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Authors: Xin Zhao, Department of Structural Engineering, Tongji University
Shehong Liu, Tongji Architectural Design (Group) Co., Ltd.

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Foundation Differential Settlement Included Time-dependent Elevation Control for Super Tall Structures

Xin Zhao[1,2,†] and Shehong Liu[2]

[1]*Department of Structural Engineering, Tongji University, Shanghai, 200092, China*
[2]*Tongji Architectural Design (Group) Co., Ltd., Shanghai, 200092, China*

Abstract

Due to the time-dependent properties of materials, structures, and loads, accurate time-dependent effects analysis and precise construction controls are very significant for rational analysis and design and saving project cost. Elevation control is an important part of the time-dependent construction control in supertall structures. Since supertall structures have numerous floors, heavy loads, long construction times, demanding processes, and are typically located in the soft coastal soil areas, both the time-dependent features of superstructure and settlement are very obvious. By using the time-dependent coupling effect analysis method, this paper compares Shanghai Tower's vertical deformation calculation and elevation control scheme, considering foundation differential settlement. The results show that the foundation differential settlement cannot be ignored in vertical deformation calculations and elevation control for supertall structures. The impact of foundation differential settlement for elevation compensation and pre-adjustment length can be divided into direct and indirect effects. Meanwhile, in the engineering practice of elevation control for supertall structures, it is recommended to adopt the multi-level elevation control method with relative elevation control and design elevation control, without considering the overall settlement in the construction process.

Keywords: Differential settlement, Elevation control, Vertical deformation, Time-dependent effects, Super tall structures

1. Introduction

The time-dependent effects of the integrated soil-foundation-structure (SFS) system for super tall structures are coupled to each other, and its calculation is a complex process of iteration, until convergence. Since the super tall structures have the features of numerous floors, heavy loads, long construction time, demanding process, and locating in the coastal soft soil areas, both the time-dependent features of superstructure and settlement are very obvious. Therefore, the influence of time-dependent effect on integrated SFS system for pile raft foundation and superstructure can not be ignored.

In the research and application of the time-dependent effect on integrated SFS system, structural elevation compensation analysis and control is an important content. In 1984, Fintel comprehensively and systematically introduced the formula for predicting the vertical deformation of concrete vertical members through integrating a large amount of data. Meanwhile, Fintel proposed a vertical deformation compensation method combining project example (Fintel, 1984). Based on Fintel's vertical deformation compensation method, Park put forward an optimized compensation scheme for vertical deformation of tall building columns (Park, 2003). On the basis of Park's research, Zhou further developed an approximate optimal simplified method through repeated trial. Besides, Zhou studied the influence of the vertical deformation compensation of core wall systems on the characteristics of steel frame-reinforced concrete structures. Zhou's research results show that it is not necessary to redesign and calculate the compensation structures (Zhou, 2006). In 2011, by using the time-dependent analysis method, Zhang calculated the Shanghai Tower's vertical deformation and analyzed the impact of vertical members' differential deformation and elevation compensation for horizontal members. Furthermore, Zhang proposed that the vertical deformation compensation values are time-dependent, and calculated the Shanghai Tower's differential deformation compensation values in construction stage (Zhang, 2011). In 2014, Jiang used time-dependent coupling effect calculation program based on fiber model, and recalculated the typical mega members' differential deformation and elevation compensation in Shanghai Tower. Jiang's calculation results are in good agreement with the Shanghai Tower's elevation actual monitoring values (Jiang, 2014). Based on Jiang's research, Yan considered the effect of moisture distribution on the time-dependent effect for mega composite members, and analyzed the influence of moisture uneven distribution for elevation compensation

[†]Corresponding author: Xin Zhao
Tel: +86-21-35375097, +86-13621816382; Fax: +86-21-35375099
E-mail: 22zx@tjadri.com

(Yan, 2015).

On the basis of the previous studies, this paper discussed the structural elevation control standards and elevation compensation scheme of super tall structures. By using the time-dependent coupling effect analysis method and considering the foundation differential settlement, this paper compared the Shanghai Tower's vertical deformation calculation and elevation control scheme considering foundation differential settlement.

2. Time-dependent Coupling Effect Analysis Method

In 2011, Zhang analyzed the structural elastic time-dependent effect and inelastic time-dependent effect in detail (Zhang, 2011). Zhang proposed that the structural elastic time-dependent effect is related to time-dependent materials, structures and loads. In Zhang's research, the coupling effect, sectional moisture distribution and foundation differential settlement are not taken into account. In 2013, based on the traditional time-dependent effect analysis method, Yu further developed a time-dependent coupling effect analysis method. Yu's method can consider the time-dependent coupling effect between deformation and internal force (Yu, 2013). In 2014, Jiang put forward a time-dependent coupling effect analysis method based on fiber model, and applied it to the structural time-dependent coupling effect calculation (Jiang, 2014). On the basis of Jiang's research, Yan considered the effect of moisture uneven distribution for structural time-dependent coupling effect, and proposed a time-dependent coupling effect analysis method considering sectional moisture uneven distribution (Yan, 2015).

Based on the previous studies and comprehensively taking into account the coupling effects of time-dependent actions, this paper further developed a new time-dependent coupling effect analysis method considering foundation differential settlement. The analysis process of this new time-dependent coupling effect analysis method is as shown in Fig. 1.

To simplify the calculation, the above time-dependent coupling effect analysis method separately considers the concrete shrinkage and creep, and foundation differential settlement. The shrinkage and creep of concrete is calculated by using ANSYS and MATLAB with B3 model and modified fiber model taking moisture uneven distribution into account (Yan, 2015). The foundation settlement deformation is directly calculated by the finite element program of general geotechnical engineering. Then, the time-dependent differential settlement is directly applied to the main structure model corresponding to each construction step, and the time-dependent coupling effect iteration is realized in the ANSYS and MATLAB programs. The vertical displacement approach is used on bearing node to consider time-dependent settlement action. This applying vertical displacement approach on bearing node

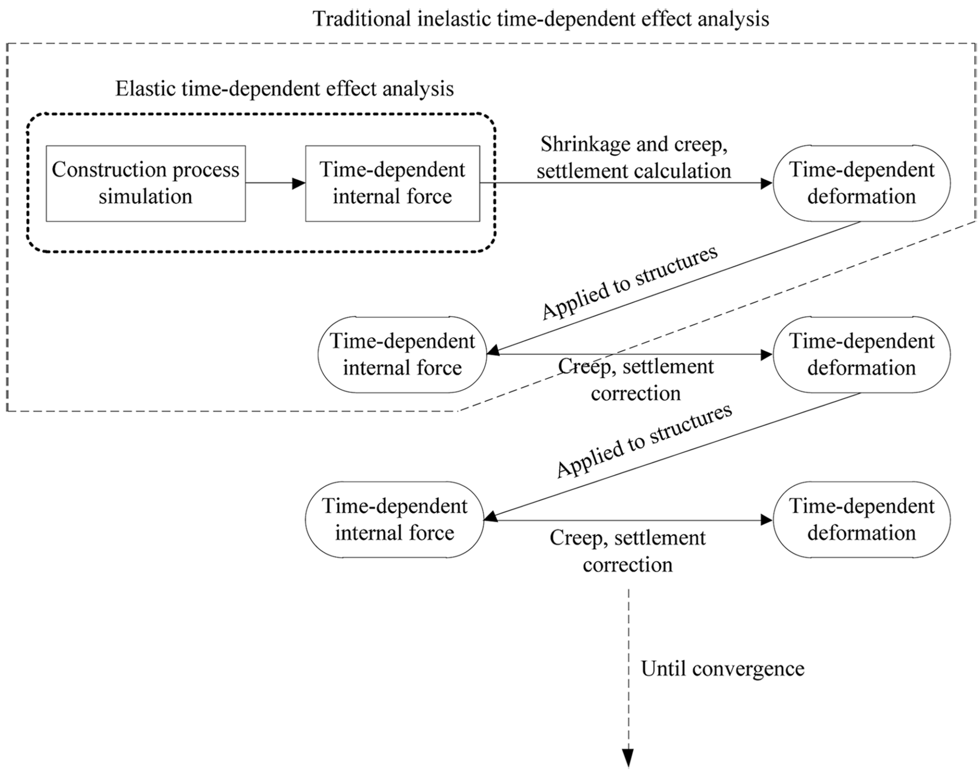


Figure 1. Analysis process of time-dependent coupling effect analysis method.

is physically clear and easy to operate.

3. Structural Elevation Control Standards and Methods

3.1. Structural Elevation Control Standards

According to the existing national code and technical specification for concrete structures, steel structures and hybrid structures of tall building, the floor elevation control has three methods: relative elevation control, design elevation control, and absolute elevation control (Zhang, 2011).

3.1.1. Relative elevation control

Control each floor's construction and installation errors. Not consider the impact of weld shrinkage deformation and load-induced compression deformation. The total height error of the structure does not exceed the allowable deviation of each floor and the cumulative compression deformation.

3.1.2. Design elevation control

Control the structural design elevation (not absolute elevation, regardless of foundation settlement). The compressive deformation (including elastic and inelastic compression deformation) due to weld shrinkage and load-induced in each floor shall be compensated. After the completion of structural construction, the overall height of the structure should meet the design requirements of the total height.

3.1.3. Absolute elevation control

Control the structural absolute elevation (consider the foundation settlement). The foundation settlement, weld shrinkage deformation and load-induced compression deformation shall be compensated. After the completion of structural construction, the absolute elevation of the key floor and the roof floor in the structure should meet the absolute elevation value of the design requirements.

At present, according to the existing national code and technical specification, it is recommended to use the relative elevation control and design elevation control method. Especially for super tall structures above 500m, it is recommended to using the combined multi-level elevation control method.

3.2. Structural Elevation Control Methods

The elevation compensation method of the vertical differential deformation in super tall structures mainly includes (Huang, 2009): (1) Floor by floor compensation method; (2) Mean compensation method in each construction segment; (3) Cumulative compensation method; (4) One-time compensation method at the top of each construction segment; (5) Mean compensation method of all floors; (6) Optimized compensation method of floor groups.

Due to the great influence of vertical differential deformation for elevation compensation in super tall structures, and as the floor by floor compensation method is the most accurate and ideal compensation method, this paper used the floor by floor compensation method.

In the process of elevation compensation, we need to define a time node, so that the structural member elevation in this time node is equal to the design elevation. This time node is called the compensation period. The compensation period is usually 1 year or 10 years after structural capping.

In addition, according to the different objects, the deformation compensation can be divided into two categories in the actual construction: elevation compensation value and pre-adjustment length value. Elevation compensation value is an accumulated amount of all floors below one floor, and pre-adjustment length value is the individual value of one floor. Elevation compensation value is the post-construction deformation, and pre-adjustment length value is the total deformation value of one floor.

In the construction process: Construction height = Design elevation + Elevation compensation value;

Steel member length = Design length + Pre-adjustment length

4. Project Case

4.1. Project Overview

The Shanghai Tower will be the engineering example used throughout this paper. The height of the building is 632 meters in the topmost with the structural height of about 580 meters, which consists of a 124-story tower, a 7-storey podium and a 5-storey basement. Standard floor plan of Shanghai Tower has a circular form, whose centre is aligned along the height and radius reduces gradually with the tower height increasing. There are 2-layer glass curtain walls in Shanghai Tower. The inner wall is arranged around the standard floor forming a circle. The outer wall is an equilateral triangle with a gap at a corner. The equilateral triangle curtain wall rotates about 1° in each floor from the bottom to the top of the building. The total twist angle is about 120°. The lateral system of Shanghai Tower is comprised of an interior reinforced concrete core tube, exterior composite mega columns and steel outrigger and belt trusses. The tower is divided into 8 zones and a sightseeing zone along the vertical. At the top of each zone, a mechanical floor and a refuge floor are arranged (see Fig. 2). And six 2-storey high outrigger trusses and eight box-type space belt trusses are arranged in the 8 equipment floors. Six outrigger trusses are distributed in zone 2, 4, 5, 6, 7, and 8.

Shanghai Tower is located in the level 7 seismic intensity area, in where the site soil conditions are class IV. Occupying a total site area of about 30,000 m^2, the Shanghai Tower has a total gross floor area of approximately 580,000 m^2, with 410,000 m^2 above ground, and 170,000

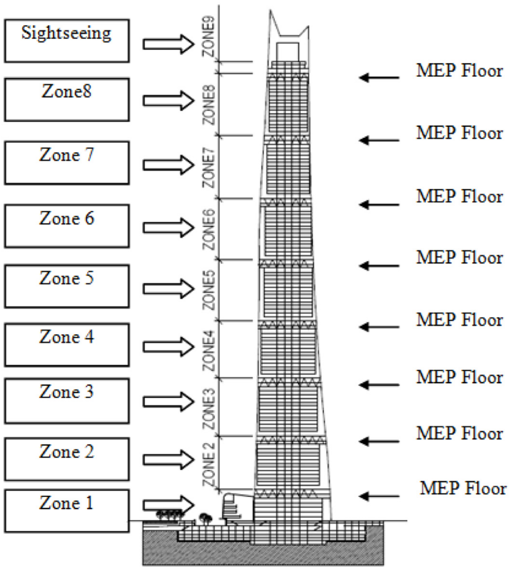


Figure 2. Vertical zoning of Shanghai Tower.

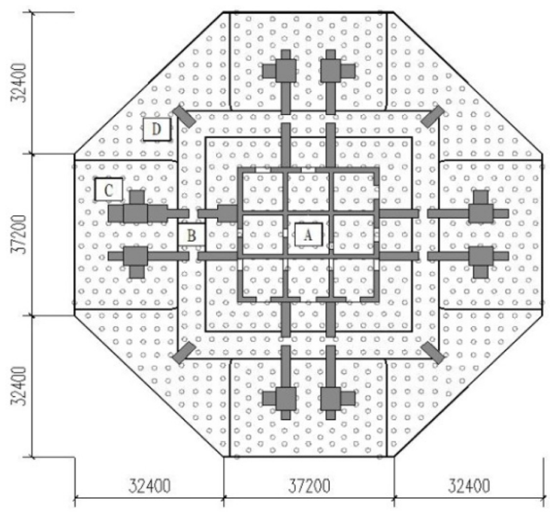


Figure 3. Pile raft layout of tower.

m^2 below ground. The entire site has a 5-storey basement, and its foundation depth is about 30 m. The thickness of raft under the tower is 6 m, and the area of raft is 8945 m^2. This uses bored piles (grouting), the concrete grade is C50, and the bearing layer of these piles is 9-21 layer silt. The number of piles is 955, the pile diameter is 1 m, the spacing of the piles is 3 m, and the piles are distributed by stiffness in a special way. Based on different foundation arrangements, the entire raft area can be divided into four areas: Area A and C using a plum flower arrangement (five wings with a center core), while Area B and D using a rectangular distribution (see Fig. 3). The effective length of the pile in Area A is 56 m, and its bearing capacity is 11,000 kN, while the effective length of the pile in other zones is 52 m, and its bearing capacity is also 11,000 kN.

4.2. Structural Elevation Control Standards

The combined multi-level elevation control standard in Shanghai Tower's structural elevation control. The combined multi-level elevation control standard is as shown in Table 1.

It should be noted that in the engineering practice of elevation control, Shanghai Tower used the combined multi-level elevation control method with relative elevation control and design elevation control without considering the overall settlement in the construction process, but need to consider differential settlement.

The elevation control reference point is in the central service core, distancing from ±0.000 floor about 50 cm (see Fig. 4). All structural height measurements take this reference point as the starting position. As shown in Fig. 4, the absolute settlement value at the central service core position is the overall settlement (h), and the relative settlement value between the central service core and mega column is the differential settlement (Δh). Obviously, the overall settlement can not cause any changes in the internal force analysis and elevation compensation, but the differential settlement will make the whole tower bend, which can affect the internal force analysis and elevation compensation.

In addition, the impact of foundation differential settlement for elevation compensation and pre-adjustment length can be divided into direct and indirect effects. The direct effects don't consider structural internal force redistribution, but the indirect effects do.

4.3. Vertical Deformation Calculation

This paper used the time-dependent coupling effect analysis method considering foundation differential settlement to calculate the total deformation, deformation before construction and deformation after construction of central service core and mega column in different times. The calculation results are shown in Figs. 5~7.

Table 1. Combined multi-level elevation control standard of Shanghai Tower

Structural height	Structural elevation control standards	Error tolerance
Floor height	Relative elevation control	±10 mm
Zone height	Relative elevation control	±30 mm
Whole structure height	Design elevation control	±100 mm

Note: The elevation control reference temperature in Shanghai is recommended to be 20ºC.

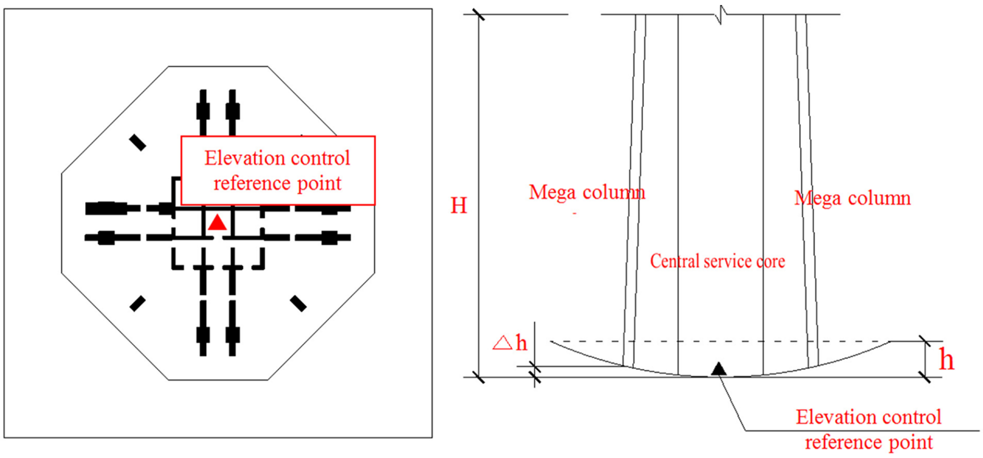


Figure 4. Reference point position and elevation control schematic diagram.

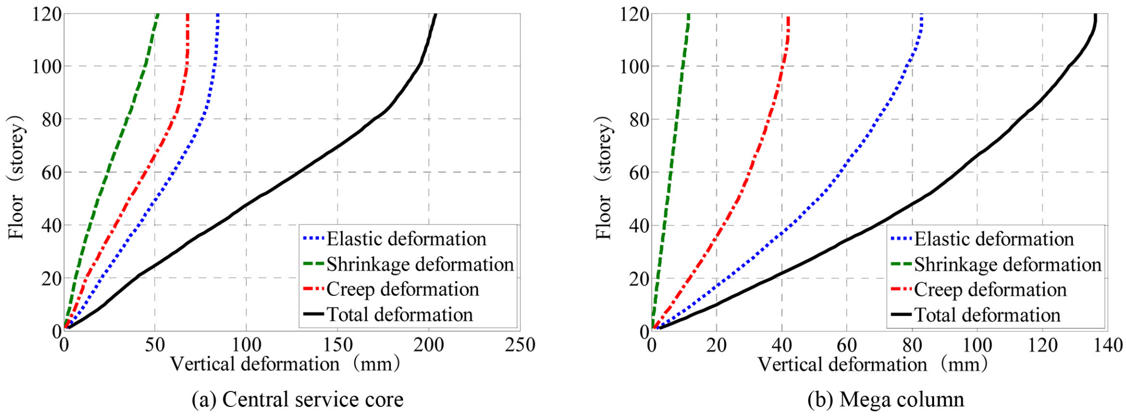


Figure 5. Total deformation (1 year after structural capping).

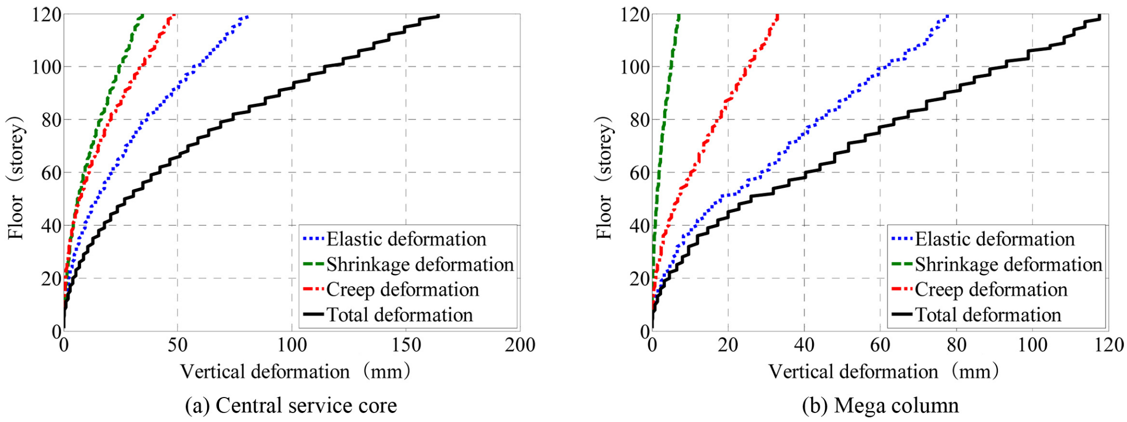
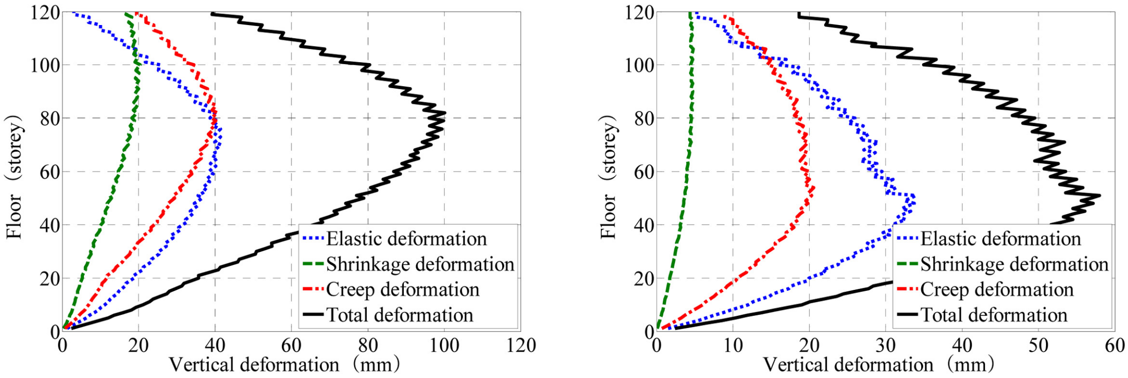


Figure 6. Deformation before construction.

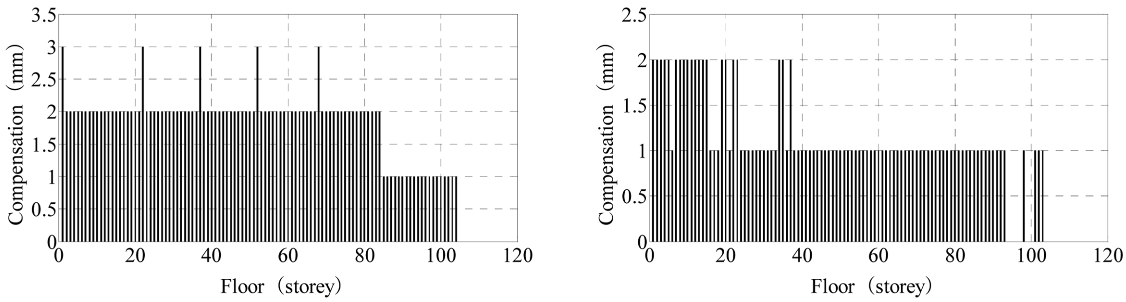
4.4. Structural Elevation Control Scheme

According to the above elevation compensation method and vertical deformation calculation results, this paper studied the vertical deformation compensation scheme of



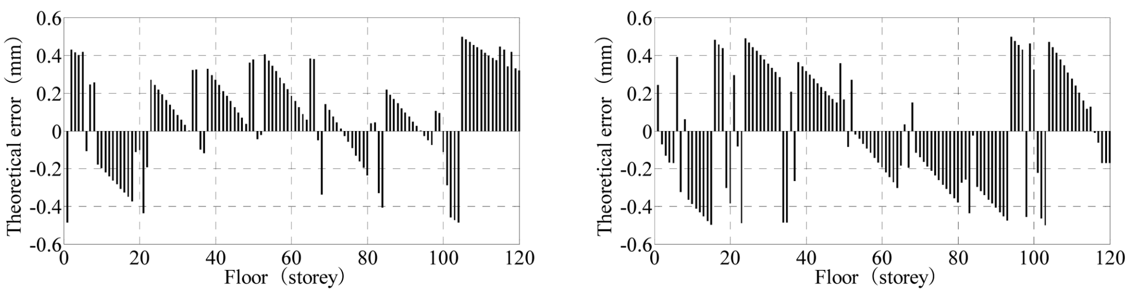
(a) Central service core (b) Mega column

Figure 7. Deformation after construction (1 year after structural capping).



(a) Central service core (b) Mega column

Figure 8. Elevation compensation values (1 year after structural capping).



(a) Central service core (b) Mega column

Figure 9. Theoretical elevation error values (1 year after structural capping).

Shanghai Tower. The compensation period is 1 year after structural capping. The elevation compensation and theoretical elevation error values of central service core and mega column are shown in Figs. 8~9. Besides, this paper compared the Shanghai Tower's vertical deformation calculation and elevation control scheme with and without considering foundation differential settlement. The comparison results are shown in Table 2.

According to Fig. 10 and Table 2, it is shown that after elevation compensation of central service core and mega column, the elevation theoretical error values of each floor, zone and the whole structure all meet the tolerance for structural acceptance.

5. Conclusions

By using the analysis method for time-dependent coupling effect, this paper compared the Shanghai Tower's

Table 2. Theoretical elevation error values of Shanghai Tower (mm)

Zones	Without differential settlement		With differential settlement	
	Central service core	Mega column	Central service core	Mega column
Zone 1	2.3	1.3	2.5	1.5
Zone 2	3.3	4.9	3.6	5.4
Zone 3	2.6	5.9	2.5	5.6
Zone 4	3.1	5.0	2.9	3.7
Zone 5	3.6	1.6	3.7	2.6
Zone 6	2.0	1.9	2.0	4.1
Zone 7	2.0	4.7	2.0	6.6
Zone 8	7.3	5.7	7.3	4.7
Whole structure	26.3	31.0	26.5	34.3

vertical deformation calculation and elevation control scheme with and without considering foundation differential settlement. The main conclusions are as follows:

(1) The foundation differential settlement cannot be ignored in vertical deformation calculation and elevation control for super tall structures. The impact of foundation differential settlement for elevation compensation and pre-adjustment length can be divided into direct and indirect effects.

(2) In the engineering practice of elevation control for super tall structures, it is recommended to adopt the multi-level elevation control method with relative elevation control and design elevation control, without considering the overall settlement in the construction process; the differential settlement needs to be considered.

(3) After elevation compensation of central service core and mega column, the theoretical error values for elevation of each floor, zone and the whole structure all meet the required tolerance for the final structural acceptance.

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