"Research on the Seismic Response and Analysis Method of Underground Structures Based on the Response Deformation Method"

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Abstract. In order to study the underground structure under the action of an earthquake, the relationship between the displacement and the stress between layers of different soils under the action of the earthquake was carried out through the finite element numerical analysis software. The influencing mechanism of soil layer depth on the seismic response of underground structure was discussed, and the seismic response law of the system was worked out. The research results indicated that the displacement response of the soil layer structure in three directions depicted obvious laws with the change of soil layer depth. There were evident similarities and differences in the response of soils with different properties to seismic responses. These conclusions provided a certain reference for the seismic design of underground structures.

1. Introduction
With the continuous development of underground engineering, the requirements for seismic design of underground structures have further increased. The key issues existed in the law of displacement distribution of layered soil and the value of spring stiffness coefficient in the response deformation method were studied, and on this basis, a reasonable, simple and practical calculation method for determining the seismic response of underground structures was proposed. Several models that can be used for seismic calculation of underground structures were proposed by Li Yingmin et al. [1]: (1) continuum model, (2) load-structure model.

The reaction deformation method based on the input method of seismic load and the substructure method in the soil-structure dynamic analysis of time procedure was theoretically deduced by Liu Jingbo et al. [2], and the results showed that the response deformation method had a relatively rigorous theoretical basis. Under the action of an earthquake, that the overlying soil of the structure would first produce shear failure and lose its shear resistance was pointed out by Du Xiuli et al. [3]. The main factors affecting the seismic safety of underground structures were proposed by Hashash Y M A et al. [4], which included: (1) structural form, size and depth of burial; (2) structural material characteristics; (3) ground motion intensity. A soil-structure overall analysis model through the response acceleration method to directly reflect the interaction between the underground structure and the surrounding soil was established by Xu Chengshun [5], which illustrated that applying a certain distributed horizontal load along the depth of the soil could better reflect the distribution characteristics of the inertial force of the lower structure and the surrounding soil under the seismic effect. The response acceleration method,
which adopted one-dimensional soil seismic response analysis to obtain the dynamic response of the soil under the action of an earthquake, was pointed out by Li Xinxing [6]. However, the calculation model of the response deformation method, the spring coefficient of the foundation, the soil displacement mode and the scope of application given in the code were not clear yet [7].

2. Establishment of finite element model and experimental methods

2.1. Common seismic calculation methods for underground structures

Common calculation methods for seismic action of underground structures included pseudo-static calculation methods and dynamic methods of time procedure. The pseudo-static calculation methods included seismic coefficient method, free field deformation method, soil-structure interaction coefficient method and response deformation method. The dynamic analysis of time-procedure method had been greatly developed in recent years since it could accurately and completely reflect the influence of the genuine earthquake. Existing research results mostly focused on two-dimensional plane models, and failed to consider the effects of neighboring existing buildings' spatial distribution and other effects. This article intended to establish a reasonable underground structure-soil analysis model, discuss the influence of earthquake action under different geological conditions, establish a corresponding structural model, analyze the interaction between the nature of the soil layer and the earthquake action, and provide a scientific basis for seismic design. The calculation of an infinite soil layer under the action of a vertical upward shear seismic wave could be equivalent to the elastic theory of bearing a certain load Q at infinity, and the rock-soil medium around the plane contact problem had an impact in the earthquake, Dong Zhengfang et al. [8] pointed. The influence of underground subway stations could not be ignored [9].

2.2. Basic data of finite element model

2.2.1. Model establishment of soil-structure in finite element analysis software

![Fig.1 Soil model](image1)

![Fig.2 Range of computing model](image2)

Table 1. Types of underlying soil

| Soil layer name           | severe(kN/m³) | Cohesion(kpa) | Initial friction angle(°) | Poisson's ratio | Initial cohesion(kN/mm²) |
|--------------------------|---------------|---------------|---------------------------|----------------|--------------------------|
| Yellowish brown silt clay| 19.1          | 30            | 25°                       | 0.35           | 20                       |
| Gray, taupe silt clay    | 18.3          | 13            | 28°                       | 0.35           | 21                       |
| Yellow-brown red clay    | 18.2          | 37            | 25°                       | 0.35           | 20                       |
| Gray silt                | 19.4          | 14            | 30°                       | 0.4            | 10                       |

The overall information of the soil structure was as follows: According to the theoretical determination of the range of influence in limited soil that had an effect on the structure, the previously determined soil structure was an underground structure with 3m high, 5m wide, 17m deep. The range of influence of the body on the structure was 3 times the width of the structure, the influence of the upper soil on the
structure was taken as 1 layer of unit soil, and the influence of the lower soil on the structure was 3 times
the height of the soil. The length in the \( x \) direction is 35 meters, the width in the \( y \) direction is 17 meters,
and the height in the \( z \) direction is 13 meters. The soil model is shown in Figure 1.

The types of underlying soil layers are shown in Table 1. The selected soil layer is the Moore
Coulomb model. The supporting conditions were: with three-way displacement restrained, the rotation
angle is not astricted and the Taft wave is used as the seismic load.

2.2.2. Unit type and node
With the mainstream finite element analysis software and the requirements of the dynamic model, the
model is divided into 13 layers each of which has a thickness of 1m from top to bottom, and a total of
8,928 nodes and 7,480 elements are established. According to the soil layer selection method of Tao
Lianjin et al. [10], the selection range was: the top surface is taken from the ground surface, the bottom
surface was taken as the design seismic reference plane, and the horizontal distance from the side wall
of the structure to the boundary was 3 times the effective horizontal width of the structure. As is shown
below.

2.3. Basic data of the second finite element model
The top surface of the subway station is 4.8m beneath the underground, and the site is mainly composed
of Quaternary Holocene sand and Pleistocene clay. The station is 120m long and adopts one-side
platform. The overall size of the model is 79.9m long in the \( x \) direction, 77m wide in the \( y \) direction, and
32.2m high in the \( z \) direction.

Soil layers of different properties were defined according to soil layer parameters, units were divided
according to selected sections, and the 2D grid lines were extended to the 3D model. The stratum
properties in the \( z \)-axis direction from top to bottom were, in turn, artificial filling, brand new Clays,
Holocene sands, Pleistocene clays, Pleistocene sands. The nodes were kept coupled by extraction, and
680 2D plane structural units were established. After expansion, 18,240 3D overall units were formed
as shown in Figure 3 and Figure 4. Under the action of Taft wave, the stress contours of each node
element in the user coordinate system are shown in Figure 5.

![Fig.3 3D unit model of underground structure](image1)
![Fig.4 Overall finite element model](image2)
![Fig.5 Stress analysis model](image3)

3. Calculation results and analysis

3.1. Analysis of inter-layer displacement
The seismic action of Taft waves in three directions was simultaneously used to calculate and summarize
the laws through the data obtained by time procedure analysis. The action of the seismic wave within
55s was adopted to draw the displacement image between layers and the displacement images of each
layer.

It can be seen from Figure 6 that under the action of seismic waves, the displacement between the
first and second layers of soil is the largest, and it decreases gradually from the third layer to the bottom.
The relative displacement of the soil layer changes most obviously from the 3rd to the 16th at the
moment of 16s. It gradually stabilized afterwards. On the whole, the changing trend of the displacement
in each layer of soil is basically similar.

From Figure 7, it can be seen that the relative displacement between layers in various directions has
a larger trend of changes in soil displacement when the earthquake action is strong before 13th seconds,
and tends to be stable in the later period, and its displacement trend changes with depth. The increase shows an obvious decreasing trend, but the changes in the displacement of the underground structure are more significant, and the relative displacement decreases with the increase in depth more obviously. This provides with effective reference value for the arrangement of soil springs, which means that soil springs in the shallow part constrain more while the lower part can be reduced accordingly.

![Fig.6 The overall interlayer displacement of the soil under the action of Taft wave](image1)

![Fig.7 Relative displacement of each layer](image2)

### 3.2. Analysis of the change trend of structural reaction force

It is known that the constraints on the finite element model are the fixed end constraints at the bottom and the free field constraints in other directions, the output inverse forces in the reaction analysis are supposed to be $F_x$, $F_y$, $F_z$ the reaction force images of the two models were respectively analyzed as shown in Figure 8.
Through the analysis of the reaction force change, it is not difficult to see that the farther the seismic wave propagates along the width direction of the structure, the smaller the influence on the structure. In the vertical direction, the structural reaction force on the soil layer closer to the structure is reduced. The larger, the more constraints should be imposed accordingly.

3.3. Analysis of the change trend of soil stress

For the load condition under the action of earthquake on the solid stress element, there are corresponding stresses in the three directions of $x$, $y$, and $z$. The stress changes with the depth direction. In the response deformation method, the load input was replaced by the spring coefficient to simplify the calculation. According to the empirical formula, the soil spring parameters are related to the inter-story displacement and the stress of the underground structure model.
4. Conclusion
Based on the dynamic finite element method and numerical simulation, the changes of the underground structure with the depth of the soil layer under the influence of earthquakes were studied, and the following conclusions are obtained:

(1) The underground structure, soil and the depth of soil layer have a certain correlation effect under the earthquake, the responded displacement of the structure in the three directions of space shows obvious regularity with the changes of the embedding depth and the seismic wave pattern.

(2) The thickness of the soil layer has a significant influence on the horizontal displacement of the underground structure. As the depth increases, the interlayer displacements in the three directions of the underground structure are significantly weakened.

(3) Under the action of the $z$-direction ground motion, the displacement along the $z$-direction of the underground structure gradually decreases with the increase of the spacing, indicating that the depth of the soil layer has a significant weakening effect on the seismic response of the structure. However, considering the effects of soil settlement and lighting, the structure spacing should be within a reasonable interval.

(4) The law of a single underground structure under the action of an earthquake in the variation of displacement was studied. The displacement characteristics of multiple underground structures have not been considered. The structure is reasonable under the influence of the height of the underground structure, soil characteristics and other factors. The value of the spacing has not been specifically quantified, and this is also the research work that should be continued in the future.

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