A Study on the Accuracy of a Static Analysis Method for Cut and Cover Tunnels

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SUMMARY:
In railway seismic design of cut and cover tunnels, the static analytical method called the 'Seismic deformation method', is generally used. This method, however, has a problem in the calculation of the coefficients of the interaction springs and some researcher developed analysis methods that used FEM models. In this study, we consider the accuracy of the static analytical method using an FEM model called the 'Ground response acceleration method'. We conduct analyses using the ground response acceleration method with seismic loads when the relative displacement of the ground obtained by the dynamic analysis reaches a maximum value. We then clarify the influence of the non-linearity of soil and the amplitude of the input motion on the accuracy of the ground response acceleration method by comparing its responses with those obtained using dynamic analyses.

Keywords: cut and cover tunnel, underground structure, FEM analysis, static analytical method

1. INTRODUCTION

In the Japanese railway seismic design code, it is generally preferable to use dynamic analysis to calculate the ground acceleration response of a cut and cover tunnel, but static analysis may also be useful for obtaining this response [Railway Technical Research Institute, 2007]. In most designs of cut and cover railway tunnels, the seismic deformation method, which is the static analysis method using an interaction spring to estimate the influence of soil around the tunnel, is adopted. The coefficients of the interaction springs used in the seismic deformation method were determined based on static loading tests on spread foundations. A linear interaction spring was adopted based on past research [Tateishi, 1992]. This method, however, has the problem that the coefficient of the interaction spring is not always calculated precisely [Muroya et al., 1992].

On the other hand, the static analysis method that used an FEM model was also developed [Tateishi, 1995]. In this method, it is not necessary to calculate the coefficients of the interaction springs by modelling the soil around the tunnel. In the seismic analytical methods using FEM, however, care has to be taken in determining the governing conditions to accurately calculate the response of the tunnel. In this study, we clarify the influence of the non-linearity of the soil and the amplitude of the input motion, on the accuracy of the ground response acceleration method by comparing its responses with those obtained by dynamic analyses.

2. ANALYTICAL METHOD

2.1. Modelling of cut and cover tunnel

The soil-structure model used in this research is shown in Fig. 2.1. This model is constructed based on the Daikai Station of the Kobe Rapid Transit Railway, which the Kobe Earthquake caused to collapse completely. A viscous boundary was assumed at the bottom of the ground model, and isodisplacement boundary conditions were used on both sides of the model. The properties of the ground and tunnel are listed in Tables 2.1 and 2.2. For the law defining the non-linearity of the soil, we used the GHE-S model proposed by Murono et al. [Murono and Nogami, 2006]. We modelled the non-linearity of the structure as shown in Fig. 2.2. We used a trilinear model and determined the folding point of the non-linearity of each column based on the method according to the current Japanese railway design code.

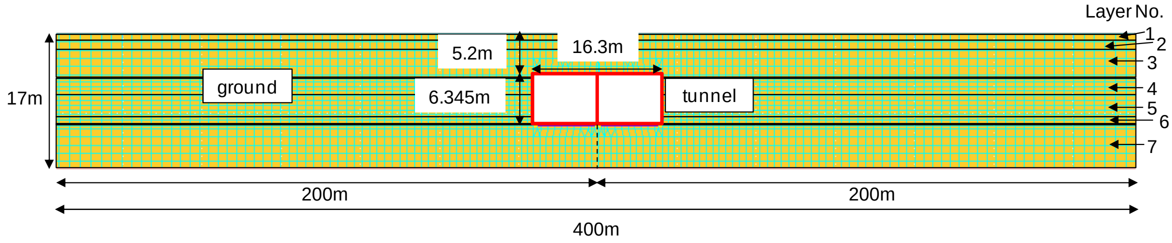


Figure 2.1. Soil-structure model

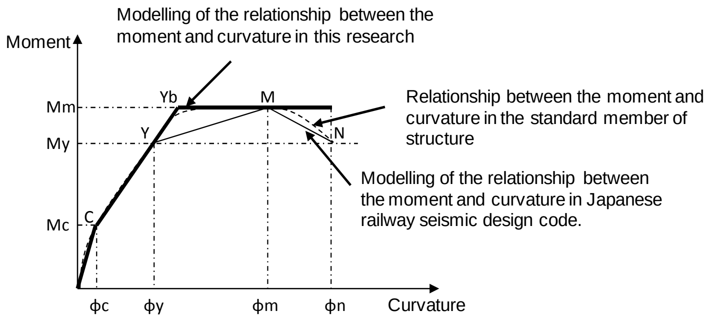


Figure 2.2. Modelling of the non-linearity of the structure

Table 2.1. Properties of the ground model

Layer No.	Type of soil	Thickness (m)	Unit weight (kN/m^3)	Shear velocity (m/s)	Poisson ratio
1	Clay	1.000	16	100	0.49
2	Clay	1.100	16	100	0.49
3	Sand	3.500	18	140	0.49
4	Sand	2.600	18	170	0.49
5	Clay	2.470	16	190	0.49
6	Sand	0.875	18	190	0.49
7	Clay	5.455	16	240	0.49

Table 2.2. Properties of the cut and cover tunnel

Unit weight	24 kN/m^3
Modulus of elasticity	30.7 GN/m^2
Thickness of member	Upper slab : 0.80 m Lower slab : 0.85 m Side wall : 0.70 m (Upper) : 0.85 m (Lower) Centre pillar : 0.40 m * 1.0 m (Interval : 2.5 m)

2.2. Input motion

In this research, we used the earthquake motion observed at Port Island near Daikai Station as the input motion. We investigated the accuracy of the ground response acceleration method in a cross section of the cut and cover tunnel and simulated the input motion as shown in Fig. 2.3 by revising the earthquake motion observed at Port Island in the direction of the cross section of Daikai Station.

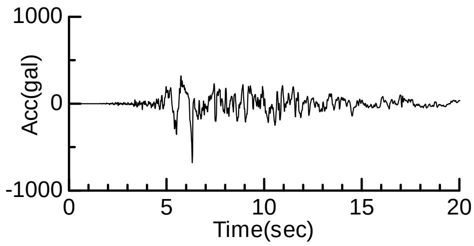


Figure 2.3. Input motion

2.3. Case study

We conducted case studies by altering the method of taking into account the soil non-linearity as shown in Table 2.3. We first conducted the dynamic analysis using the soil-structure model and input motion shown in Figs. 2.1 and 2.3. We then conducted three types of static analyses using the ground response acceleration method. For Cases 1 and 2, we conducted analyses using the seismic loads at the time when the relative displacement of the ground between the depth of the upper and lower slabs obtained by dynamic analysis reached a maximum value. For Case 1, we took into account the non-linearity of soil using the GHE-S model. On the other hand, for Case 2, we modelled the characteristics of soil using an equivalent linear model. Finally, for Case 3, we extracted the maximum shear stress of each layer and determined the seismic loads to give the maximum shear stress as shown in Fig. 2.4.

Table 2.3. Case study

Analytical method	Case No.	Non-linearity of soil	Calculation of seismic loads
Dynamic analysis	-	GHE-S model	Inputting the earthquake motion at the bottom of the ground model
Ground response acceleration method	Case 1	GHE-S model	Inputting the acceleration at the time when the relative displacement of the ground between the depth of upper and lower slabs obtained by the dynamic analysis takes a maximum value
	Case 2	Equivalent linear model	
	Case 3	GHE-S model	Fig. 2.4

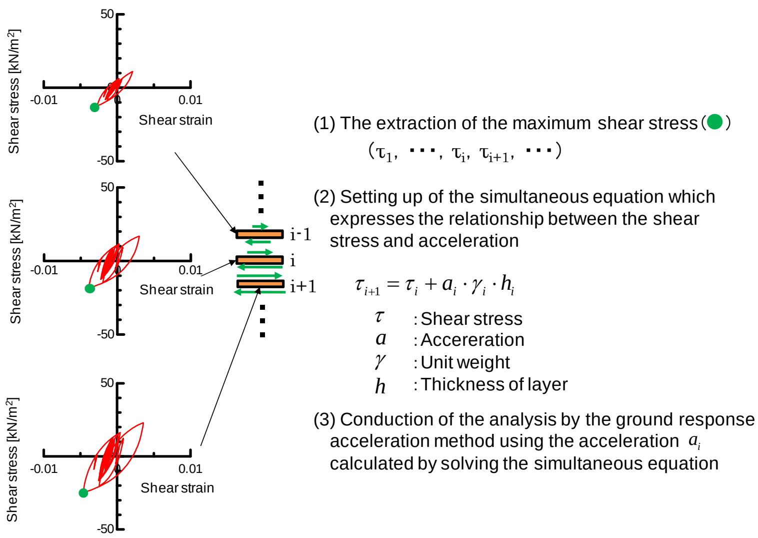
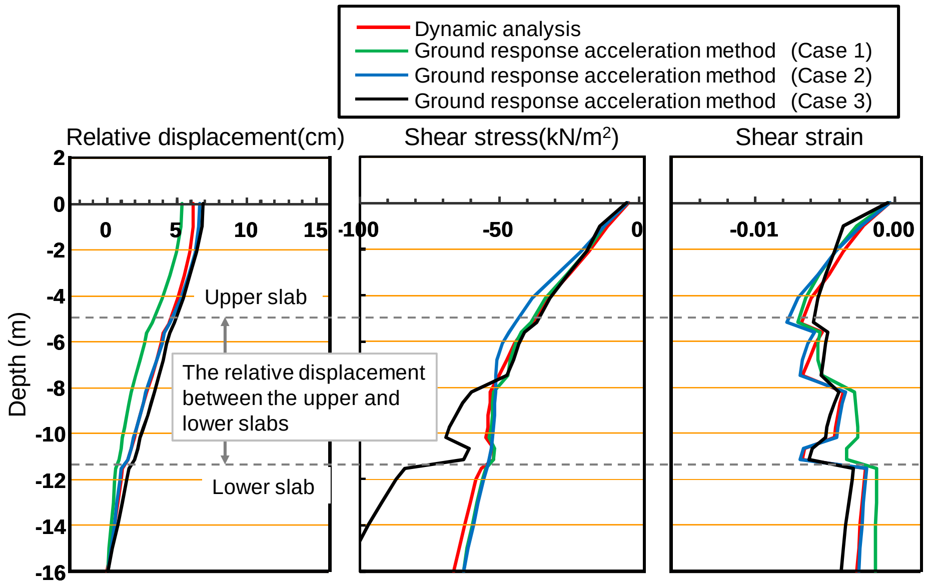


Figure 2.4. Calculation of seismic loads (Case 3)

3. RESPONSE OF THE GROUND

The comparison of snapshots of the relative displacement, shear stress and shear strain of the ground is shown in Fig. 3.1. For the dynamic analysis, we focused on the values at the time when the relative displacement of the ground between the depth of the upper and lower slabs reached a maximum value. For the ground response acceleration method (Case 1, Case 2 and Case 3), the values at the final step are shown in this figure. The comparison of the relative displacement between the depth of the upper and lower slabs for each case is shown in Table 3.1. We can see that the deformation of the tunnel for Case 1 was smaller than for the other cases. This result occurred because the shear strain was underestimated for Case 1, especially at the relatively deep position. The relative displacements and shear strain for Cases 2 and 3 were in good agreement with those for dynamic analysis. On the other hand, the comparison of shear stress showed that the value for Case 3 was larger than for the other cases at a relatively deep position because the seismic loads which give the maximum shear stress were used for Case 3.



(a) Relative displacement (b) Shear stress (c) Shear strain

Figure 3.1. Comparison of the response of the ground

Table 3.1. Comparison of the relative displacement of ground between the depth of upper and lower slabs

Analytical method	Case No.	Relative displacement (cm)
Dynamic analysis	-	3.36
Ground response acceleration method	Case 1	2.63
	Case 2	3.51
	Case 3	3.26

The relationships between the shear stress and shear strain for all cases are compared in Fig. 3.2. For dynamic analysis, the shear stress and shear strain were close to their maximum values around the upper slab, but, around the lower slab, we can see that the relationship between the shear stress and shear strain reached its maximum point and turned back in the opposite direction. The characteristic of wave propagation for dynamic analysis, which was that the earthquake motion propagated from the lower side to the upper side, caused this relationship as shown in Fig. 3.3. For Case 1, on the other hand, the relationship between the shear stress and shear strain moved along the skeleton curve of the GHE-S model and reached the point on the skeleton curve when the maximum relative displacement was obtained for the dynamic analysis. The shear strain around the lower slab for Case 1, therefore, became smaller than for the dynamic analysis. For Cases 2 and 3, the relationship between shear stress and shear strain at the final step agreed well with that for the dynamic analysis. For Case 3, however, the response of the ground may not be in good agreement with that for the dynamic analysis under the other condition. This is because the seismic loads which give the maximum shear stress are used.

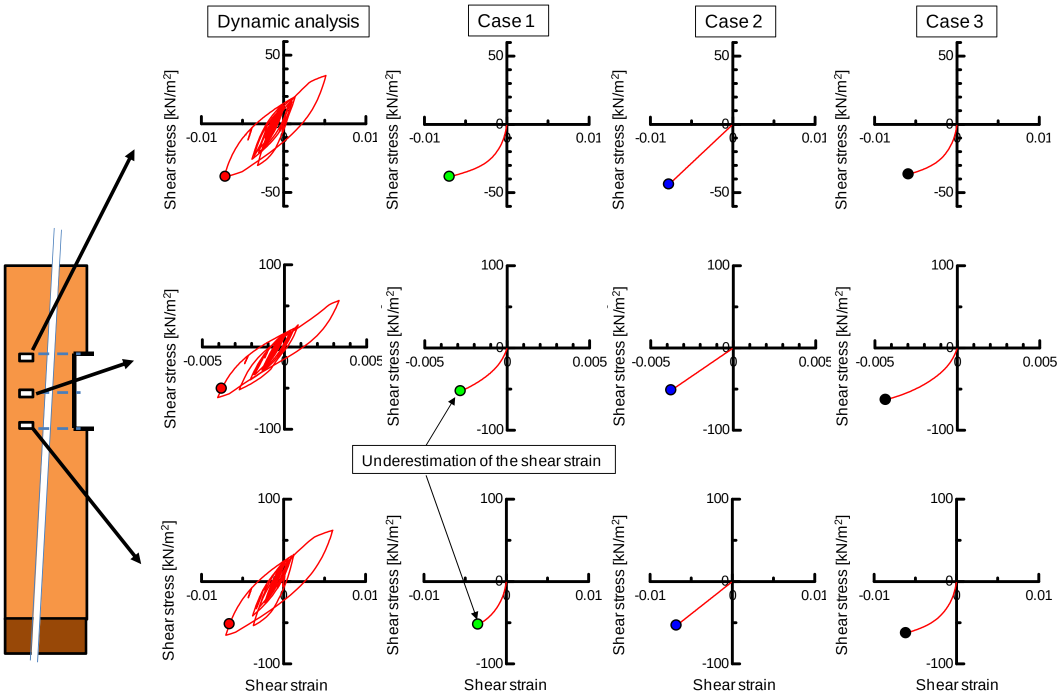


Figure 3.2. Relationship between the shear stress and shear strain

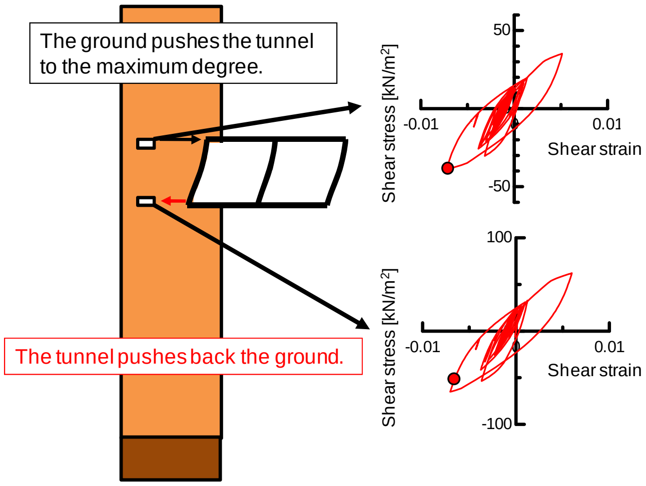


Figure 3.3. Image of the relationship between the shear stress and shear strain for dynamic analysis

4. RESPONSE FOR THE CUT AND COVER TUNNEL

4.1. Deformation of the cut and cover tunnel

The comparison of the deformation of the cut and cover tunnel for all cases is shown in Fig. 4.1. The relative displacements of the centre pillars for all cases are compared in Table 4.1. We can see that the relative displacement for Case 1 was smaller than that for the dynamic analysis. As shown in Section 3, this result occurs because the shear strain was underestimated. For Case 2, on the other hand, the displacement was larger than that for the dynamic analysis. This result indicates that the underestimation of the shear modulus of the soil by modelling its characteristics using the equivalent linear model caused the excessive deformation of tunnel. Finally, for Case 3, the deformation of the tunnel is in good agreement with that for the dynamic analysis. Therefore, the ground response acceleration method conducted using the seismic loads determined on the basis of the maximum shear stress of each layer is applicable to the estimation of the response for the cut and cover tunnel.

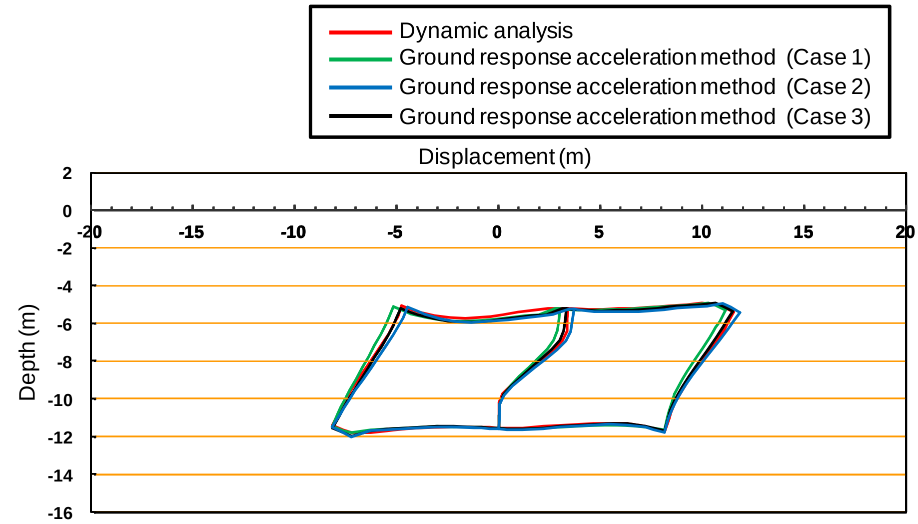


Figure 4.1. Comparison of the deformation of the cut and cover tunnel(Increase of deformation by earthquake motion is magnified 100 times)

Table 4.1. Comparison of the relative displacement of the centre pillar

Analytical method	Case No.	Relative displacement (cm)
Dynamic analysis	-	3.41
Ground response acceleration method	Case 1	3.00
	Case 2	3.71
	Case 3	3.33

4.2. Sectional force for the cut and cover tunnel

The bending moment and shearing force of the lower slab are compared in Figs. 4.2 and 4.3. In comparison with the results for the dynamic analysis, the bending moments of some parts of the members for Case 1 are underestimated. This result indicates that the accuracy of the evaluation of the shear strain of soils using the ground response acceleration method also affects the sectional forces for the cut and cover tunnel.

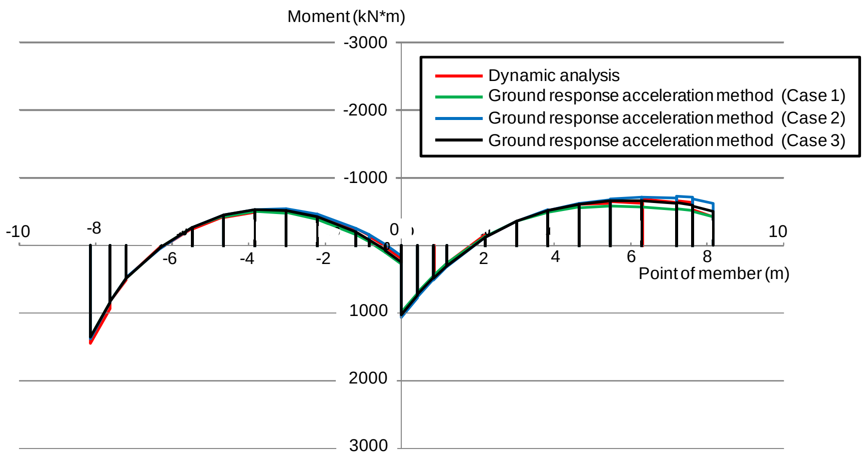


Figure 4.2. Comparison of the bending moment of the lower slab

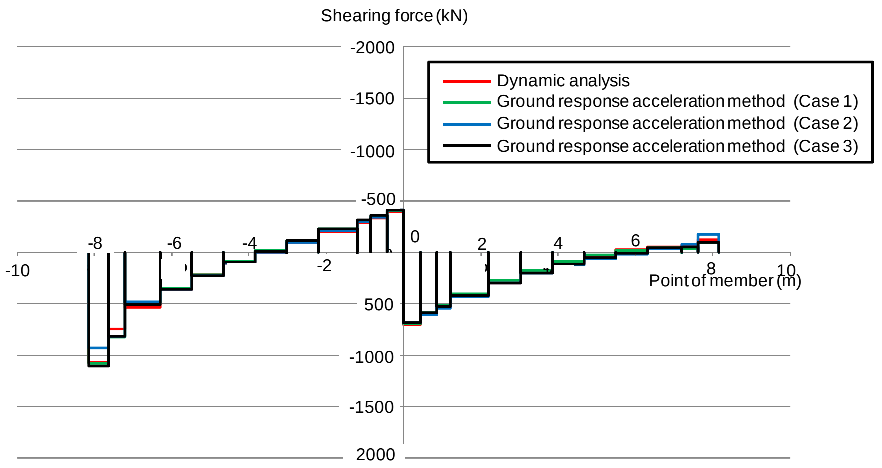


Figure 4.3. Comparison of the shearing force of the lower slab

5. INFLUENCE OF THE AMPLITUDE OF INPUT MOTION ON THE ACCURACY OF THE ANALYSIS OF THE GROUND RESPONSE ACCELERATION METHOD

5.1. Analytical method

As shown in Section 4, the response for the cut and cover tunnel in Case 1 became smaller than that for the dynamic analysis because of the underestimation of the shear strain of the soil around the lower slab of the tunnel. On the other hand, it is clear that the response of the tunnel was calculated accurately using the ground response acceleration method for Cases 2 or 3. The precision for calculating the response of the tunnel, however, was affected by some conditions, such as the amplitude of input motion, ground properties and the height of tunnel. In this study, we clarify the influence of the amplitude of input motion on the accuracy of the ground response acceleration method by adjusting the maximum acceleration of ground motion to six levels; 400 gal, 500 gal, 600 gal, 680 gal, 750 gal, and 850 gal. The maximum input acceleration in Fig. 2.3 is 680 gal.

5.2. Results

The comparison of the relative displacements for cut and cover tunnels and those of the ground between the depth of the upper and lower slabs is shown in Table 5.1 and Fig. 5.1. The evaluation of shear strain for Case 1 is not particularly influenced by the turn of the hysteresis loop in the case where the maximum acceleration of input motion is relatively small as shown in Fig. 5.2. Therefore, the smaller the maximum acceleration of input motion becomes, the smaller the difference between the relative displacement obtained by the dynamic analysis and that obtained by Case 1.

Table 5.1. Comparison of the relative displacement of the ground and the tunnel

		Ground between the depth of upper and lower slabs				Tunnel (Centre pillar)			
		Dynamic analysis	Ground response accleration method			Dynamic analysis	Ground response accleration method		
			Case 1	Case 2	Case 3		Case 1	Case 2	Case 3
400gal	Relative displacement (cm)	1.22	1.31	1.29	1.44	1.38	1.47	1.47	1.57
	Ratio to dynamic analysis		1.07	1.06	1.18		1.07	1.07	1.14
500gal	Relative displacement (cm)	1.78	1.61	1.83	2.06	1.92	1.84	2.04	2.15
	Ratio to dynamic analysis		0.90	1.03	1.16		0.96	1.06	1.12
600gal	Relative displacement (cm)	2.58	2.15	2.66	2.72	2.68	2.44	2.89	2.79
	Ratio to dynamic analysis		0.83	1.03	1.05		0.91	1.08	1.04
680gal (Wave shown in Fig.2.3)	Relative displacement (cm)	3.36	2.63	3.51	3.26	3.41	3.00	3.71	3.33
	Ratio to dynamic analysis		0.78	1.04	0.97		0.88	1.09	0.98
750gal	Relative displacement (cm)	4.05	2.81	4.20	3.70	3.93	3.22	4.31	3.73
	Ratio to dynamic analysis		0.69	1.04	0.91		0.82	1.10	0.95
850gal	Relative displacement (cm)	4.90	3.29	5.14	4.31	4.55	3.70	5.18	4.36
	Ratio to dynamic analysis		0.67	1.05	0.88		0.81	1.14	0.96

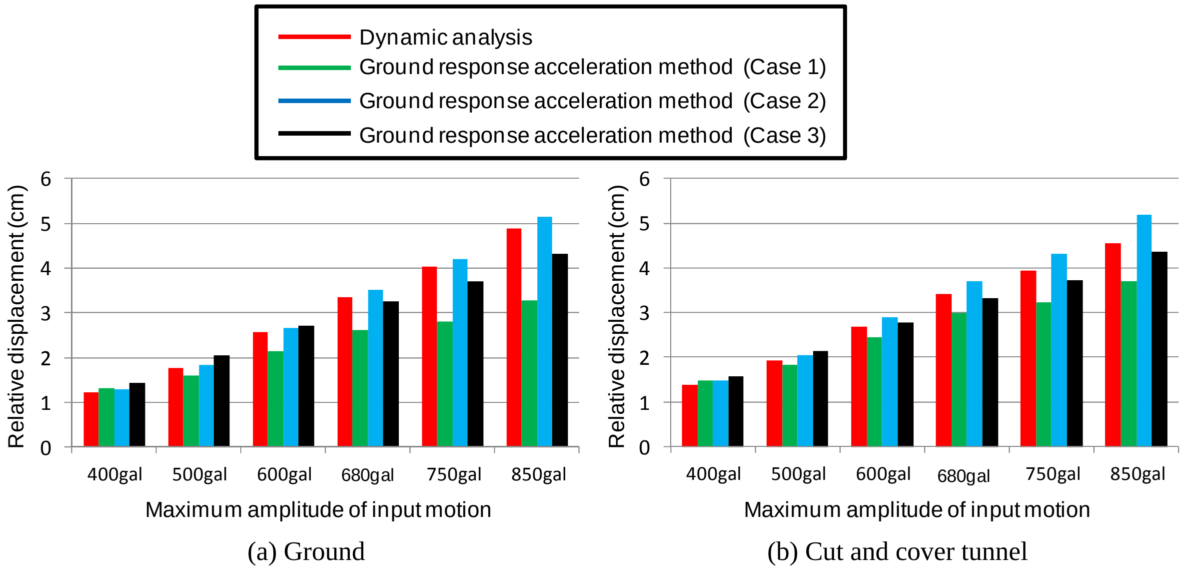


Figure 5.1. Relationship between the relative displacement and amplitude of input motion

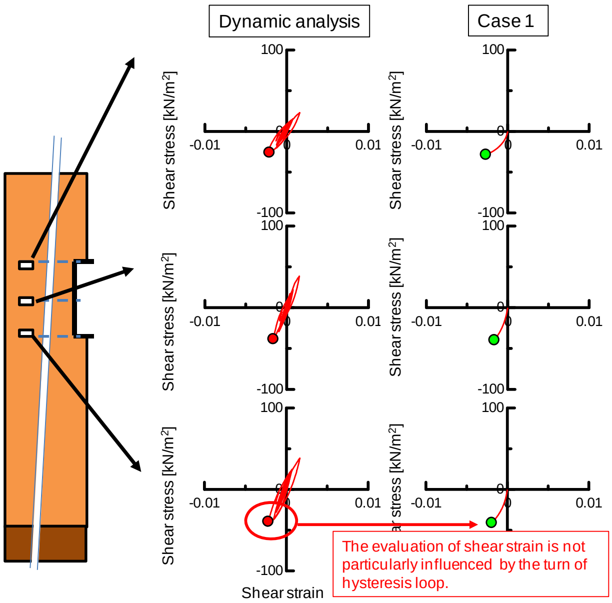


Figure 5.2 Relationship between the shear stress and shear strain for Case 1 (Maximum acceleration of input motion: 400 gal)

For Case 2, the deformation of the cut and cover tunnel was overestimated by about 10 percent without regard to the amplitude of the input motion. This overestimation occurred because the shearing rigidity of the soil evaluated using the equivalent linear model was smaller than that evaluated using the GHE-S model and the tunnel deformed easily because of the relatively small shear modulus of supporting soils around the tunnel. However, the deformation of the tunnel was over estimated by about 10 percent at most, therefore, the ground response acceleration method using the equivalent linear model is useful in seismic design.

Finally, as the maximum acceleration of input motion became small, the relative displacement obtained for Case 3 became larger than that obtained by the dynamic analysis. The difference between the two relative displacements, however, was small, as shown in Fig. 5.1. The larger the maximum acceleration of input motion became, on the other hand, the smaller the displacement calculated by Case 3 became in comparison with that obtained by dynamic analysis. Figure 5.3 compares the relationships between the shear stress and shear strain for Case 3 and the dynamic analysis. The maximum input acceleration in Fig. 5.3 was 850 gal. We can see that the point at which the shear strain was at a maximum, was located opposite to the point where the maximum relative displacement was obtained. In addition, the hysteresis loop in the dynamic analysis returned in the opposite direction without reaching the skeleton curve just before the maximum relative displacement was obtained. For Case 3, on the other hand, the relationship between shear stress and shear strain moved along the skeleton curve. This problem rarely occurs because the maximum point of relative displacement is generally located near the maximum point of shear strain. When applying the ground response acceleration method as shown in Case 3, however, we have to take into account the characteristics of the hysteresis loop.

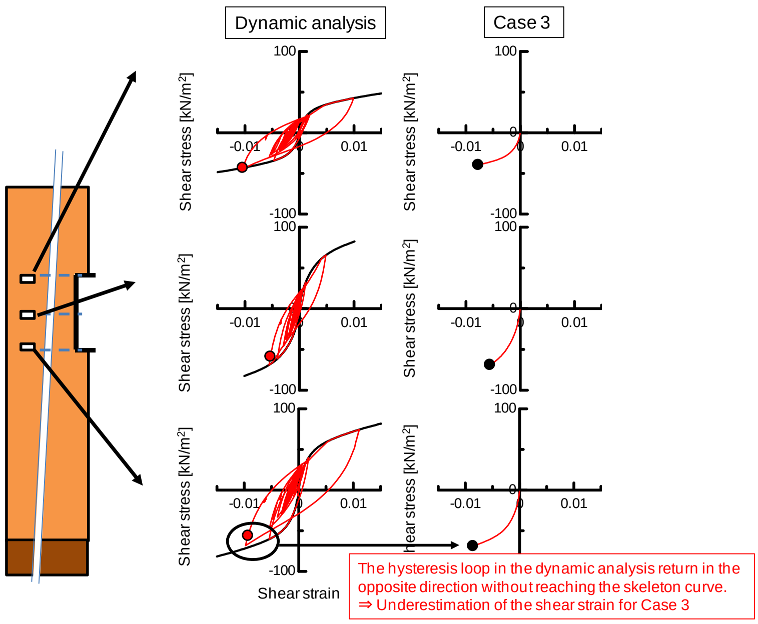


Figure 5.3 Relationship between the shear stress and shear strain for Case 3 (Maximum acceleration of input motion: 850 gal)

6. CONCLUSIONS

In this study, we examined the effect of the non-linearity of soil and the amplitude of input motion, on the accuracy of the ground response acceleration method, by comparing the responses calculated with those obtained using dynamic analyses. The results were as follows:

1) When applying the ground response acceleration method taking into account the non-linearity of soil, and using the seismic loads when the relative displacement of the ground between the depth of upper and lower slabs reached a maximum value, the response for the ground response acceleration method became smaller than that for the dynamic analysis, because the shear strain of the ground was underestimated. This method must be used carefully if the input motion has a large amplitude.
2) When applying the ground response acceleration method, using the equivalent linear model and the seismic loads when the relative displacement of the ground between the depth of upper and lower slabs reached a maximum value, the deformation of the tunnel calculated by the ground response acceleration method became larger than that calculated by dynamic analysis, because the support by soils around the tunnel was underestimated. However, the deformation of the tunnel was over estimated by about 10 percent at most, therefore, the ground response acceleration method using the equivalent linear model is useful in seismic design.
3) When applying the ground response acceleration method using the seismic loads to give the maximum shear stress of each layer, the deformation of the tunnel is in good agreement with that for the dynamic analysis. The larger the maximum acceleration of input motion became, however, the smaller the displacement calculated by Case 3 compared with that obtained by dynamic analysis. Therefore, we need to fully understand the characteristics of the hysteresis loop.

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