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Seismic stability of reinforced soil structure constructed after the mid Niigata prefecture earthquake

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ABSTRACT: The mid Niigata prefecture earthquake in 2004 damaged a number of structures including embankments, earth slopes and retaining walls. This paper describes numerical techniques to evaluate the performance of structures constructed before and after the mid Niigata prefecture earthquake. Deformation analysis was conducted by the Newmark's sliding block analysis that implements the ground water level estimated by the seepage analysis and the response acceleration of the structure subjected to the earthquake by the finite element analysis. From the results of the current numerical analysis, the instillation of the reinforcement can increase the stiffness of the reinforced soil, resulting into the decrease of the deformation at the crest of the structure. The numerical analysis in this study revealed that the performance of the reinforced structure constructed after the earthquake significantly improved as compared to that of the structure constructed before the earthquake.

1 INTRODUCTION

1.1 *The mid Niigata prefecture earthquake*

The mid Niigata prefecture earthquake of magnitude 6.8 on Richter scale occurred Japan on October 23, 2004. The epicenter was lat. 37° 17′N. and 138°52′ E. About five thousand people were injured in this earthquake. The damage caused by this earthquake amounts to three trillion yen. The feature of this earthquake is strong aftershock in which the maximum magnitude exhibited 6.5. A number of structures including embankments, earth slopes and retaining walls were severely damaged. Among a large number of damaged earth slopes, this paper is focused one collapsed earth slope for railway. Moreover the reconstruction of the collapsed earth slope for railway was presented. The numerical analyses were conducted to evaluate the seismic stability of the collapsed earth slope and reconstructed retaining wall.

1.2 *Collapsed earth slope*

An earth slope supporting both up and down railway tracks collapsed on a length of 65 m and a height of 4–12 m as shown in Figures 1 and 2 (Tateyama & Kato 2005, Morishima, Saruya & Aizawa 2005). The total amount of collapsed soil volume was estimated at 13,000 m^3. The collapsed earth slope was located at the upper part of Shinano river terrace. The collapsed earth slope was located at the eroded valley walls by the Shinano River with the tip of pond fed by the Ishida River following into the Shinano River. The geological feature is that a foundation is medium-grained sandstone; a sedimentary layer on the foundation is

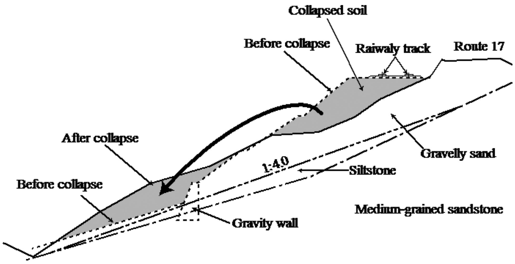

Figure 1. Collapsed earth slope at the Jouetsu-line.

Figure 2. Collapsed earth slope at the Jouetsu-line.

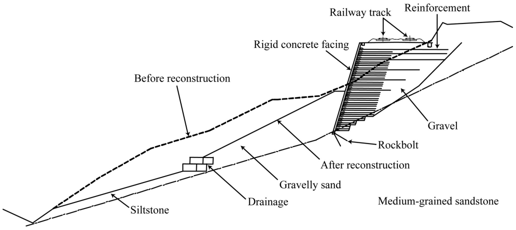

Figure 3. Schematic figure of reconstructed geosynthetic-reinforced soil retaining wall (GRS-RW) with a full height rigid facing.

siltstone and the backfill of collapsed earth slope is gravelly sand.

1.3 *Reconstructed retaining wall*

In the planning of the reconstruction of collapsed earth slope, the reconstruction using the same amount of collapsed backfill with the stable inclination of earth slope was thought to be practically difficult based on the current design code. It was important for the reconstruction that the small amount of backfill soil should be used, the permanent structure was preferable and the seismic stability should be higher than that of the collapsed earth slope. As a result, the geosynthetic-reinforced soil retaining wall (GRS-RW) with a full-height reinforced concrete facing was adopted as an alternative structure of the collapsed earth slope. For the GRS-RW with full-height rigid facing, it is very effective to use a rigid facing and to connect the reinforcement layers to the back of the facing to increase the seismic stability of reinforced soil RWs, as validated by high seismic performance of a number of reinforced soil RWs of this type during recent severe earthquakes, including the 1995 Hyogoken Nambu Earthquake (Tatsuoka et al. 1996). The GRS-RW with full-height rigid facing will be hereafter referred to as GRS-RW.

Figure 3 shows the schematic figure of reconstructed GRS-RW. For the reconstruction, the collapsed soil was excavated up to the surface of the siltstone. After the excavation, the rock bolts were installed into the siltstone to reinforce the foundation of the rigid facing of the GRS-RW. The backfill soil of the GRS-RW was constructed until the height of 13 m with the reinforcement installing at the vertical spacing of 30 cm. The amounts of used backfill soil and concrete for the facing of the GRS-RW for the reconstruction were respectively 4600 m^3 and 300 m^3. Figure 4 shows the reconstructed GRS-RW.

Figure 4. Reconstructed GRS-RW with full height rigid facing.

2 NEWMARK'S SLIDING BLOCK ANALYSIS

In this study, Newmark's sliding block analysis (Newmark 1965) was adopted for the seismic deformation analysis. It is a simplified procedure employed in the design code of railway structures in Japan (RTRI 2007), in which the seismic deformation of earth slopes or GRS retaining walls subjected to a strong ground motion can be calculated by integrating the equation of rotational motion of a soil mass contained within the critical circular slip surface by assuming the failure mass as a rotational rigid block. The equation of rotational motion is solved for the rotation caused by the difference between the driving and resisting moments. The critical slip surface is determined by the conventional modified Fellenius method (Fellenius 1927) using a specific acceleration or seismic coefficient to yield a safety factor of 1.0. Hereafter, this acceleration and seismic coefficient will be referred to as the yield acceleration and yield seismic coefficient, respectively. Newmark's sliding block analysis will be hereafter referred to as Newmark analysis. Refer to Shinoda et al. (2006) for an application of the Newmark analysis of earth and GRS slopes.

The seismic stability analysis is conducted with the conventional modified Fellenius method to determine the center and radius of the critical circular slip surface and yield acceleration. The safety factor in the above seismic stability analysis can be obtained from the following equation:

$$FS = \frac{M_r}{M_d} = \frac{M_{rw} + M_{rc} + M_{rt} - k_h M_{rk}}{M_{dw} + k_h M_{dk}} \tag{1}$$

where FS is the safety factor; k_h, seismic coefficient; M_r, overall resisting moment; M_d, overall driving moment; M_{rw}, resisting moment due to the self-weight of soil; M_{rc}, resisting moment due to soil cohesion; M_{rt}, resisting moment due to the design strength of reinforcement; M_{rk}, decrease in the resisting moment per unit seismic coefficient due to the self-weight of soil subjected to a seismic inertia force; M_{dw}, driving moment due to the self-weight of soil; and M_{dk}, driving moment per unit seismic coefficient due to the seismic inertia force. By substituting $FS = 1.0$ and arranging Equation 1, the yield seismic coefficient is obtained as follows:

$$k_y = \frac{M_{rw} + M_{rc} + M_{rt} - M_{dw}}{M_{dk} + M_{rk}} \tag{2}$$

Subsequently, after selecting the design ground motion, the seismic stability analysis is conducted by using the above-determined center and radius of the critical slip surface. The seismic coefficient is updated as follows:

$$k_h(t) = \frac{A(t)}{g} \tag{3}$$

where $A(t)$ is the acceleration time history, and g is the gravitational acceleration. The input ground motion was directly used for the standard Newmark analysis without considering the response of a structure as the above acceleration time history.

The above seismic stability analysis is performed up to the end of the acceleration time history. During the seismic stability analysis, the difference between the overall driving and resisting moments is calculated, and the equation of rotational motion is obtained as follows:

$$J\ddot{\theta}(t) = M_d(t) - M_r(t) = M_{dw} + k_h M_{dk} - M_{rw} + k_h M_{rk} - M_{rc} - M_{rt} \tag{4}$$

where θ is the rotational angle of the soil mass and J is the moment of inertia expressed as follows:

$$J = \Sigma\left(J_{g,i} + \frac{1}{g} \cdot R_{g,i}^{\;2} \cdot W_i\right) \tag{5}$$

where $J_{g,i}$ is the polar moment of inertia of the i-th slice and $R_{g,i}$ is the distance between the center of the slice and that of the critical circular slip surface of the i-th slice. The angular acceleration, angular velocity, and rotation of the soil mass are obtained as follows:

$$\ddot{\theta}_{t+\Delta t} = \frac{1}{J}\Delta M_{t+\Delta t} \tag{6}$$

$$\dot{\theta}_{t+\Delta t} = \dot{\theta}_t + \frac{1}{2} \cdot \left(\ddot{\theta}_t + \ddot{\theta}_{t+\Delta t}\right) \cdot \Delta t \tag{7}$$

$$\theta_{t+\Delta t} = \theta_t + \dot{\theta}_t \cdot \Delta t + \frac{1}{6} \cdot \left(2 \cdot \ddot{\theta}_t + \ddot{\theta}_{t+\Delta t}\right) \cdot \Delta t^2 \tag{8}$$

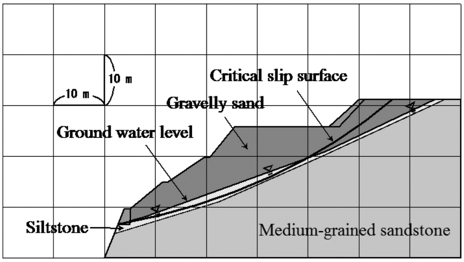

Figure 5. Analytical model for the current Newmark analysis.

The accumulated rotation of the soil mass is computed using Equation 8 only when the angular velocity is positive. Finally, the seismic deformation is obtained as follows:

$$d_t = R \cdot \theta_t \tag{9}$$

In this paper, the seismic deformation is defined as a rotational displacement along the critical slip surface of the failure mass according to the RTRI design code.

For the above standard Newmark analysis, the input ground motion was directly used without considering the response of a structure. However, when the height or stiffness of a structure affects the response, the numerical result by the Newmark analysis using the input ground motion may cause an impermissible error. To evaluate the seismic stability of the collapsed earth slope and reconstructed GRS-RW accurately, the response acceleration obtained from the dynamic analysis was used for the current Newmark analysis. Additionally, the ground water level was obtained from the nonstationary seepage analysis. Refer to Matsumaru et al. (2007) for detailed explanation of seepage and dynamic analyses.

3 NUMERICAL RESULT

Figures 5 and 6 show the analytical model of collapsed earth slope and reconstructed GRS-RW used for the current Newmark analysis. From the site observation after earthquake, a critical slip surface of the collapsed earth slope was assumed as shown in Figure 5. For comparison, the same critical slip surface was adopted in the calculation of the reconstructed GRS-RW. As mentioned above, the ground water lever was set over the layer of the siltstone from the result of the seepage analysis. Table 1 shows the soil properties used for the current Newmark analysis, which were obtained from laboratory tests. Two type of cohesion of the gravel at the peak and residual were used for the current analysis.

Tables 2 and 3 show the safety factors, yield accelerations and displacements obtained from the stability

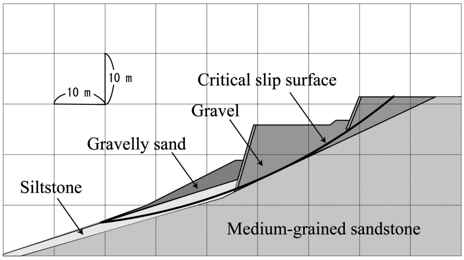

Figure 6. Analytical model for the current Newmark analysis.

Table 1. Soil properties used for the Newmark analysis.

	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (degrees)
Siltstone	17.9	0.67	33.6
Gravelly sand	17.9	3.67	33.6
Gravel	19.8	81.7 (0.0)	47.1

Table 2. Result of collapsed earth slope.

Safety factor	Yield acceleration (gal)	Displacement (m)
1.48	0.163	1.42

Table 3. Result of reconstructed GRS-RW.

Safety factor	Yield acceleration (gal)	Displacement (m)
3.69	0.865	0.0

and Newmark analysis for the collapsed earth slope and reconstructed GRS-RW. The safety factor and yield acceleration of the reconstructed GRS-RW were higher than those of the collapsed earth slope. This is possibly due to the use of gravel as the backfill and geosynthetics as the reinforcement. The displacement of the collapsed earth slope obtained from the Newmark analysis was 1.42 m, while the displacement of the reconstructed GRS-RW exhibited zero, resulting into high seismic stability. Figure 7 shows the time history of displacement, angle velocity, angle acceleration and acceleration of the collapsed earth slope in the Newmark analysis. From the start of the earthquake, a large displacement was exhibited. For the reconstructed GRS-RW, because of the zero displacement, such time history could not be obtained.

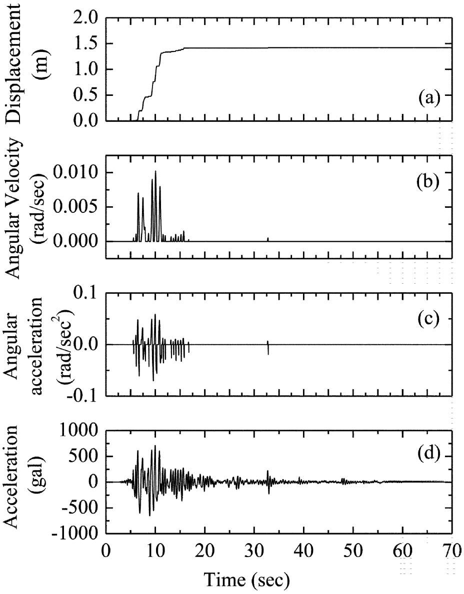

Figure 7. Time history of the collapsed earth slope in the Newmark analysis; (a) displacement, (b) angle velocity, (c) angle acceleration and (d) acceleration.

4 CONCLUSIONS

The mid Niigata prefecture earthquake in 2004 damaged a number of structures including embankments, earth slopes and retaining walls. The paper reports an evaluation of seismic stability of collapsed earth slope and reconstructed geosynthetic-reinforced soil retaining wall (GRS-RW) with full height rigid facing. A deformation analysis method adopted in this paper is Newmark's sliding block analysis based on the results of dynamic and seepage analysis, which can consider the effect of response of the structure.

The numerical results in this paper successfully show a discrepancy between the seismic stability of collapsed earth slope and reconstructed GRS-RW. The seismic stability of the collapsed earth slope was lower than that of the reconstructed GRS-RW. This is due to the use of geosynthetics as reinforcement and gravel as backfill soil for the reconstructed GRS-RW. The GRS-RW with full height rigid facing can be constructed as an important structure having a high seismic stability.

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