A Simplified Response Displacement Method for Seismic Calculation of Shallow Buried Structures Using New Load-Structure Model

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Abstract. The two models commonly used in response displacement method were introduced. And then, put forward a simplified response displacement method (SRDM) using new load-structure (NL-S) model. Based on the classical response displacement method (CRDM), SRDM simplified the earthquake action of input underground structures, and neglected some computations which are cumbersome and small. Finally, SRDM was verified by an example. In the calculation, the general analysis of SRDM was carried out by changing the following 3 aspects: soil properties, seismic wave type, PGA. The 3 methods of time history method (THM), CRDM and SRDM were used for calculation. The results of SRDM were compared with the results of the other two methods. The calculation results shows that the SRDM is the most convenient and suitable for practical engineering application, and its calculation precision is high.

1. Introduction

With the development of urbanization, people began to develop and utilize the underground space vigorously, and the underground structure engineering technology has also been greatly developed [1]. In the early stage of underground engineering construction, it is considered that the underground structure is buried in the rock and soil layer its influence on earthquake is very small, the surrounding rock and soil layer is a natural protective layer of underground structure. But in 1995 Kobe earthquake [2] and the 1999 Chi Chi earthquake in Taiwan [3] have caused irreparable damage in a large number of subway stations, tunnels and utility tunnels, then rasied the seismic research of underground structure in the world. Since the seismic research of underground structure has been carried out, scholars at home and abroad have made a lot of research results. At present, the commonly used pseudo static methods [4] for seismic response analysis of underground structures include seismic coefficient theory [5], free field deformation method [6], soil structure interaction coefficient method [7], response displacement method [7,8], response acceleration method [9,10], pushover method [11-13] and integral response displacement method [14,15]. In these methods, reaction displacement method has been widely used because of its clear physical concept and simple calculation. It has also been written as a recommended method for seismic computation of underground structures. Because of the different understanding of the reaction displacement method, the current calculation model of the reaction displacement method has not been unified, and there are many versions. Some of these models are early put forward, which only reflect one or two aspects of earthquake action. The theory of the model itself is not perfect, while some models pursue the completeness of theoretical concepts,
involving many parameters, and the computation workload is large, so it is inconvenient for engineering application. In order to solve the above problems, a simplified calculation model of reaction displacement method is proposed and its reliability is verified by an example.

2. Common calculation models of response displacement method

2.1. The calculation model in ”rail code” [16]
The classical response displacement method is used in ”rail code”, as shown in Figure 1. Soil springs are set up at 4 weeks in the structure and the shear is considered. In this model, the seismic action is divided into 3 parts: the relative displacement of the soil layer, the surrounding shear and the structural inertia force.

2.2. The calculation model in ”building code” [17]
The response displacement method is used in ”building code”, as shown in Figure 2. The soil spring is set on the side and bottom of the structure, and the shear is taken into account on the top surface. In the calculation model, the soil spring is not set at the top of the structure, and the shear effect is not considered in the side and the bottom of the model.

2.3. Analysis of the two models
Through the above comparison, we can see that the calculation model of the response displacement method in ”rail code” is more reasonable, its theoretical concept clear, and the calculation of earthquake action is complete, so the following analysis and model simplification based on this model, and the simplified model is shown in Figure 3.
The following is the reasoning process of NL-S model: In the classical response displacement method, the seismic action is mainly composed of 3 parts, the formation deformation, the structural shear force and the structure inertia force. In the model of Figure 2, a normal and tangent spring is applied to the structure to indicate the effect of soil deformation on the structure. However, from the calculation steps of the response displacement method, it can be found that the horizontal deformation of the structure is assumed to be the seismic response of the free field soil during the computation. Only the horizontal deformation of the model is calculated, and the vertical deformation is not considered. Therefore, the vertical deformation of the vertical soil layer in the classical model can be removed in the classical model. The relative displacement is calculated in the response displacement method, the structural bottom is taken as the reference point. Therefore, the bottom displacement is 0, and the earth spring at the bottom can be removed. A simplified model, such as Figure 3, can be obtained through the above calculation. The calculated soil spring stiffness at this time is $K_{vS}$ and $K_{h}$, and the calculation amount is greatly reduced compared to the 6 soil layer spring stiffness before the simplification.

3. Verification of NL-S model
The utility tunnel structure is selected by the classical reaction displacement model and the NL-S model in this paper. Taking the result of time history analysis as a reference, the calculation results of the response displacement method under the two models are compared with those of the dynamic time history analysis method. In order to verify the universality of the NL-S model, we calculated and compared the properties of these 3 aspects by changing the type of the input seismic wave, peak ground acceleration (PGA), the property of the soil layer.

3.1. Calculation model and parameter
The underground structure selected in this paper is a double compartment utility tunnel. Its standard section is shown in Figure 4. The total width of the utility tunnel is 10m, the height is 4m, the thickness of the top plate, the bottom plate and the side plate are all 0.5m, and the thickness of the middle diaphragm is 0.4m. The concrete material is C40, density $\rho=2500$Kg/m$^3$, elastic modulus $E=32.5$GPa, Poisson's ratio $\nu=0.2$. This paper selects 2 points of A and B on the section to do the reaction analysis. A is the connection between the side plate and the top plate, B is the connection between the side plate and the bottom plate.

Figure 4. Cross section diagram of a double compartment utility tunnel (mm)

When the calculation process to establish two-dimensional finite element model, the depth of utility tunnel is 3m, the width of in soil is 7 times the width of the structure, the soil depth calculate to seismic datum (shear wave velocity $\geq 500$m/s). The calculation is simplified as follows: 1. There is no slip and separation between soil and structure during earthquake, and the structure is coupled with the soil layer. 2. It is assumed that both the soil and the underground structure are in the linear elastic state in the calculation process.

3.2. Results and analysis
Before calculating, we found that the change of calculation results of the bending moment of the section B and the deformation of the side plate are the greatest in the calculation of underground
structure similar to the structure in this paper. Therefore, the two values are taken as the control factors in the following analysis.

3.2.1. Different soil properties.
The equivalent homogeneous soil is equivalent homogenization of the soil parameters, such as foundation coefficient, bulk density and elastic modulus, when calculating. In order to get the accuracy of the equivalent homogenization of the layered soil in the seismic response analysis of the utility tunnel, the error analysis is made for the layered soil layer and the homogeneous soil layer. The parameters of the soil layer before the homogenization are shown in Table 1, after the homogenization in Table 2. In the calculation, the Kobe wave with a PGA of 0.2 was selected.

| Serial number | Type       | Thickness (m) | Bulk density (kN/m$^3$) | C (kPa) | $\Phi$ (°) | $V_s$ (m/s) | G (MPa) | $\nu$ |
|---------------|------------|---------------|-------------------------|---------|------------|------------|---------|------|
| 1             | Backfill   | 0.5           | 18.5                    | 10      | 10         | 115        | 26      | 0.33 |
| 2             | Fine sand  | 2.5           | 18.7                    | 7       | 12         | 160        | 36      | 0.31 |
| 3             | Fine sand  | 3             | 19                      | 7       | 26         | 200        | 79.5    | 0.28 |
| 4             | Silty clay | 34            | 20.1                    | 13      | 20         | 251        | 120.3   | 0.30 |
| 5             | Round pebble | 22           | 520                      |         |            |            |         | 0.25 |

| Thickness (m) | Depth (m) | Bulk density (kN/m$^3$) | C (kPa) | $\Phi$ (°) | $V_s$ (m/s) | G (MPa) | $\nu$ |
|---------------|-----------|-------------------------|---------|------------|------------|---------|------|
| 40            | 40        | 19.91                   | 12.14   | 19.83      | 240        | 110.8   | 0.30 |

| The bending moment at B (kN·m) | Homogeneous soil | Results | Relative error-THM | Results | Relative error-THM | Relative error-CRDM |
|--------------------------------|------------------|---------|---------------------|---------|---------------------|----------------------|
| Homogeneous soil                | 400.62           | 8.32%   | 389.19              | 10.93%  | 2.85%               |
| Layered soil                    | 360.59           | 10.50%  | 356.32              | 11.54%  | 1.19%               |

| The displacement of side wall (mm) | Homogeneous soil | Results | Relative error-THM | Results | Relative error-THM | Relative error-CRDM |
|-----------------------------------|------------------|---------|---------------------|---------|---------------------|----------------------|
| Homogeneous soil                  | 4.91             | 1.03%   | 4.69                | 3.49%   | 4.48%               |
| Layered soil                      | 4.56             | 11.49%  | 4.63                | 13.20%  | 1.53%               |
From the above Table 3, it can be seen that the bending moment calculated by the equivalent structural seismic response and the deformation value of the side wall are all larger than those before the equivalent. The bending moment of section B calculated by different methods is different. The calculation of THM is the largest and the calculated value of CRDM is the second, and the SRDM is the smallest. Before and after equivalent treatment, the bending moment of section B is calculated by SRDM, compared with the THM, the error is about 11%, but compared with the CRDM, the error is 2.85%. The results of the side plate deformation calculated by different methods are different, and their values are between 4.09-4.91. From the above analysis, we can see that the result of the SRDM is accurate when the soil is changed, and the result will not be abrupt.

3.2.2. Different input wave kinds.
The time history curves of 3 kinds of waves are chosen such as El-Centro wave, Kobe wave and Taft wave and shown in Figure 5. The PGA of these seismic waves is 0.2. The calculation results are shown in Table 4.

![Figure 5. Different input wave kinds](image)

**Table 4. Calculation results under different seismic waves**

|                            | The results of CRDM | Relative error-THM | The results of SRDM | Relative error-CRDM |
|--------------------------|---------------------|--------------------|---------------------|---------------------|
| The bending moment at B (kN·m) |                     |                    |                     |                     |
| El-centro wave            | 400.98              | 7.32%              | 380.69              | 12.01%              | 5.06%               |
| Kobe wave                 | 360.59              | 10.48%             | 356.32              | 11.51%              | 1.18%               |
| Taft wave                 | 351.01              | 12.04%             | 326.98              | 18.06%              | 6.85%               |
| The displacement of side wall (mm) |           |                    |                     |                     |
| El-centro wave            | 4.91                | 1.03%              | 4.69                | 3.50%               | 4.48%               |
| Kobe wave                 | 4.56                | 11.5%              | 4.63                | 13.20%              | 1.54%               |
| Taft wave                 | 4.36                | 2.98%              | 4.33                | 2.36%               | 0.07%               |

From Table 4, it is known that the response of the calculated is quite different because of the spectral different of the selected seismic waves. The bending moment of the section B and the deformation of the side wall are basically descended from the order of El wave, Kobe wave and Taft wave. When the Taft wave is input, the bending moment calculated by two methods can reach the maximum error compared with the THM. The maximum error of the CRDM is 12.04, and the maximum error of SRDM is 18.06. The maximum error of the bending moment calculated by the SRDM is 18.06 (THM), and 6.85 (CRDM), the maximum error of the side plate deformation is 13.20 (THM) and 4.48 (CRDM). From the above analysis, we can see that with the change of wave, the trend of bending moment and side plate deformation is consistent with THM, and its value is very small compared with CRDM.
3.2.3. Different peak ground acceleration.
The Kobe wave is used to input the PGA to 0.05g, 0.2g, 0.5g and 0.8g respectively. The calculation results are shown in Figure 6 and Figure 7. The PGA of seismic wave is adjusted according to the following formula:

\[ a'(t) = \frac{a'_{\text{max}}}{a_{\text{max}}} a(t) \]  

(1)

The \( a'(t) \) and \( a'_{\text{max}} \) are the adjusted seismic acceleration curves and the PGA. \( a(t) \) and \( a_{\text{max}} \) are the seismic acceleration curves and the PGA of the original ground.

From the above Figure 6 and Figure 7, it can be seen that the bending moment and the deformation value of the side wall are all increasing with the increase of PGA. The moment calculated by the THM is the largest, the result of the CRDM method is the second, and the result of SRDM is the smallest. The results of the deformation calculation of the side plate that the value of the CRDM is the largest, the value of THM is the second, and the value of the SRDM is the smallest. From Figure 6 and 7, it can be seen that with the increase of PGA, the calculation results of various methods are very consistent, and the simplified method has high calculation precision.

4. Conclusion
Based on response displacement method principle and model, combined with the two model of response displacement method commonly used in the calculation and the problems such as parameters needed for the calculation process is complicated, this paper proposes a SRDM with NL-S model, through theoretical analysis and the calculation can be concluded as follows: The concept of NL-S model is clear. The calculation of seismic load is much less than the CRDM, the calculation is simple and the precision is high. When the soil properties change, the calculation results of the SRDM are consistent with the results of THM and CRDM. There is no abrupt change and high accuracy. Compared with the CRDM, the maximum error of bending moment is 2.85%, and the maximum error of side plate deformation is 4.48%. When the input seismic wave changes, the calculation results of the SRDM are in agreement with the results of the other two methods, and the calculation precision is high. With the increase of PGA, the bending moment calculated by the 3 methods and the deformation value of the side plate all show an increasing trend. The SRDM is in agreement with the calculation results of the other two methods, and the error is small, especially it is close to the results of the CRDM. Through the above theoretical analysis and numerical calculation, it is found that the SRDM is simple and accurate for the calculation of seismic response of underground structures, which is more suitable for manual calculation and practical engineering applications than CRDM and THM.

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