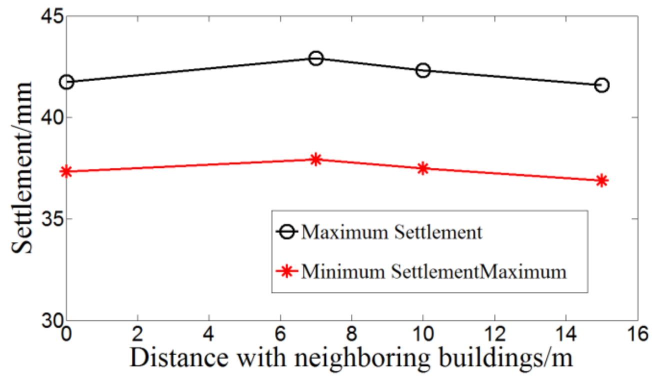

Fig. (8). Relationships between raft settlement and distance with neighboring buildings.

4.3. Deformation Modulus of the Cushion

Cushion is a layer of granular materials with a thickness of 200-500mm, which is a very important part in the rigid-pile composite ground-raft foundation system. It enables the redistribution of stress between piles and soil, thus taking full advantage of the soil strength to increase the overall bearing capacity of the foundation. The deformation modulus of the cushion is the key factor to decide the stress and settlement of the foundation. So the finite element models with the cushion deformation modulus being 10MPa, 20MPa and 40MPa are established to unveil the mechanism of this effect.

Fig. (**9**) shows that cushion deformation modulus has little effect on the tensile stress of the raft. The shear stress and compression stress have a tendency to increase with the increase of cushion modulus. The harder the cushion is, the weaker its redistribution effect is. So the composite foundation acts more like a pile foundation, the raft itself resists the differential settlement, which certainly leads to larger stress. In such circumstances, the great stiffness of the thick raft ensures a sufficient safety factor for the superstructure.

From Fig. (**10**), we can conclude that the settlement of the raft decreases with the increase of cushion modulus. On one hand, it is because the compression of the cushion decreases. On the other hand, larger cushion modulus means

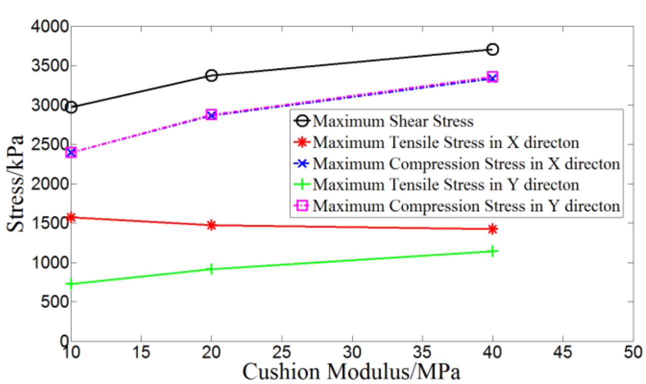

Fig. (9). Relationships between raft stress and deformation modulus of cushion.

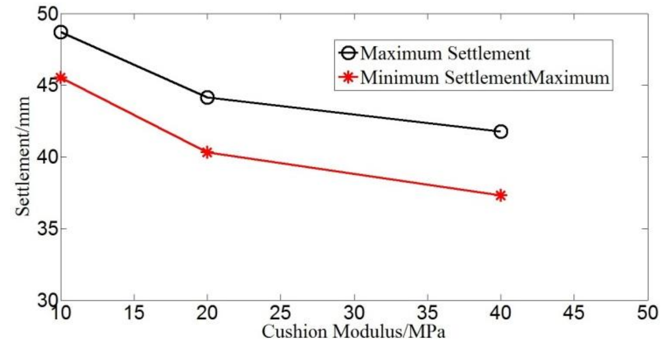

Fig. (10). Relationships between raft settlement and deformation modulus of cushion.

larger stiffness, which distributes more loads to the pile and reduces the settlement. So the effects of cushion modulus on the stress and settlement of raft are contradictory. Taking into account the acceptable settlement limits and based on the engineering experience, the deformation modulus of cushion is recommended to be 20-40MPa.

CONCLUSION

(1) The secondary development of ADINA is implemented by presenting the importing program ETA and the rapid modeling program DFTA. The two programs realize convenient modeling of complicated structures and help with the parametric study of the effects of site factors on the performance of rigid-pile composite foundation.

(2) The ground soil range has a big influence on the stress and settlement of the raft. Such effect becomes stable when the soil range reaches 2 to 3 times of the raft dimension in both length and width direction. So in the designing process, a soil range of 2 to 3 times of raft dimension should be considered to get a more accurate result.

(3) Neighboring buildings can be neglected in analyzing the performance of rigid-pile composite foundation in usual conditions, i.e. the distance between two neighboring buildings is larger than 7m.

(4) The deformation modulus of cushion influences the stress and settlement of the raft significantly. With the increase of cushion modulus, the stress increases and the settlement decreases. But both of them become stable as the modulus reaches 40MPa. The recommended value of the cushion modulus is 20-40MPa.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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REFERENCES

[1] G.F. Sowers, *Building on Sinkholes: Design and Construction of Foundations in Karst terrain*: American Society of Civil Engineers: New York, 1996.

[2] T. Waltham, F. Bell and M. Culshaw, *Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction*: Springer: Chichester, 2004.

[3] G. Zheng, X.N. Gong, Y.L. Xie and G.X. Li, "State-of-the-art techniques for ground improvement in China," *China Civil Eng. J.*, vol. 45, no. 2, pp. 127-146, 2012.

[4] X.N. Gong, "Development of composite foundation and its application in high-rise building," *China Civil Eng. J.*, vol. 32, no. 6, pp. 3-10, 1999.

[5] Y.Q. Liang, "Application of CFG pile composite foundation in huadu high-rise building," *Achitect. Struc.*, vol. 36, supp. 1, pp. 24-26, 2006.

[6] G.L. Ni, K.Z. Su, Z.Y. Zhang, J.H. Guo and Y.F. Xie, "Theory of rigid pile composite foundation and its application in guangdong province," *Chinese J. Rock Mechan. Eng.*, vol. 25, supp. 2, pp. 4160-4168, 2006.

[7] J.J. Zheng, S.W. Abusharar and X.Z. Wang, "Three-dimensional non-linear finite element modeling of composite foundation formed by CFG–lime piles," *Comp. Geotech.*, vol. 35, pp. 637-643, 2008.

[8] R.P. Orense, N. Chouw, and M.J. Pender, "*Soil-Foundation-Structure-Interaction：Journal of the Structural Division,*" *The international workshop on soil-foundation-structure interaction, November 26-27, 2009*, Auckland, New Zealand. Taylor & Francis Group: London, 2010.

[9] F.Y. Liang, L.Z. Chen and X.G. Shi, "Numerical analysis of composite piled raft with cushion subjected to vertical load," *Comp. Geotech.*, vol. 30, pp. 443-453, 2003.

[10] J.K. Bai and L.Z. Chen, "Non-linear response analysis of structures with composite foundation cushion under horizontal ground motion," *Earthquake Resist. Eng. Retrofit.*, vol. 31, no. 2, pp. 55-59, 2009.

[11] J.F. Zhang, "*Research on Static and Dynamic soil-pile-strueture Interaction of Tall building*," PhD thesis, Xi'an University of Architechture and Technology, Xi'an, 2005.

[12] Z.Q. Hu, J.X. Wang, L.L. Liu and L.J. Jiao, "Finite element analysis of seismic behavior of composite foundation with bedding cushion," *Rock and Soil Mechanics*, vol. 29, pp. 587-592, 2009.

[13] C.L. Su, "*Numerical Analysis of Aseismic Capability of Rigid Pile Composite Foundation*," MSc thesis, Henan University, Kaifeng, 2010.

[14] S.Y. Wu and E.X. Song, "Mechanism analysis of earthquake responses of rigid pile composite foundation," *Rock and Soil Mechanics,* vol. 30, no. 3, pp. 785-792, 2009.

[15] G. Yue and Q. Chen, *Basic Applications and Detail Examples of ADINA*. China Communication Press: Beijing, 2008.

[16] F.X. Zhou and S.R. Li, "Generalized Drucker-Prager strength criterion," *Rock and Soil Mechanics,* vol. 29, no. 3, pp. 747-751, 2008.

[17] T. Belytschko, W.K. Liu and B. Moran, *Non-linear finite elements for continua and structures.* John Wiley & Sons Ltd.: New York, 2000.

[18] Ministry of Housing and Urban-Rural Development of the People's Republic of China and General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, "*Code for design of concrete structures*," GB50010-2010, 2010.

[19] Department of Housing and Urban-rural Development of Guangdong Province, "*Technical specification for concrete structures of tall building*," DBJ 15-92-2013, 2013.

[20] R.D. Cook, *Concepts and applications of finite element analysis.* John Wiley & Sons Ltd.: New York, 2007.

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