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Supertall Building Pile-Raft Foundation Designs on Soft Soil
软土地基超高层建筑桩筏基础设计方法


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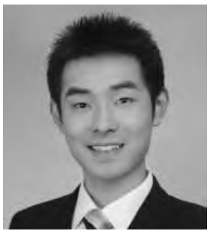
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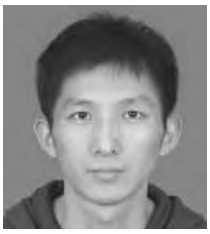
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Abstract

The design improvements and optimizations of super high-rise building pile-raft foundations on soft soil have been made as below: considerations of the impact in the whole construction process on the upper structural system, consideration of combined actions of pile-raft foundations in analytical methods; adoption of variable rigidity concepts to control raft differential settlements; analysis and calculations of different pillars forms and core tube punching lines. According to the analysis of temperature and stress fields, reasonable control methods can be applied for internal and external temperature differences in a thick raft of mass concrete construction.

Keywords: Pile-Raft Foundation, Combined Action, Variable Rigidity, Punching Lines, Interior and Exterior Temperature Differences

摘要

对软土地基超高层建筑桩筏基础的设计进行了完善和优化：考虑上部结构施工全过程的影响，提出一种适用于桩筏基础共同作用的数值计算方法；采用变刚度调平概念，控制筏板的差异沉降；对巨柱和核心筒的不同形式冲切线进行分析和计算；根据温度场和应力场的分析，得到了厚筏板大体积混凝土施工时里表温差合理的控制方法。

关键词：桩筏基础 ， 共同作用 ， 变刚度调平， 冲切线， 里表温差

Introduction

Pile-raft foundation is a major arrangement type for supertall building foundations in soft soil areas. This paper introduces research on pile-raft foundations frequently used for supertall buildings in soft soil areas in order to improve design approaches for pile-raft foundations.

The Shanghai Tower, still under construction, will be the case study used throughout the article (see Figure 1). The tower is composed of two parts – a 124-story tower and a five-story commercial annex. The completed structural height of the tower will be 580 meters while the completed construction height of the tower will be 632 meters along with a five-story basement with a 30-meter deep foundation. The upper structure utilizes a "core mega frame" while the underground structures employ shear walls that connect the core and the mega frame together. Foundation construction utilizes pile-raft foundations where the raft under the tower has a thickness of six-meters with a total of 955 piles, each with a diameter of one-meter, and the piles are distributed by stiffness in a spatial way. Based on different foundation arrangements, the entire raft area can be divided into four zones: Zone A and C using a

引言

桩筏基础是软土地区超高层建筑的一种主要基础形式。本文对软土地基超高层建筑常用的桩筏基础进行了多项研究，以完善桩筏基础设计方法。

文中分析所采用工程实例为正在建造的上海中心大厦（见图1）。上海中心大厦由124层塔楼和5层商业裙房组成，塔楼结构高度580m，建筑顶高度632m。整个场地下设5层地下室，基础埋深约为30m。上部结构采用核心筒-巨型框架结构，地下部分在核心筒和巨型框架之间有剪力墙连接。基础采用桩筏基础，塔楼下筏板厚度6米，桩总数955根，桩径1m，采用空间变刚度布桩。根据布桩方式不同，整个塔楼筏板可分为四个区域：A、C区采用梅花布桩，B、D区采用矩形布桩；A区有效桩长56米，B、C、D区有效桩长52米（见图2）。

超高层建筑桩筏基础共同作用分析— 变基床系数迭代法

超高层建筑桩筏基础共同作用分析方法
采用有限单元法将上部结构、筏板基础、桩土三者进行整体建模。其中上部结构采用壳单元和梁元模拟，筏板基础采用壳单元模拟，桩土采用三维实体单元模拟，共同作用基本方程如下：

plum flower arrangement [five wings with a center core] while Zone B and D use a rectangular distribution. The piles produced in zone A are 56-meters long and the piles for the other zones are 52-meters long (see Figure 2).

Combined Action Analysis of the Pile-Raft Foundation of Supertall Buildings – Iteration Method of Variable Coefficients of Subgrade Reactions

Combined Action Analysis of the Pile-Raft Foundation of Supertall Buildings Method

By adopting the FEM [Finite Element Method], the combination of the upper structural system, raft foundation, and foundation soil completes the entire modeling system. The upper structure is modeled by shell elements and beam elements, the raft foundation is modeled by shell elements, and the foundation soil uses three-dimensional solid models, and the combined action equation is shown as below:

$$\left[k_u + k_r + k_p + k_s\right]\{U\} = \{P\}$$

In this equation: k_u–upper structure stiffness matrix; k_r–rafted foundation stiffness matrix; k_p–pile foundation stiffness matrix; k_s–soil stiffness matrix; U–node displacement vector; P–load vector.

In actual supertall building designs, the distribution of the pile-raft foundation is usually dense. Assuming that the foundation is only contacting the raft while neglecting the interaction between the foundation soil and rafts, the action of pile on raft should be equivalent to that of the vertical spring on the top of the pile and this combined action can be expressed by a basic formula:

$$\left[k_u + k_r + k_{ps}\right]\{U\} = \{P\}$$

In this equation: k_{ps}–spring stiffness matrices stand for the equivalent stiffness of the entire pile-raft system.

The action of pile on raft is equivalent to that of the vertical spring on the top of the pile. Spring stiffness matrices [K_{ps}] can be gained by a variable coefficient of the subgrade reactions' iteration method.

The value of the top of the pile stiffness (such as determining the initial pile stiffness by an average pile reaction and basic settlement calculation method or by the pile testing method) is assumed to be a constant normal stiffness in order to obtain the formation of pile soil stiffness matrix [K_0]. By using this iteration method and taking considerations of the Mindlin-Geddes method, the values of the reaction on the top of the pile, settlement deformation, and spring stiffness matrices [K_{ps}] can be obtained in its relative order.

Case Study

In the FEM model of the Shanghai Tower, the shear walls and mega columns are using shell elements, the regular beams and columns use beam elements, the foundation uses thick shell elements, and the pile-soil system uses vertical spring elements.

The identification of stiffness iterative convergence during the iteration of vertical spring of the column is shown in the equation below:

$$\varepsilon = \frac{100\sqrt{\sum_{i=1}^{n}(k_{li} - k_{pi})^2}}{\sum_{i=1}^{n} k_{li}}$$

Figure 1. Shanghai Tower Rendering (From: Cui, Yong)
图1. 上海中心大厦效果图（出自：崔勇）

$$\left[k_u + k_r + k_p + k_s\right]\{U\} = \{P\}$$

式中：k_u－上部结构刚度矩阵；k_r－筏板基础刚度矩阵；k_p－桩刚度矩阵；k_s－土体刚度矩阵；U－节点位移向量；P－荷载向量。

在实际超高层建筑中，桩筏基础一般布桩较密，可假定仅桩与筏板接触，不考虑地基土与筏板作用。将桩对筏板的作用等效为作用在桩顶处的竖向点弹簧，这样共同作用基本方程可表示为：

$$\left[k_u + k_r + k_{ps}\right]\{U\} = \{P\}$$

式中：k_{ps}–弹簧刚度矩阵，代表整个桩土体系的等效刚度。

桩对筏板的作用等效为作用在桩顶处的竖向点弹簧。竖向点弹簧刚度矩阵[K_{ps}]采用变基床系数迭代法得到，方法如下：

假定桩顶刚度（例如通过平均桩反力以及基础计算沉降方法确定初始桩刚度，或者通过试桩方法确定桩刚度），并以此刚度作为常刚度形成桩土体系刚度矩阵[K_0]。通过迭代方法，利用考虑桩相互影响的Mindlin-Geddes方法，求解得到桩顶反力和沉降变形值，并得到桩弹簧刚度矩[K_{ps}]。

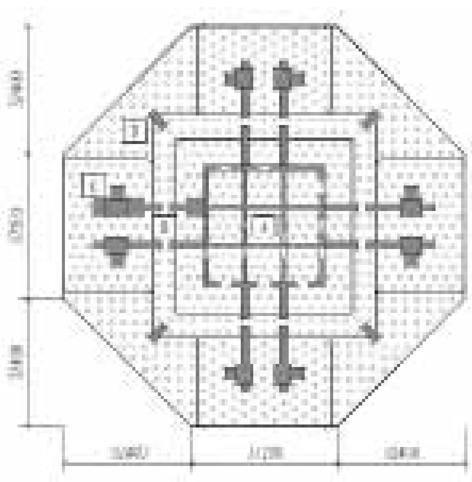

Figure 2. Pile-raft distribution zones of the tower (From: Chao, Si)
图2. 塔楼筏板桩位分区布置图（出自：巢斯）

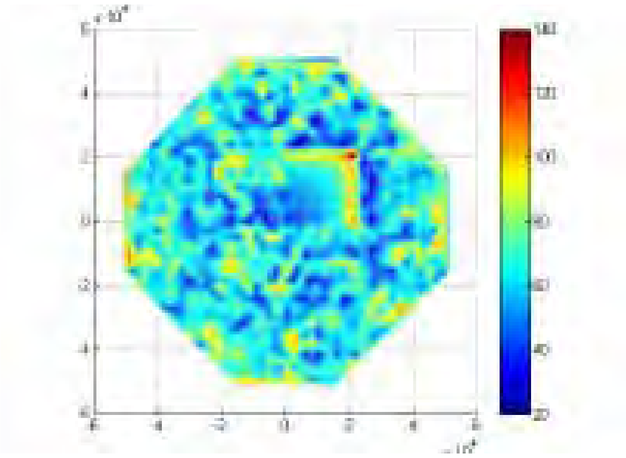

Figure 3. Ultimate spring stiffness distribution (kN/mm) (From: Chao, Si)
图3. 弹簧最终刚度分布图（kN/mm）（出自：巢斯）

In this equation: ε–Exponential Convergence; k_{li}, k_{pi} – the *i*-th [i.e. 1st, 2nd, 3rd, 4th, etc.] spring stiffness value of the *i*-th spring before and after the first iteration; *n* –the spring number.

The assumed initial stiffness value for the pile-soil system spring is set to be at a constant normal stiffness of 50kN/mm during the iteration process while the maximum value, minimum value, and ε -value will be obtained (see Table 1).

Based on the previous calculation, the final value of the spring stiffness has an equivalent value to the combined action effect of the upper structure, foundation, and pile-soil (see Figure 3).

Adjusted Pile-Raft Foundation Stiffness Design for Supertall Buildings

Design Methods

The initial vertical support stiffness of the natural foundation and uniformly arranged pile-rafts are evenly distributed. When setting up the raft plates above the foundation and pile-rafts with limited stiffness and uniformly distributed loads, the pile-raft and soil interaction should lead to the changes in vertical support in the stiffness distribution of the foundation or pile group. The changes in stiffness are weaker inside and stronger on the outside. The subsidence deformation presents itself in a butterfly distribution – smaller on the outside and larger on the inside – and the substrate reaction proposes as a saddle distribution – smaller on the inside and larger on the outside.

In order to even out the deformed settlements, adjustments should be made to the vertical stiffness distribution of the foundation or foundation piles such as changing the pile diameter, pile length, minimizing the differential settlement, or significantly reducing the foundation and capping internal forces.

Case Study

The pile-raft foundation in the Shanghai Tower controls the raft center and periphery differences by changing the length (52m/56m) and the distribution of foundations (plum flower profile/rectangle profile). This

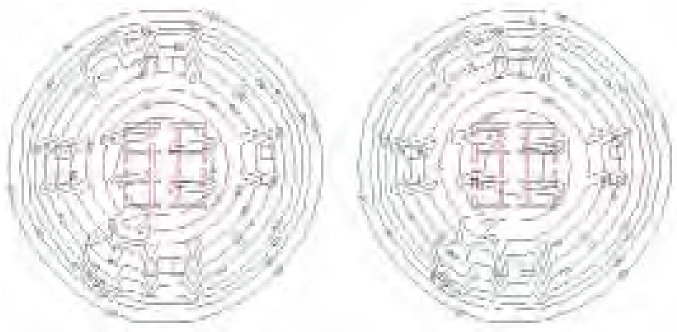

Figure 4. Isopleth comparison of settlement (From: Jiang, Wenhui)
图4. 沉降等值线对比图（出自：姜文辉）

实例分析

上海中心有限元模型中，剪力墙、巨柱采用壳单元，普通梁柱采用梁单元，基础采用厚壳单元，桩土体系采用竖向点弹簧单元。

桩竖向点弹簧迭代时，刚度值迭代收敛判别指标如下式：

$$\varepsilon = \frac{100\sqrt{\sum_{i=1}^{n}(k_{li}-k_{pi})^2}}{\sum_{i=1}^{n}k_{li}}$$

式中： ε - 收敛指标； k_{1i} ，k_{pi} - 第i个弹簧在一次迭代前后的弹簧刚度取值；n -弹簧数目。

桩土体系弹簧初始刚度取值假定为常刚度50kN/mm，迭代过程中得到弹簧刚度的最大值、最小值和 ε （见表1）。

由此计算得到的最终弹簧刚度取值为考虑了上部结构-基础-桩土共同作用效应的等效值（见图3）。

超高层建筑桩基变刚度调平设计

设计方法

天然地基和均匀布桩的初始竖向支承刚度是均匀分布的，设置于其上的刚度有限的筏板受均布荷载作用时，由于桩土的相互作用导致地基或桩群的竖向支撑刚度分布发生内弱外强的变化，沉降变形出现内大外小的碟形分布，基底反力出现内小外大的马鞍形分布。

为了使变形沉降更趋于平缓，通过调整地基或基桩的竖向支承刚度分布，如调整桩径、桩长、桩距，促使差异沉降减到最小，基础或承台内力显著降低。

实例分析

上海中心桩筏基础通过改变桩长（52m/56m）和布桩方式（梅花布桩/矩形布桩）控制筏板中心和边缘的计算差异沉降。本文分别对桩长52米等长和桩长52/56m变刚度设计进行了沉降计算对比，计算得到二者沉降等值线图（见图4）。

从计算结果可以看出，采用变刚度设计，中心点的沉降可以减少约10mm，相当于减少了约20%的差异沉降，减少了底板由于差异沉降引起的弯矩值。从沉降计算的绝对值来看，最大沉降约为

	Initial Value 初始值	1st Iteration 第一次迭代	2nd Iteration 第二次迭代	10th Iteration 第十次迭代	20th Iteration 第二十次迭代	29th Iteration 第二十九次迭代	30th Iteration 第三十次迭代
Max	50	84.2	90.2	110.1	134	143. 6	144
Min	50	56.1	50.8	31.4	25.8	22.9	23
ε		0.816%	0.257%	0.150%	0.083%	0.047%	0.045%

Table 1. The value of spring stiffness in the iteration process (kN/mm)
表1. 迭代过程弹簧刚度取值（kN/mm）

paper separately calculates and compares the 52-meter equal length piles with the 52/56-meter stiffness changing piles and the results are shown in the settling isograms (see Figure 4).

The calculation results can clearly illustrate that, with the use of variable stiffness design, the settlement can be reduced by approximately 10 mm. There is also an equivalence to approximately 20% in reduction in the differential settlement and reduces backplane bending that are caused by the differential settlements. From the absolute values of the settlement calculation, the maximum settlement is 124 mm, the pillars at the settlement are 80 mm, but the final settlement value is subject to long-term observations for verification.

Supertall Building Construction Process Analysis

It will take a fairly long time from the beginning of construction to the completion of a supertall building. Throughout the entire process, the geometry of the structure, strength of the materials, structural stiffness, and loading levels will be constantly changing.

Case Study

This article's non-linear analysis of supertall building construction is mainly focused on the changes in raft moments during the whole construction process and the raft movement differences between a construction analysis and a one-time load. Take the Shanghai Tower as an example, the loading process can be divided into ten phrases (see Figure 5) and the working conditions are as follows:

- Operating condition 1: The final result of construction analysis;
- Operating condition 2: One-time loading;
- Operating condition 3: Construction analysis phase I;
- Operating condition 4: Construction analysis phase II;
- Operating condition 5: Construction analysis phase III;
- Operating condition 6: Construction analysis phase IV;
- Operating condition 7: Construction analysis phase V;
- Operating condition 8: Construction analysis phase VI;
- Operating condition 9: Construction analysis phase VII;
- Operating condition 10: Construction analysis phase VIII;
- Operating condition 11: Construction analysis phase IX;
- Operating condition 12: Construction analysis phase X;

The calculations provide the raft foundation's raft moment changes during the whole construction process and the final movement in the one-time load and the construction load raft (see Figure 6).

Choosing Supertall Building Pile Foundation Raft Punching Lines

The core of the supertall building takes most of the loads while the number of piles arranged in some areas underneath the core cannot stabilize the structural loads from above. Therefore, the selection of punching lines and resistance are crucial factors in selecting the thickness of the base plate.

Case Study

Connecting the core tube to the mega columns by the wall of the wings improves the punching shear resistance. However, since the selection of punching lines varies and is complicated, the quantity of the selected punching lines may be more than one.

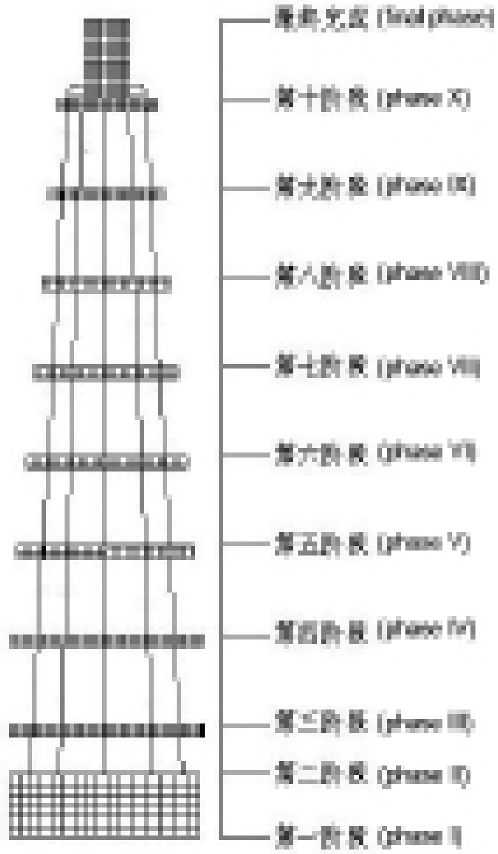

Figure 5. Construction phase illustration (From: Chao, Si)
图5. 施工过程阶段示意图（出自：巢斯）

124mm，巨柱处沉降约80mm，但最终沉降值还有待于长期观测来验证。

超高层建筑施工全过程分析

超高层建筑从开始施工到最后完成并且投入使用需要经历一段较长的时间，其间结构的几何形态、材料强度、结构刚度、荷载水平都是随时间不断变化。

实例分析

本文超高层建筑施工非线性分析，主要研究施工全过程中筏板弯矩的变化和分别采用施工分析与一次性加载时筏板弯矩的区别。以上海中心为例，加载按十个阶段（见图5），工况如下：

- 工况1：施工分析最终结果；
- 工况2：一次性加载；
- 工况3：施工分析第一阶段；
- 工况4：施工分析第二阶段；
- 工况5：施工分析第三阶段；
- 工况6：施工分析第四阶段；
- 工况7：施工分析第五阶段；
- 工况8：施工分析第六阶段；
- 工况9：施工分析第七阶段；
- 工况10：施工分析第八阶段；
- 工况11：施工分析第九阶段；
- 工况12：施工分析第十阶段；

计算得到筏板基础的施工全过程弯矩变化及一次性加载和施工加载筏板最终弯矩（见图6）。

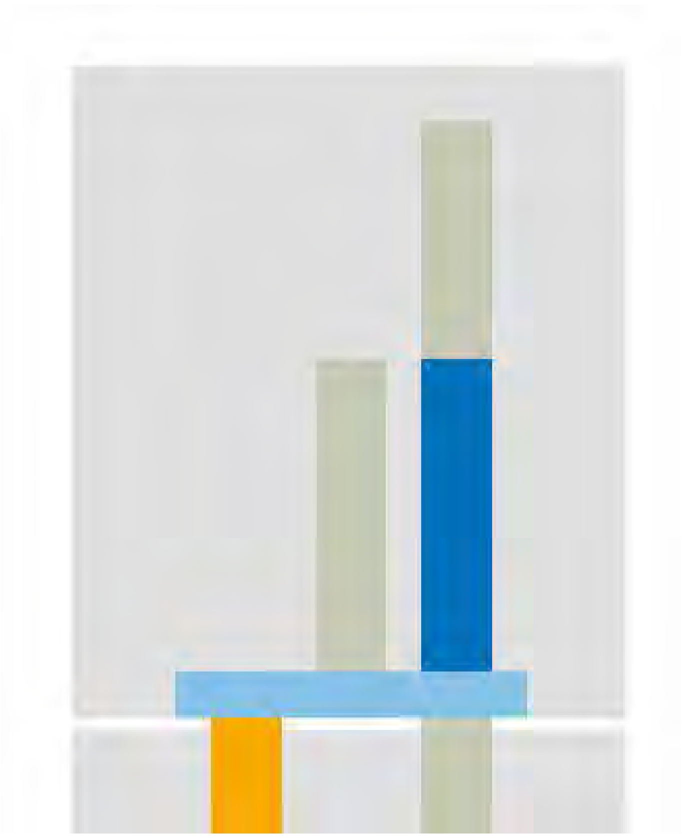

Figure 6. Construction analysis of the raft's bending moment (From: Chao, Si)
图6. 施工分析筏板弯矩图（出自：巢斯）

This paper selected four different forms of punching lines for testing (see Figure 7). Based on the code [4] requirements for the punching lines, three punching lines are selected between the first row of the column (wall) and the 45 degree bevel line within the pile boundary to obtain forces against punching shear of the three punching lines within the four groups of punching forms (see Table 2).

Reasonable Construction Temperature Control of Supertall Building Rafts

During raft constructions in supertall buildings, controlling harmful fractures caused by temperature differences is a key issue. Engineering practices illustrate that the main reason for the fracture is due to the temperature differences between inside and outside that causes volume deformations due to the energy release from the heat of hydration during the mass concrete hardening process. These fractures can become safety risks in the structural components during construction.

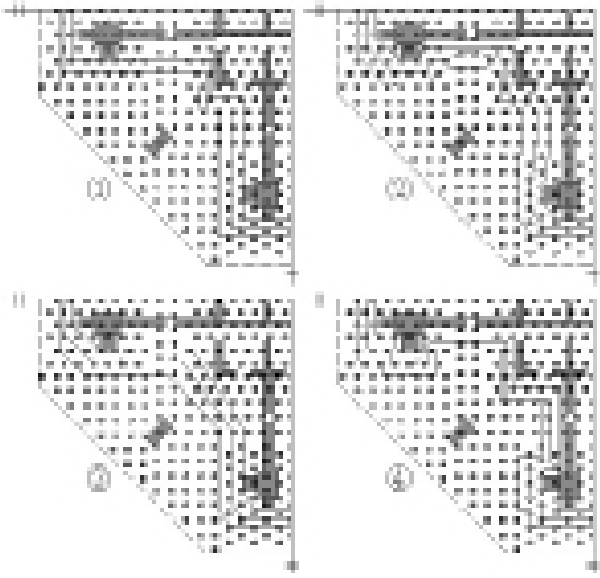

Figure 7. Selection of four different punching lines (From: Jiang, Wenhui)
图7. 四种冲切线形式选取示意图（出自：姜文辉）

超高层建筑桩基筏板冲切线选取

超高层建筑核心筒所占总荷载的比例较大，而核心筒下有限的面积内往往所布置的桩数不能平衡上部结构荷载，因而冲切线的选取及抗冲切力的大小是决定底板厚度的一个重要因素。

实例分析

将核心筒与巨柱通过翼墙连为一体，提高抗冲切能力，但冲切线的选取更为复杂多样，可能的冲切线有多条。

本文选取了四组不同形式的冲切线（见图7）进行试算，冲切线按照规范[4]的要求，选取从柱（墙）边起第一排桩边缘至45°斜边线范围内桩边缘不同的连线，得出了三道冲切线在这四组冲切形式下的抗冲切力（见表2）。

超高层建筑筏板施工温度的合理控制

超高层建筑筏板施工过程中，一个关键问题就是控制由温差引起的贯穿性有害裂缝。工程实践表明，大体积混凝土在硬化过程中由于大量水化热的释放而产生的里表温差和体积变形是导致裂缝产生的主要原因，成为结构构件的安全隐患。

实例分析

上海中心桩筏基础，筏板混凝土总方量为60000m³，采用强度等级为C50R90的泵送商品混凝土，施工时间在3月底，采用一次性连

情况冲切线 Situation Punching Line	第一种（单位：MN） 1st Form (Unit: MN)	第二种（单位：MN） 2nd Form (Unit: MN)	第三种（单位：MN） 3rd Form (Unit: MN)	第四种（单位：MN） 4th Form (Unit: MN)
冲切线 Punching Line	总和（冲切/桩反） Total (punching/pile reaction)	总和（冲切/桩反） Total (punching/pile reaction)	总和（冲切/桩反） Total (punching/pile reaction)	总和（冲切/桩反） Total (punching/pile reaction)
第一道 First	2457 (1271.6/1185.4)	2471 (1399.4/1071.6)	2484 (1250/1234)	2732 (1735.1/996.9)
第二道 Second	2343 (839.9/1503.1)	2404 (1051/1353)	2394 (841.4/1552.6)	2573 (1307.4/1265.6)
第三道 Third	2460 (675.3/1784.7)	2379 (707.6/1671.4)	2409 (599.6/1809.4)	2459 (899.9/1559.1)

Table 2. The calculated punching resistance result of each punching line (From: Jiang, Wenhui)
表2. 各冲切线的抗冲切力计算结果（出自：姜文辉）

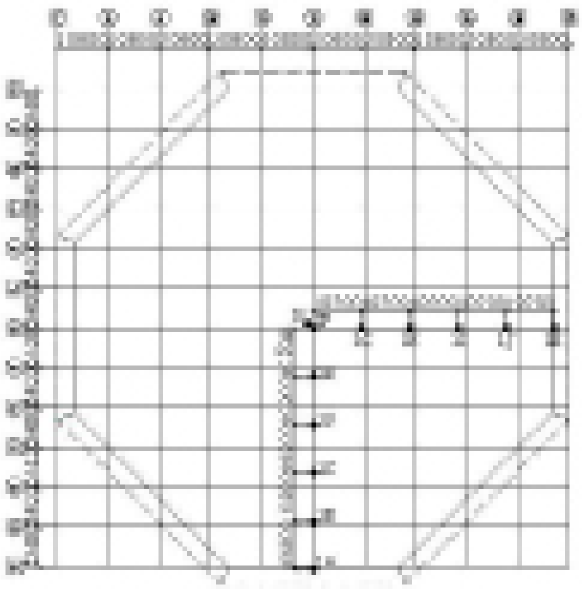

Figure 8. Temperature measuring points in the foundation raft (From: Chao, Si)
图8. 基础底板混凝土测温点布置（出自：巢斯）

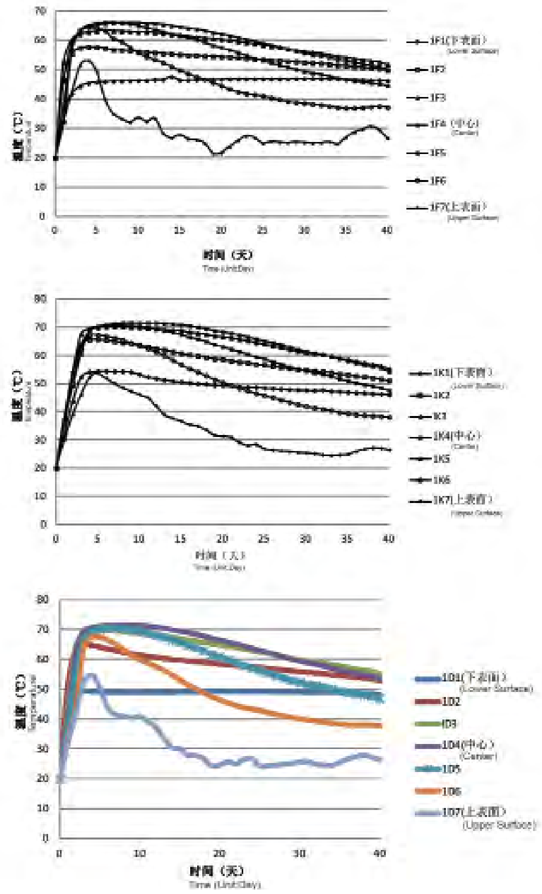

Figure 9. Temperature changing curve of measuring points 1F, 1K and 1D (From: Chao, Si)
图9. 实测点1F、1K、1D的温度变化曲线图（出自：巢斯）

Case Study

In the pile foundation of the Shanghai Tower, there is a total raft concrete volume of 60,000 m^3 adopting pumped commercial concrete with C50R90 strength level. The construction period takes place at the end of March with a disposable continuous casting of 15°C average temperature and 20°C molding temperature.

In the temperature measurement point layout of the foundation concrete slab (see Figure 8), there are a total of 80 temperature measurement points distributed in the concrete foundation slab. This paper only examines the temperature changing curve at three points, 1D, 1F, and 1K (see Figure 9). At the same time, the finite element software illustrates the pile-raft foundation model of the Shanghai Tower in order to simulate the temperature distribution field in the pile-raft foundation construction. The software also obtains the measured value of the raft temperature and compares the results between the actual and calculated raft temperatures (see Table 3).

In the stress distribution field of the raft, maximum tensile stress values in critical time intervals are extracted in order to graph the raft concrete maximum tensile stress versus time curve (see Figure 10). The maximum tensile stress in the construction process cannot exceed the concrete tensile strength.

续浇筑，平均气温为15℃，入模温度约为20℃。

基础底板混凝土测温点布置（见图8），混凝土基础底板共计80个温度测点。本文仅作出1D、1F、1K三个监测点的温度实测变化曲线（见图9）。与此同时，采用有限元软件建立上海中心桩筏基础模型，模拟上海中心筏板基础施工时的温度场，得到筏板温度实测值与有限元计算值对比结果(见表3)。

在筏板应力场中，提取重要时间步的最大拉应力值，得到筏板混凝土最大拉应力随时间变化曲线（见图10）。发现施工过程中最大拉应力始终没有超过混凝土抗拉强度。

Summary

Multiple solutions can be adopted in the construction process to control mass concrete interior and exterior temperature differences:

结论

施工过程中可采取多种措施控制大体积混凝土温升和里表温差：

- 跟踪混凝土里表温差的变化采取有效的技术和养护措施。
- 在设计中，适当在混凝土外表面增设分布钢筋，以适当提高混凝土的抗拉强度。

	实测值 Actual Testing Value		有限元计算值 Calculated FEM			
测点编号 Testing Points	最高温度(℃) Max. Temperature (°C)	里表温差(℃) In-Out Temp. Difference (°C)	最高温度(℃) Max. Temperature (°C)	里表温差（℃） In-Out Temp. Difference (°C)	最高温度误差 Max. Temperature Error	里表温差误差 Inside-Outside Temperature Error
1D	71.5	42.7	73.7	39	3.00%	8.67%
1F	71.5	38.4	73.7	37.7	3.00%	1.82%
1K	66.1	41	68.4	39	3.48%	4.88%

Table 3. The comparison of temperature of the actual raft value and finite element calculation (From: Chao, Si)
表3. 筏板温度实测值与有限元计算值对比（出自：巢斯）

- Keep track of the concrete temperature from both the inside and outside while utilizing effective techniques and maintenance measures.
- During the design phase, distribute steel bars appropriately on the outside of the concrete to increase the concrete tensile strength.
- During the concrete proportion design phase, use the post-strength of the concrete, e.g. replacing R28 with R90, can reduce the amount of cement used and decrease the total heat of hydration value.
- Use cement with a low rate of heat of hydration with the consideration of mixing active agents to replace some cement parts which could reduce the heat released from the hydration process. This can also decrease the heating rate of hydration, thereby, delaying the emergence of the concrete temperature peak time.
- Adding the appropriate amount of superplasticizer can reduce water consumption, reduce concrete shrinkage, and reduce the heat of hydration at an early stage.
- Maintain proper work habits while a protection layer is required on the concrete surface to reduce the temperature differences that may occur between the surface and internal concrete.

Conclusion

Using the Shanghai Tower as a case study, this paper analyzes design methods related to pile-raft foundations for supertall buildings in soft soil areas. This paper introduces the iteration method of the variable coefficient of the subgrade reaction and analyzes the combined action on foundations that are conducted based on the iteration method. The analysis results verify the rationality of the stiffness modification theory and examine the entire construction process of the supertall building; With the calculation and analysis of different punching lines in the pile-raft foundation, results provide the regular distribution and the most unfavorable punching lines of the lower punching lines in the core and mega columns of supertall buildings; By investigating the temperature and stress distribution fields during the mass concrete construction period, rational temperature control methods can be obtained.

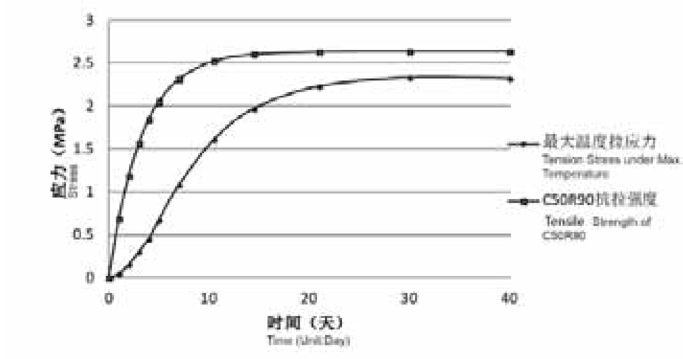

Figure 10. Maximum tensile stress in the concrete versus time curve (From: Chao, Si)
图10.　混凝土最大拉应力随时间变化曲线图（出自：巢斯）

- 在混凝土配合比设计时，可利用混凝土的后期强度，如采用R90取代R28，可减少水泥用量，降低水泥的水化热总量。
- 选用低水化热水泥，并考虑用活性掺加剂来替代部分水泥用量，可以降低水化热释放，同时也延缓水化热发热速率，从而延迟混凝土温度峰值的出现时间。
- 掺加适量高效减水剂，可以减少水的用量，降低混凝土收缩，同时降低早期水化热量。
- 做好养护工作，混凝土表面需要覆盖保护层，以减小混凝土表面与内部混凝土的温度梯度。

结语

本文以上海中心大厦为例，研究分析了软土地基超高层建筑桩筏基础的相关设计方法。提出变基床系数迭代法，并以此方法为基础进行共同作用分析，验证变刚度调平理论的合理性以及对超高层建筑进行施工全过程分析；对桩筏基础不同形式的冲切线进行分析计算，给出了超高层建筑中筒核和巨柱下冲切线的一般分布规律和最不利冲切线；分析筏板基础大体积混凝土施工时的温度场和应力场，得到合理的温差控制方法。

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