Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
 ISBN 978-0-367-14328-2

Seismic behavior of temporary retaining wall structures

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ABSTRACT: Temporary retaining walls used for constructing open-cut tunnels, foundation structures, and more are very important for excavation work. Details of these structure vary according to construction cost, purpose, and site conditions.

The period in which this structure is used is often not as long as the term "temporary" suggests. Nowadays, however, the number of structures used for a relatively long time has been increasing as the number of large and/or complex work projects have increased.

In Japan, the designs of such structures generally do not take earthquake forces into consideration. For the aforementioned reasons, we have begun considering the need for seismic designs in temporary retaining walls.

In this paper, we use the finite element analysis method to investigate the behaviors of strut-type temporary earth-retaining walls during earthquakes. A basic analysis model was constructed based on the measurement data at the time of construction, and we then used this analysis model to analyze the behavior of retaining walls during earthquakes.

Based on the analysis results, we evaluated the behaviors of the temporary earth retaining walls during earthquakes.

1 INTRODUCTION

Earth-retaining walls for excavation work are temporary structures and are not used like permanent structures such as cut-and-cover tunnels. Earthquake-resistant designs have therefore not been applied to temporary earth-retaining walls, and there are no clear seismic design methods pertaining to temporary earth-retaining walls, either. However, in the case of large-scale excavation work requiring a long period of time or in the case of the presence of important structures adjacent to excavation sites in urban areas, the influence of earthquakes cannot be ignored.

In Japan, we have experienced not only rare major earthquakes, such as the Hyogo-ken Nanbu Earthquake (1995) and Tohoku Region Pacific Offshore Earthquake (2011), but also frequent small and medium-sized earthquakes, such as the Osaka Hokubu Earthquake (2018). With this background, the necessity of considering the earthquake resistance of temporary earth-retaining walls for the excavation work has also increased, so we researched the seismic design of such walls.

2 STRUCTURES TO BE CONSIDERED

There are many types of temporary earth-retaining walls. Each differs with respect to combinations of earth-retaining wall type and supporting system type. These combinations are decided by the structural characteristics according to the site conditions. Therefore, the structures of such walls change depending on various factors, such as soil characteristics, form of any adjacent structures, and workability. It is not easy to propose a common seismic design method that is applicable to all combinations. We will show not only the concept but also the way of earthquake-resistant design for strut-type (internal support) temporary earth-retaining walls used rather frequently that can be applied to walls with a height of up to more than or equal to a medium excavation depth.

In addition, considering the period of service as a temporary structure and the role of the structure, L1 (Level 1) earthquake ground motion level was used as the seismic action. The L1 earthquake ground motion is one of two levels constituting earthquake level classifications for seismic designs in Japan. L1 is the level of relatively frequent earthquakes, and it is an earthquake scale of roughly 200 to 300 gal.

3 SEISMIC DESIGN METHODS FOR STRUCTURE LOADED WITH EARTH PRESSURE

There are two methods used in the seismic designs of structures upon which force from the ground acts. One is a *seismic deformation method* used in cut-and-cover tunnels and U-shaped retaining walls. The other is based on earthquake ground pressure applied to the design of anti-earth-pressure retaining walls typified by an L-shaped retaining wall (see Table 1). Strut-type temporary earth-retaining walls are designed such that struts transmit forces horizontally. These are not as rigid as cut-and-cover tunnels, though. In the seismic deformation method design, dynamic numerical analysis is performed to obtain ground displacement during an earthquake. This calculated ground displacement is given as an external force to the underground structure modeled through the spring model. As a result, deformation of the underground structure and section force can be calculated.

This method is used in cut-and-cover tunnels under the assumption that the ground and underground structures behave identically. Since this method can be applied on the condition that the ground and structures behave identically, it is an important judgment criterion whether the ground and the temporary earth-retaining wall behave identically.

The seismic design method based on the seismic deformation is adopted from the following three conditions:

1. There is a transmission of responses to the earth-retaining wall on the opposite side via the struts.
2. It is not a structure whose side wall and base plate resist earth pressure from a single side, as do anti-earth-pressure retaining walls.
3. The seismic design is the same method as that for cut-and-cover tunnels.

Table 1. Seismic design method

Step	Seismic deformation method	Seismic earth pressure method	Dynamic analysis
1	Design of temporary structure (normal time)		
2	Calculation of ground deformation (earthquake)	Calculation of seismic earth pressure	Initial stress analysis
3	Calculation of response value of retaining wall (Input of ground deformation (Step 2))	Beam and spring analysis (Input of seismic earth pressure (Step 2))	Dynamic analysis
4	Step 1 + Step 3	-	Step 1 + Step 3

4 STUDY ON SEISMIC DESIGN METHODS FOR STRUT-TYPE TEMPORARY EARTH-RETAINING WALLS

4.1 *Study flow*

In the past there were no cases where the seismic behaviors of temporary earth-retaining walls were measured, so the seismic behaviors of these walls are still unknown. With due consideration for the use of the seismic deformation method as a seismic design method, we conducted dynamic numerical analyses to evaluate the seismic behavior of strut-type temporary earth-retaining walls.

4.2 *Summary of dynamic numerical analysis*

We analyzed two strut-type temporary earth-retaining walls in alternate-layer ground consisting of sandy soil layers and clay layers (see Figure 1). Case 1 is a type of wall with an excavation depth of 8.6 m and case 2 is one with an excavation depth of 21.6 m (a deeply excavated wall). In case 1, the earth-retaining wall is made of rigid steel sheet piles (type IV), and in case 2, a soil cement diaphragm wall is used. The characteristic values of retaining walls and struts are shown in Table 2.

The bending stiffness EI of the earth-retaining wall is about 5 times higher in case 2 than in case 1. The bending stiffness EI of diaphragm walls is equal to the bending stiffness of the inserted steel. The penetration depth of the earth-retaining wall is set to the longer length of the balanced penetration depth in the temporary state. For nonlinear dynamic numerical analysis, we used an analysis program in which the shear strength of the soil can be considered. For the constitutive model of the soil, a multi-spring model combined with a hyperbolic model was used. The struts and the retaining walls were treated as elastic-beam elements.

4.3 *Analysis results of the dynamic numerical analysis*

4.3.1 *Difference of response*

Figure 2 shows the time history of the horizontal displacement at the top of the two earth-retaining walls (the left side and the right side). Cases 1 and 2 have different conditions such as the rigidity of the earth-retaining wall, the number of struts, the excavation size and so on. However, the time history of the horizontal displacement of the top of the earth-retaining wall in cases 1 and 2 are nearly equal.

The difference in horizontal displacement between the left and right sides is also shown in the figure. Although there is a slight response difference, there is hardly any difference in the

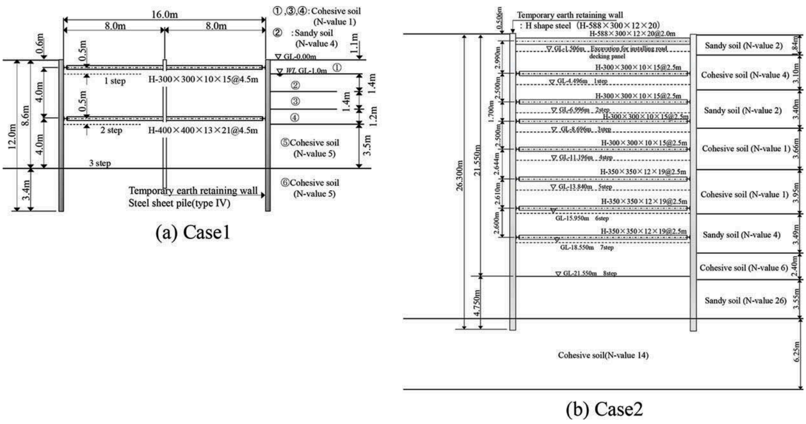


Figure 1. Analysis model

Table 2. Characteristics values

(a) Case1

		Type	Area (m^2/m)	Moment of inertia of area (m^4/m)
Earth-retaining wall		Steel sheet pile (type IV)	2.42×10^{-2}	3.86×10^{-4}
Strut	1st stage	H-shape steel (H-300)	2.63×10^{-3}	4.48×10^{-5}
	2nd stage	H-shape steel (H-400)	4.86×10^{-3}	1.48×10^{-4}

(b) Case2

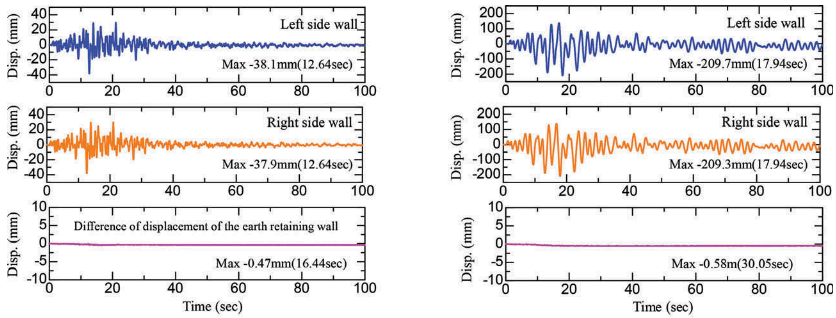
		Type	Area (m^2/m)	Moment of inertia of area (m^4/m)
Earth-retaining wall		H-shape steel (H-588×300)	3.12×10^{-2}	1.90×10^{-3}
Road decking beam		H-shape steel (H-588×300)	9.36×10^{-3}	5.70×10^{-4}
Strut	1~4th stage	H-shape steel (H-300)	4.74×10^{-3}	8.08×10^{-5}
	5~7th stage	H-shape steel (H-350)	6.87×10^{-3}	1.59×10^{-4}

phases of the two time history waves. From this analysis result, it can be considered that the seismic deformation method can be applied as the seismic design method for strut-type temporary earth-retaining walls.

4.3.2 *Displacement, bending moment and shear stress of earth-retaining walls*

As shown in 4.3.1, since the difference in the responses between the right and left sides is small, we discuss here the response value on the right side for simplicity. The maximum values of the horizontal displacement and the cross-section force on the earth-retaining wall on the right side for each case are shown in Figure 3. In this figure, two deformation modes are described. One is the maximum displacement of the earth-retaining wall on the excavation side (mode 1), the other is the maximum displacement on the back ground side (mode 2).

Horizontal displacement to the excavation side of the earth-retaining wall is assumed to be positive and, regarding the bending moment, the tensile moment at the front side is assumed to be positive. Each value shows the value of the increment during an earthquake (the value at the time of the earthquake minus the value after the final excavation step). As for the horizontal displacement and the bending moment shown in Figure 3, when the maximum displacement occurs on the excavation side (mode 1), the maximum moment occurs near the position of the lowest strut. As a result, the tension on the back ground side of the earth-retaining wall (the negative bending moment) is dominant. When the maximum displacement occurs in the back ground direction (mode 2), the bending moment becomes maximum near the position of the final excavation depth. Tension on the excavation area side of the earth-retaining wall (the positive bending moment) then occurs. As for the vertical distribution of the shear force, in both modes 1 and 2 the shear force became maximum at the position of the lowest strut. The axial force of the lowest struts is 100 kN/m in case 1 and about 400 kN/m in case 2.



(a) Case1 (b) Case2

Figure 2. Time history of horizontal displacement

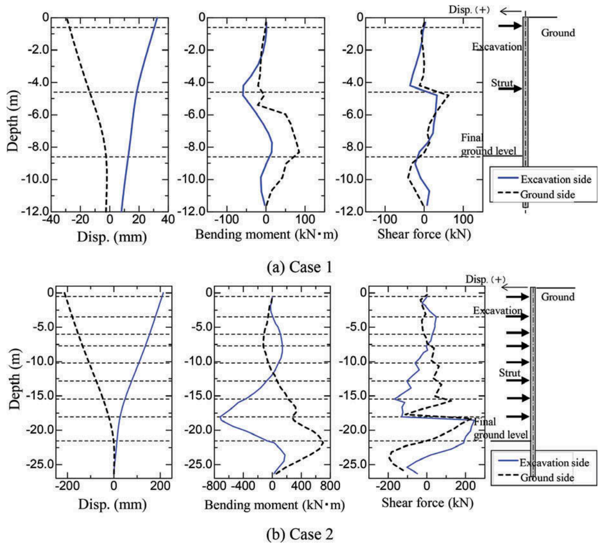


Figure 3. Results of dynamic numerical analysis (Maximum value)

4.4 *Investigation by the seismic deformation method*

For both modes 1 and 2, static analyses by the seismic deformation method are performed. The results are compared with the dynamic numerical analysis shown in 4.3.2. Calculations of the response value by the seismic deformation method were carried out using the both-side model shown in Figure 4. In this model, the earth-retaining wall and the strut, and the strut and the pile supporting it are assumed to be connected according to the pin joint models. Under the seismic deformation method, displacement of the ground is directly given to a structure model. The displacement of the ground can be obtained from the nonlinear dynamic numerical analysis. Figure 5 shows the vertical distribution of the horizontal displacement, the bending moment and the shear force (both of which are shown only in cross-section 1) when the ground displacement is given. In this figure, the horizontal displacement to the excavation side is assumed to be positive and the bending moment causing tension on the excavation side of the wall is assumed to be positive. This figure shows only the increment during an earthquake. As for the horizontal displacement, when the result of the maximum value in the vertical direction obtained from the dynamic analysis is compared with the analysis result by the seismic deformation method, the displacement of the dynamic analysis is about twice that obtained from the seismic deformation method in both case 1 and case 2 (see -o-).

The reason for these results is presumed to be that the ground displacement used for the seismic deformation method is calculated by response analysis of the pseudo-continuous soil layer model. Therefore, the influence of removing the soil (excavation) is not considered in the result of the seismic deformation method. In order to consider the influence of excavation entailing the soil removal, ground response analysis was performed with reduced initial shear modulus G0 of soil (a reduction of about 30% (in case 1) and a reduction of about 40% (in case 2)). Analysis results obtained from the seismic deformation method based on new ground displacement calculated by changing the initial shear modulus are additionally shown in Figure 5 (see - ■ -).

In this study, we also add the force of the strut generated at the time of the earthquake obtained from the result of the dynamic numerical analysis. As a result, the vertical distributions of horizontal displacement and sectional force in both case 1 and case 2 were almost consistent with the results of the dynamic numerical analysis.

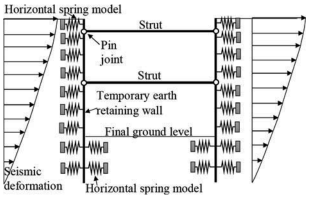


Figure 4. Analysis model

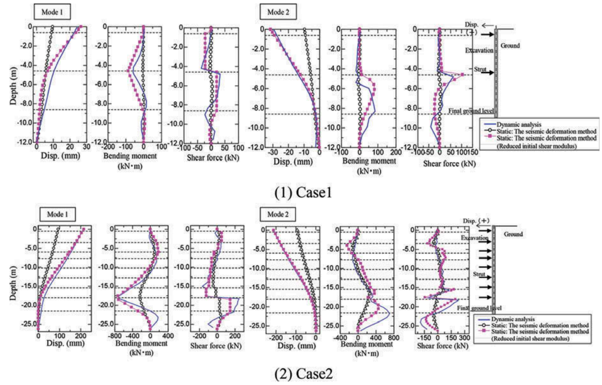


Figure 5. Comparison of result of dynamic analysis and static analysis

5 CONCLUSIONS

Seismic designs for strut-type temporary earth-retaining walls (L1 earthquake) were studied. In this study, we dealt with two types of strut-type retaining walls: a retaining wall composed of steel sheet piles and a retaining wall composed of soil cement diaphragms. From the results, we understood that it is possible to study the seismic deformation method. This method is the same as the method applied to cut-and-cover tunnels constructed after the use of temporary earth-retaining walls. Therefore, it is possible to design both temporary and permanent structures using the same design method. When applying the seismic deformation method, however, it is necessary to consider the structure conditions of strut-type temporary earth-retaining walls, as shown below.

1. Evaluation of ground displacement with consideration for the soil and
2. Consideration of strut forces caused by earthquakes.

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