Dynamic Performance Analysis of Ancient Buildings Based on Soil-Structure Interaction

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Abstract. This paper takes Guangyue Tower as the research object and uses ANSYS software to establish three finite element models of its upper timber structure, timber structure and high platform foundation and wooden structure, high platform foundation and soil mass. Through modal analysis, it is concluded that when the soil-structure interaction is considered, the natural frequency of the structure is reduced, and its influence on the high-order natural frequency of the structure is greater than the influence on the low-order natural frequency. Select El-Centro wave, Taft wave and artificial wave to analyze the dynamic performance. The results show that only considering the wood structure or wood structure and the high platform will make the calculated displacement smaller, so the influence of the existence of the foundation soil on the superstructure should be considered.

Keyword. Ancient building, soil-structure interaction, dynamic response.

1. Introduction

Guangyue Tower is a building with quadruple eaves and cross ridge on the top of the mountain. It was built in the 7th year of Hongwu in Ming Dynasty and is located in Liaocheng, Shandong Province [1]. Huijuan Zhai [2] of Chang'an University conducted an elastoplastic analysis of the three-dimensional model of Xi'an city tower and city wall, and the results proved that the failure of the wooden structure's tenon-and-mortise joint is the main reason for the failure of ancient wooden structure under earthquake; Zhaobo Meng, Minzhe Wu, Weibing Hu [3] analyzed the seismic response of the Xi'an Bell Tower finite element model with foundation, and the results showed that the soil-structure interaction affects the seismic response; Xiaohong Deng [4] used ANSYS to establish the finite element model of the pier and the soil below the pier, and carried out the earthquake Reaction analysis shows that the stiffness of the structure will affect the interaction.

At present, most papers only consider part of the wood structure, high platform foundation and foundation soil model for comparative analysis, and cannot correctly evaluate the dynamic performance of ancient buildings under actual conditions. This paper compares the structure's dynamic performance by establishing the upper timber structure (T model), the upper timber structure and the elevated foundation model (T-P model) and the timber structure, the elevated foundation and the foundation soil model (T-P-S model).

2. Establishment of Finite Element Model

2.1. Establishment of Wood Structure Model (T Model)

According to the literature [5], the wood parameters in the direction along the grain are mainly taken, the wood parameters are adjusted and revised according to the "Technical Specification for
Maintenance and Reinforcement of Ancient Building Wood Structures” [6], and the elastic modulus is adjusted according to the “Combined Structure Design Code” [7]. Make adjustments, as shown in table 1 and table 2.

| Wood name | Elastic Modulus (MPa) | Density (kg/m³) | Poisson's ratio |
|-----------|-----------------------|-----------------|----------------|
| Old wood  | $6.23 \times 10^3$    | 410             | 0.25           |

Table 2. Before and after revision of component size and material parameters.

| Name                  | Column                      | Beam                       |
|-----------------------|-----------------------------|----------------------------|
|                       | First and second floors     | Three and four floors      | First floor               | Second floor               | Three and four floors      |
| Section size diameter before correction (m) | 0.6                         | 0.4                        | 0.30 \times 0.3           | 0.21 \times 0.37           | 0.25 \times 0.45           |
| Corrected equivalent diameter of cross section (m) | 0.75                        | 0.6                        | 0.3 \times 0.3            | 0.21 \times 0.37           | 0.25 \times 0.45           |
| Elastic Modulus (MPa) | $1.02 \times 10^4$         | $1.16 \times 10^4$         | $6.23 \times 10^3$        | $6.23 \times 10^3$        | $6.23 \times 10^3$        |

The roof slab and floor slab are equivalent to the concentrated load acting on the top of the corresponding column according to the principle of area equivalence. The concentrated mass of the column top is calculated to be 4889 kg. The beam and column simulation adopts BEAM188 element. The tenon and tenon joint simulation adopts COMBIN14 element. Mass load adopts MASS21 element, and the finite element model established by ANSYS software is shown in figure 1.

![Figure 1. T model.](image)

2.2. The Establishment of the Combined Model (T-P Model) of Wood Structure and High Platform Foundation

In order to facilitate the establishment of the finite element model of the high platform foundation, this paper ignores the masonry and only establishes the rammed earth model. The material parameters and geometric parameters of the high platform foundation rammed earth are shown in table 3 and table 4.

Table 3. Material parameters of high platform rammed earth.

| Name                    | Thickness (m) | Elastic Modulus (MPa) | Density (kg/m³) | Poisson's ratio |
|-------------------------|---------------|-----------------------|-----------------|----------------|
| High platform rammed    | 9.38          | 20.9                  | 1870            | 0.347          |
Table 4. Geometric parameters of high platform base.

| Name           | Top bottom side length(m) | Bottom side length(m) | Height(m) | Center arch |
|----------------|---------------------------|-----------------------|-----------|-------------|
| High stylobate | 31.62                     | 34.43                 | 9.38      | Cross       |

Coupling connection is adopted between the upper wooden structure and the high platform foundation, and between the column foot and the column foundation. The high platform foundation rammed soil simulation adopts SOLID45 unit, and the combined model of the wood structure and the high platform foundation (T-P model for short) is shown in figure 2.

![Figure 2. T-P model.](image)

2.3. Establishment of the Overall Model (T-P-S Model)

According to the stratum structure of the Guangyue Tower section, the foundation soil adopts SOLID45 unit. Assuming that the soil quality of each soil layer is uniform, it is simplified to 6 layers, and the calculated depth is 30m. The spring-damper COMBIN14 unit is used when setting the viscoelastic artificial boundary. The base surface of the elevated platform is defined as the contact surface, and the CONTA174 contact unit is used for simulation; the ground soil surface is the target surface, and the TARGE170 target unit is used for simulation. The wooden structure is connected with the high platform foundation in a coupling manner. The high platform foundation and the foundation soil are connected by the MPC algorithm. The foundation soil has a viscoelastic artificial boundary on the side and a fixed boundary at the bottom. The overall finite element model (referred to as T-P-S model), as shown in figure 3.

![Figure 3. T-P-S model.](image)

3. Establishment of Finite Element Model

The natural frequencies of the three models are shown in table 5 (the previous 10th order is an example). Draw frequency comparison curve according to natural frequency, as shown in figure 4.
Table 5. Comparison of the natural frequencies of the three models (Hz).

| Order | T model       | T-P model     | T-P-S model  |
|-------|---------------|---------------|--------------|
| 1/2/3 | 0.752/1.152/1.724 | 0.736/1.140/1.685 | 0.733/1.140/1.606 |
| 4/5/6 | 2.040/2.503/2.689 | 2.02/2.484/2.664   | 1.666/1.746/2.017 |
| 7/8/9 | 2.832/3.150/3.686 | 2.806/3.107/3.678   | 2.025/2.278/2.293 |
| 10    | 3.833         | 3.822         | 2.294        |

It can be seen from figure 4 that the natural frequency of the T-model and the T-P model has basically the same change trend before the thirteenth order. After the 13th order, the vibration degree of the high platform foundation participating in the structure increases, and the natural frequency decreases significantly. The first three-order natural frequencies of the T-P-S model are basically the same as those of the T-P model, but as the order increases, the natural frequencies of the T-P-S model increase slowly and gradually become smoother. In the fourth-order formation, the shape of the high platform base changes significantly, that is, the degree of participation increases; in the seventh-order formation, the ground soil vibration drives the upper structure, and the participation of the two makes the natural frequency of the T-P-S model after the fourth order and the T model, The T-P model is quite different.It shows that the soil-structure interaction will reduce the natural frequency of the structure; the influence of the soil-structure interaction on the high-order natural frequency is greater than the low-order natural frequency; in the overall analysis, if the soil-structure interaction is considered, the vibration. The type order should be greater than 6.

4. Seismic Response Analysis
Choose El-Centro wave and Taft wave and artificial wave generated according to the fitting of Guangyue Tower location, after amplitude modulation, input three kinds of seismic wave acceleration time histories along the X direction, and use the complete transient analysis method for seismic response analysis. For the three models, the node at the top of the column and the node at the variable section of the column are selected, and the displacement time history curve is drawn. According to the calculation results, it is found that the maximum displacements of the three models all occur at the top node of the through column, so this article will compare the displacement of the top of the column and the floor displacement.

4.1. Contrast and Analysis of the Top Joints
According to the displacement and acceleration peaks of different models under the action of the three seismic waves, the corresponding dynamic coefficients are obtained, as shown in table 6.
Table 6. Displacement and peak acceleration of the top node of the column.

| Seismic wave | Finite element model | El-Centro wave | Taft wave | Artificial wave |
|--------------|----------------------|----------------|-----------|----------------|
|              | T                    | T-P            | T-P-S     | T             | T-P            | T-P-S         |
| Peak displacement(cm) | 2.28 | 2.37 | 5.75 | 2.28 | 3.21 | 6.55 | 3.24 | 3.19 | 9.28 |
| Peak acceleration(m/s²) | 0.83 | 0.88 | 1.38 | 1.07 | 0.81 | 1.47 | 1.25 | 1.03 | 1.34 |
| Dynamic coefficient | 1.30 | 1.38 | 2.17 | 1.68 | 1.27 | 2.31 | 1.96 | 1.62 | 2.10 |

The peak acceleration of the top node of the T-P-S model under the action of seismic waves is greater than that of the T model and the T-P model. The T-P-S model under the action of El-Centro wave is 66% larger than the T model; the T-P-S model under the action of Taft wave is larger than the T-P model 81%; The T-P-S model is 30% larger than the T-P model under the action of artificial waves, and the dynamic coefficient of the T-P-S model is basically larger than that of the T model and the T-P model. It can be seen that the calculation results obtained by simply establishing the finite element model of the upper wooden structure for seismic analysis are relatively small. The interaction between the wooden structure, the high platform foundation and the foundation soil will affect the displacement of the column top under the earthquake. When analyzing the seismic response of ancient wooden buildings, the influence of the existence of foundation soil on the superstructure should be considered.

4.2. Comparative Analysis of Floor Displacement

Table 7 shows the maximum displacement of the column top relative to the column foot and the maximum interlayer displacement angle under the action of three seismic waves. Figures 5-7 shows the comparison curves of the displacement response of the three models under different seismic waves.

Table 7. The maximum displacement (D) of the structure floor (cm) and the displacement angle (DA) between floors under each working condition.

| Seismic wave | Model | First floor | Second floor | The third floor | Fourth floor |
|--------------|-------|-------------|--------------|----------------|--------------|
|              |       | D   | DA   | D   | DA   | D   | DA   | D   | DA   |
| EL wave      | T     | 0.39 | 1/1760 | 0.73 | 1/1224 | 1.34 | 1/574 | 2.28 | 1/473 |
|              | T-P   | 0.96 | 1/705 | 1.32 | 1/1224 | 1.74 | 1/780 | 2.36 | 1/606 |
|              | T-P-S | 2.72 | 1/250 | 3.84 | 1/394 | 5.07 | 1/271 | 6.80 | 1/228 |
|              | T     | 0.36 | 1/912 | 0.69 | 1/634 | 1.30 | 1/532 | 2.28 | 1/407 |
| Taft wave    | T     | 1.36 | 1/500 | 1.82 | 1/895 | 2.38 | 1/578 | 3.20 | 1/496 |
|              | T-P   | 3.19 | 1/213 | 4.36 | 1/374 | 5.68 | 1/242 | 7.66 | 1/199 |
|              | T-P-S | 0.52 | 1/1059 | 1.04 | 1/854 | 1.91 | 1/400 | 3.24 | 1/324 |
| Artificial wave | T     | 1.58 | 1/431 | 2.10 | 1/849 | 2.54 | 1/485 | 3.27 | 1/391 |
|              | T-P   | 2.92 | 1/233 | 3.99 | 1/409 | 5.19 | 1/292 | 6.85 | 1/255 |

Figure 5. T model floor displacement curve comparison. Figure 6. T-P-S model floor displacement curve comparison. Figure 7. T-P model floor displacement curve comparison.
It can be seen from table 7 and figures 5-7 that under the same seismic wave, the relative displacement of each floor column top of the T-P model and the T-P-S model is larger than that of the T model, and the T-P-S model has a significant increase. Under the same seismic wave, the displacement of the column top node is the largest, and the relative displacement of the top layer and the displacement angle between layers are greater than one to three floors. The analysis shows that when the time history analysis of wooden structure ancient buildings, only considering the main wooden structure or the combination of the wooden structure and the high platform will make the calculated displacement smaller. Therefore, in the corresponding analysis, the influence of the existence of the foundation soil on the superstructure should be considered.

5. Conclusion
(1) From the point of view of the natural frequency, when considering the soil-structure interaction, the natural frequency of the structure is reduced. The influence of the soil-structure interaction on the high-order natural frequency of the structure is greater than that of the low-order natural frequency. In the analysis, if the soil-structure interaction is considered, the mode order should be greater than 6.

(2) Under the action of seismic waves, the horizontal displacement and acceleration response of the T-P-S model through column top node and the node at the variable cross-section are greater than the T model and T-P model; with the increase of the floor height, the relative column foot displacement of each floor gradually increases, and the relative displacement of the top floor And the displacement angle between layers is greater than one to three layers, that is, the top layer is relatively weak.

(3) When analyzing the dynamic performance of ancient wooden buildings, considering only the main wooden structure or the combination of the wooden structure and the high platform will make the calculated displacement smaller, so the influence of the existence of the foundation soil on the superstructure should be considered.

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