# Analysis and simulation on unequal settlement of ancient masonry pagodas

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## Abstract

This paper analyzes the main causations that make the unequal settlement of ancient masonry pagodas, and illustrates the influences induced by adverse factors. A famous Chinese leaning pagoda, Huqiu pagoda in Suzhou city, has been selected as a research object, to study the characteristics of applying modern analysis technique to ground deformation of ancient masonry pagodas. A practical simplified model was developed, and the inclination status of Huqiu pagoda has been simulated by finite-element analysis software ANSYS.
*Keywords: ancient masonry pagoda, unequal settlement, influencing factor, simplified model, modeling technology.*

## 1 Introduction

The masonry pagoda is a main type of the Chinese pagodas. Because masonry structures have big deadweight and are sensitive to the deformation of the ground, the many masonry pagodas are on the leaning status. In order to control and strengthen the inclined masonry pagoda, the reasons of inclination and the infection of the unequal settlement of ground must be analyzed.

The unequal settlement of ancient pagoda is the embodiment of the ground deformation virtually. In the analyzing process of leaning status of ancient pagoda, we should give priority to the ground deformation, and consider added deformation aroused by deflection of center of gravity of superstructure. On the long-term load, the compress deformation of subsoil under the ancient pagoda is basically completed. So, in the analysis of ground deformation, we may not consider the influence of time, but calculate final settlement of ground directly.

The method of analyzing final settlement of ground is usually plotted into *classical theory* and *numerical simulation*, for example, the *layered summation*

WIT Transactions on The Built Environment, Vol 95, 
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR070431

*method* and *finite-element analysis method*. With the computer technique developing quickly, finite-element analysis of the ground deformation has been an important means.

In this paper, a famous Chinese leaning pagoda, Huqiu pagoda in Suzhou city, has been selected as a research object, to study the characteristics of applying modern analysis technique to ground deformation of ancient masonry pagodas. A practical simplified model was developed, and the leaning status of Huqiu pagoda has been simulated by finite-element analysis software ANSYS.

## 2 The main causations that induce ancient pagoda to incline

Owing to lack of valid reconnaissance technology, most ancient architects are difficult to obtain detailed geological information. When the masonry pagoda was built on a weak ground and the ground has not been treated, the heavy deadweight will bring on bearing layer into plastic deformation, which is the precondition of pagoda inclination.

When the thickness and distribution of the subsoil layers with larger difference, it will cause ancient pagoda to settle unevenly. The Huzhu Pagoda on Tianma mountain in Shanghai was built in AD1079, its gradient is already 6°52′ now (Fig. 1), non-uniform subsoil layers is one of the important factors that induce this pagoda to incline [1].

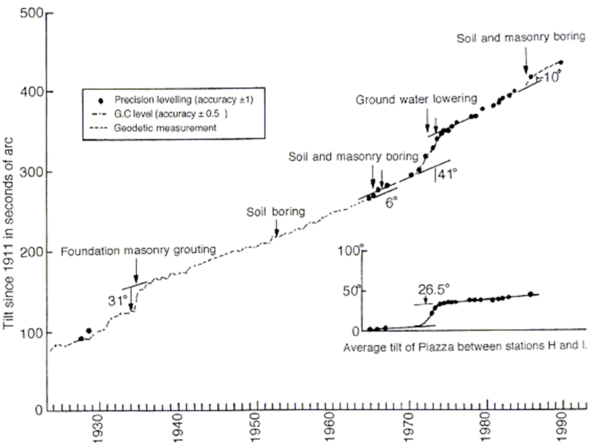


Figure 1: Huzhu Pagoda on Tianma Mountain in Shanghai.

Figure 2: Change in inclination of the grounds in the 20th century.

The variety of water table is also an influence factor should be considered. When the water content of the ground soil of the pagoda is discrepant, the ground will settle unequally on the compress process, and induce pagoda body to incline. Besides the excessive base pressure and unequal compress soil layer, the variety of water table is also an important factor that induce famous Pisa tower to incline. The tower has been shown to be very sensitive to ground disturbance and changes in ground water conditions (Fig. 2). In the late 1960s and early 1970s, pumping from the alluvial sands caused subsidence and the tower tilted further towards the south west by some 41 arc seconds. When the pumping was reduced, the rate of movement returned to its former level [2].

The slope slack is one of the familiar geological disasters in a mountainous area. In the many reasons that affect stabilization of the slope, ill engineering geological condition is an inherent reason, but the heavy rainfall and artificial slope digging are extrinsic reasons. Many Chinese pagodas were built on the hillside, and easy to slip along slope when abrupt instance happens.

The White pagoda in Lanzhou city built 550 years ago lies on the south slope (Fig. 3), and inclining along with creepage of the slope southwards. By the measure to the pagoda that is before reinforcing, the pagoda top has deviated from the centre of shape to 555mm, the leaning degree reaches 3.84% [3].

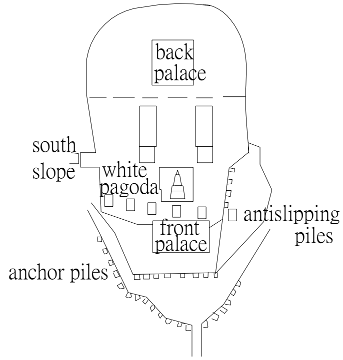


Figure 3: White pagoda on the slope.

Some ancient pagodas have larger slenderness ratio and high center of gravity, and are highly sensitive to the condition of ground. Once the ground is slantwise, the leaning side will have concentrated base pressure, exacerbate eccentric compression of structure, and lead to a vicious circle of inclination.

Literature [3] introduces that after inclination of the white pagoda, the center of gravity deviates from the centre of shape continuously, induces the pagoda body to incline southwards unceasingly.

# 3 The inclined status and correlative datum of Huqiu pagoda

## 3.1 The leaning status of Huqiu pagoda

Situated on the Huqiu Hill of ancient city Suzhou, the Huqiu Pagoda was built between AD 959 and 961 and is considered as the one with the oldest age and the greatest inclination among existing Chinese pavilion style masonry pagodas (Fig. 4). The pagoda is a seven-story tube structure, with 47.68 meters in height and 6100 tons in weight, and it is supported by 12 brick pier foundations built on the ground directly (Fig. 5). Ever since its construction, the groundwork of the pagoda has started to subside unevenly, causing the pagoda to incline northward. Under the erosion by winds and rains and with the development of uneven foundation settlement, the pagoda has deteriorated severely. During the years of 1981 to 1986, Chinese civil engineering community carried out a major rehabilitation program to this ancient pagoda which was then on the verge of collapse. At conclusion of the project, the foundation settlement and the structure inclination have been well stabilized [4]. As present, the pagoda maintains a tip deflection of 2.325 m with an angle of inclination of 2°48' (Fig. 6), and the north out pier foundation had sunk 45cm deep in the ground, the drop in level of second floor from north to south is 60cm.

Figure 4: Huqiu pagoda condition.

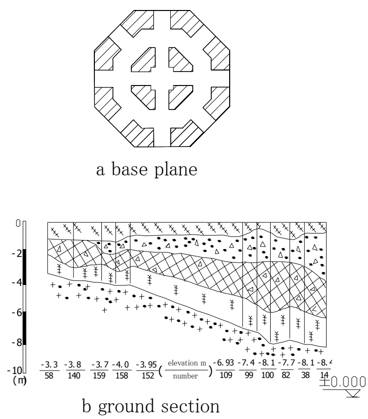


Figure 5: The base plane and ground section.

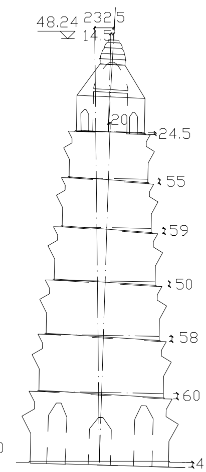


Figure 6: Leaning condition of the pagoda.

### 3.2 Geological datum of Huqiu pagoda

By the original ground datum provided by the cultural relic protection department of Suzhou city, Huqiu hill is formed by volcano eruption and the hill is composed by tuff and rhyolite. The rock surface of the hill peak is high in the southwest and low in the northeast, and the gradient is 1:4. The Huqiu pagoda is built on the filling layer of the peak, thus, the soil layer is thin in the southwest and thick in the northeast.

The ground layers of Huqiu pagoda (Fig. 5) that superincumbent instance are 1) Plain filling layer with rocks and silty clay, in partial area, clayey granules are lost, then come to be big holes. 2) Clayey loam layer, it is the main bearing layer. 3) Decay rock layer, which is dry and close-grained. 4) Base rock layer, composed by tuff and rhyolite and has firm texture.

### 3.3 Expert argumentation for the Leaning reasons of Huqiu pagoda

During years of 1978 to 1981, the national cultural relic bureau and Suzhou government organized experts and technicians to make reconnaissance and research to Huqiu pagoda. The main reasons of unequal settlement of the pagoda were analyzed as follows. 1) The pier foundations are built on the ground of the filling layer directly, the base stress is over large. 2) The pagoda is built on the soil layer with rock slope, and the bearing layer of ground is thick in the north and thin in the south, thus, resulting in the unequal compress deformation. 3) The base and ground of the pagoda have not been treated well, because surface water filters into ground, corrades the filling soil layer form south to north, and takes on many holes in the north part, it induces the unequal settlement to evolve. 4) The eccentric pressure of inclined pagoda exacerbated the unequal compression deformation.

## 4 The analysis of unequal settlement of Huqiu pagoda

### 4.1 Construction of finite-element models

Based on the main reasons of the unequal settlement of Huqiu pagoda, three finite-element simplified models are constructed. The conception on constructing models is listed in Tab. 1.

By the conception on constructing models, we can construct 3D models by AutoCAD firstly, then, switch CAD model to ANSYS by file SAT, and use the ANSYS10.0 to make analyses and calculation.

Table 1: Conception on constructing models.

| Condition | Reason of unequal settlement | Conception on constructing model |
|---|---|---|
| 1 | The thickness of the filling soil layer under the pagoda is unequal. | By the geological section of Huqiu pagoda, construct a simplified ground model with four unequal soil layers (Fig. 7(a)). |
| 2 | Surface water filters into ground and corrades ground form south to north; the filling soil layer in the north of the pagoda takes on many holes. | On the base of the model of condition 1, divide the plain filling layer and the clayey loam layer into the south part and north part by the bound of the center of pagoda, and define different deformation modulus for the two parts to simulate the different void ratios (Fig. 7(b)). |
| 3 | The eccentric pressure of inclined pagoda exacerbated the unequal compression deformation. | On the base of the model of condition 2, apply an equivalent moment on the pagoda body to simulate the effect aroused by eccentric pressure (Fig. 7(c)). |

 
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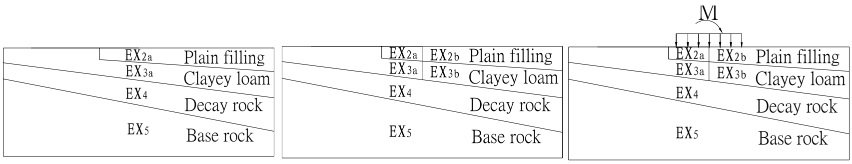



(a) condition 1 (b) condition 2 (c) condition 3

Figure 7: Simplified ground models.

## 4.2 Preprocessor and solution

### 4.2.1 Definition of material properties

By actual reconnaissance and correlative geological reports, the material properties of superstructure and ground of Huqiu pagoda (before reinforcing) have been obtained and listed in Tab. 2.

Table 2: Material properties of Huqiu pagoda.

| Position | Elastic modulus (or deformation modulus) $EX$ ( $MP_a$ ) | | | Density (g/cm$^3$) | Poisson ratio |
|---|---|---|---|---|---|
| | Condition 1 | Condition 2 | Condition 3 | Each condition | Each condition |
| 7th storey | 1694 | 1694 | 1694 | 1.80 | 0.15 |
| 2nd-6th storey | 1386 | 1386 | 1386 | 1.80 | 0.15 |
| 1st storey, foundation | 1694 | 1694 | 1694 | 1.80 | 0.15 |
| mixed filling soil | 2.0( $EX_1$ ) | 2.0( $EX_1$ ) | 2.0( $EX_1$ ) | 1.90 | 0.30 |
| plain filling layer | 4.0( $EX_2$ ) | 4.0( $EX_{2a}$ )<br>2.4( $EX_{2b}$ ) | 4.0( $EX_{2a}$ )<br>2.4( $EX_{2b}$ ) | 1.80 | 0.30 |
| clayey loam layer | 6.4( $EX_3$ ) | 6.4( $EX_{3a}$ )<br>4.8( $EX_{3b}$ ) | 6.4( $EX_{3a}$ )<br>4.8( $EX_{3b}$ ) | 2.00 | 0.32 |
| decay rock layer | 80.0( $EX_4$ ) | 80.0( $EX_4$ ) | 80.0( $EX_4$ ) | 2.40 | 0.20 |
| Base rock layer | 25000( $EX_5$ ) | 25000( $EX_5$ ) | 25000( $EX_5$ ) | 2.55 | 0.20 |

### 4.2.2 Definition of element type

The model of Huqiu pagoda is composed of pagoda body (superstructure) and ground. In order to get the influence of ground deformation to the superstructure, it is need to construct model by actual conformation. Because the conformation of the pagoda body is quite complicated, we select Solid186 as the element type of pagoda body to adapt irregular mesh. The ground soil is defined as Solid95, which is defined by 20 nodes and having three degrees of freedom per node (x, y, and z direction). Solid95 has plasticity, creep, stress stiffening, large deflection, and large strain capabilities. The level displacement between soil and superstructure is less, and it is not need to analyze the relative displacement, so, we do not select contact element type.

### 4.2.3 Definition of meshing precision

The free meshing has been selected, which can mesh automatically according to curvature of graph and adjacent extent of lines. Free meshing is classed into 10 levels, the level 1 is the most precise, and the level 10 is the coarsest.

Because the elastic modulus of the superstructure is biggish, and is looked as whole, we select level 6 as precision of pagoda body to save computing time.

Three levels, level 10, level 6 and level 1, have been compared to know the influence of meshing precision to ground deformation. The analysis indicates that the unequal settlement is aroused by ground deformation mostly, and the meshing precision has a larger influence to the deformation. As the meshing precision is higher, the result is closer to actual value (Tab. 3), so, we select level 1 as meshing precision for ground (Fig. 8).

### 4.2.4 Load and boundary

Load contains deadweight of superstructure and deadweight of soil, it is listed in Tab. 2. The boundary is concerned on restriction of soil and effective deformation area. In order to simplify model, we compare the influence of base dimension and restriction of boundary, and get the effective area and the condition of boundary. The selected dimension of base (Fig. 9) is 42m long horizontally, which is about 3 times of the foundation width; 15m deep vertically, which is larger than the foundation width and comes into rock. The soil supports pressure most, the influence of pull and shear force is small, the boundary condition is selected as that the horizontal soil of bottom is restricted on two ways. For the vertical soil wall, we made contradistinctive analysis of two instances that one has horizontal restriction, and the other has not horizontal restriction. It is shown by the results (Tab. 4) that the difference is small, so we select the instance that has horizontal restriction.

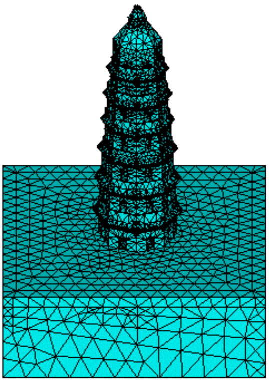


Figure 8: The meshing precision.

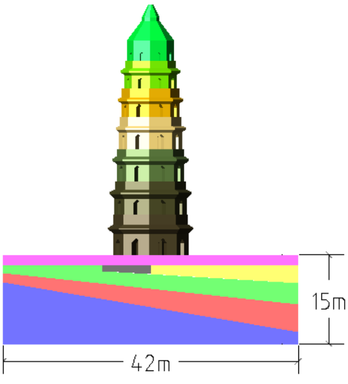



Figure 9: The dimension of base.

### 4.2.5 Analysis type

Because deformation of soil is large displacement on the process of settlement, the material of soil ought to select nonlinear material, and can adopt nonlinear analysis option. Considering the nonlinear analysis will take a lot of time, we made compare to linear analysis and nonlinear analysis. It is shown by the results (Tab. 5) that the settlement difference is little, which is 4.45cm, less than 10%. Considering the computing time, at last we select linear analysis.

Table 3: The infection of meshing precision to settlement (cm).

| The level of meshing | South of base | North of base | Settlement difference |
|---|---|---|---|
| 10 | 5.96 | 39.19 | 33.23 |
| 6 | 4.18 | 41.20 | 37.02 |
| 1 | 3.87 | 49.83 | 45.96 |

Meshing precision of superstructure is level 6, line elastic analysis.

Table 4: The influence of horizontal restriction to settlement (cm).

| horizontal restriction | South of base | North of base | Settlement difference |
|---|---|---|---|
| yes | 3.87 | 49.83 | 45.96 |
| no | 3.85 | 50.12 | 46.27 |

Meshing precision of superstructure is level 6; the base is level 1, line elastic analysis.

Table 5: The influence of analysis type to settlement (cm).

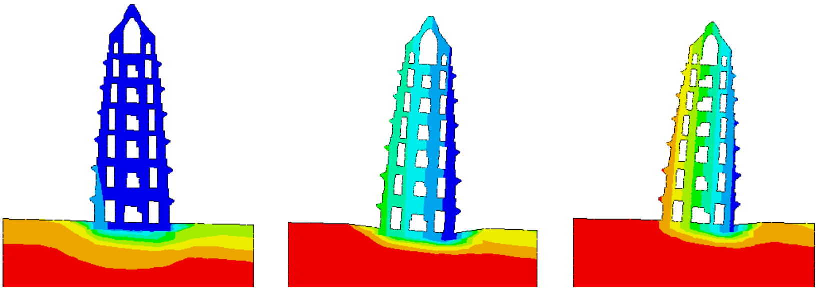
| Analysis type | South of base | North of base | Settlement difference |
|---|---|---|---|
| linear | 3.87 | 49.83 | 45.96 |
| nonlinear | 3.73 | 54.14 | 50.41 |

Meshing precision of superstructure is level 6; the base is level 1.

## 4.3 Results and appraisement

The final analysis results of unequal settlement are listed in Tab. 6, the vertical displacement of ground is shown in Fig. 10.

It is known from Tab. 6 that the more factors are considered, the results are closer to actual settlement difference. The analysis results indicate that the insufficient ground bearing capacity and non-uniform subsoil layers are direct factors that induce Huqiu pagoda to incline, and the corrasion of water table and eccentric compression exacerbated the incline.



(a) Condition 1 (b) Condition 2 (c) Condition 3

Figure 10: Ground deformations under different conditions.

Table 6: Settlement of ground (cm).

| Condition | South of base | North of base | Settlement difference | Actual settlement difference |
|---|---|---|---|---|
| 1 | 20.03 | 23.05 | 3.02 | 45.00 |
| 2 | 16.16 | 32.94 | 16.78 | |
| 3 | 3.87 | 49.83 | 45.96 | |

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