A PREPARATION ON PRACTICAL SEISMIC EVALUATION METHOD OF THE EXISTENT SLOPES

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ABSTRACT :

Slope failures on expressways were observed after the Japan Mid Niigata earthquake of 2004 and Noto Hanto earthquake of 2007, and it is an urgent task to evaluate the seismic stability of existing slopes along expressways. However, it is not realistic to check the seismic performance of whole slopes along an expressway by a detailed and complicated method. Thus, it is important to have a practical method to point out relatively weak sections in terms of seismic resistance. In this study, a seismic evaluation method for expressway embankments was proposed as a combination of a conventional pseudo-static approach and the sliding block model. The proposed method was applied to actual sites in Japan, and it showed that the proposed method enables a seismic performance assessment of an expressway system in a simple and easy way.

KEYWORDS: Earthquake, embankment, slope failure, stability assessment, lifeline

1. INTRODUCTION

Even one failure may leads to the malfunction of a system when the component of the system, such as an expressway embankment, is connected in a line. For example, the malfunctions of expressways occurred because of slope failures on the Kanetsu Expressway during the Mid Niigata earthquake of 2004 and on the Noto Expressway during the Noto Hanto earthquake of 2007 (JGS, 2007a; 2007b). As for the seismic evaluation of the expressway embankments, it is important to grasp the location of failures and the degree of the deformation along the whole line (Tokida *et al*, 2008). There have been some studies concerning numerical analyses to calculate the minute seismic sliding displacement of embankments (e.g. Ling *et al*., 1995). However, it is not realistic to carry out these detailed seismic performance evaluations for the whole line. Therefore, even numerical analysis methods are not at the state of the art level from a macro-scopic point view, so a simple and easy way to conduct seismic evaluations to point out relatively weak sections is necessary. In this study, a seismic stability evaluation method to be used for seismic performance evaluation of expressway embankments between interchanges (called "I.C." in the following) is proposed. Moreover, a case study with the proposal method applied to an expressway in Japan is introduced.

2. SEISMIC STABILITY EVALUATION OF EXPRESSWAY EMBANKMENT

2.1. Summary

One of the difficulties of seismic stability evaluation for expressway embankments is that 'it is very long'. In other words, the shape of structures, the ground conditions and earthquake motion conditions vary greatly along expressways. For example, an expressway system can be divided into an I.C. unit as shown in the Fig. 1. Here, an I.C. unit is defined as a section between two I.C.s of an expressway. And the seismic performance of each I.C. unit has to be evaluated to point out the relatively weak section. The outline of the seismic performance assessment for each I.C. unit is summarized in Fig. 2. First of all, each I.C. unit was divided into small components, and some components were categorized as embankment sections. Then, the seismic performance of the embankments was evaluated by a 3-step seismic evaluation method described later. Finally, the order of priority for seismic reinforcement was evaluated, and it enables the planning of the efficient seismic reinforcement.

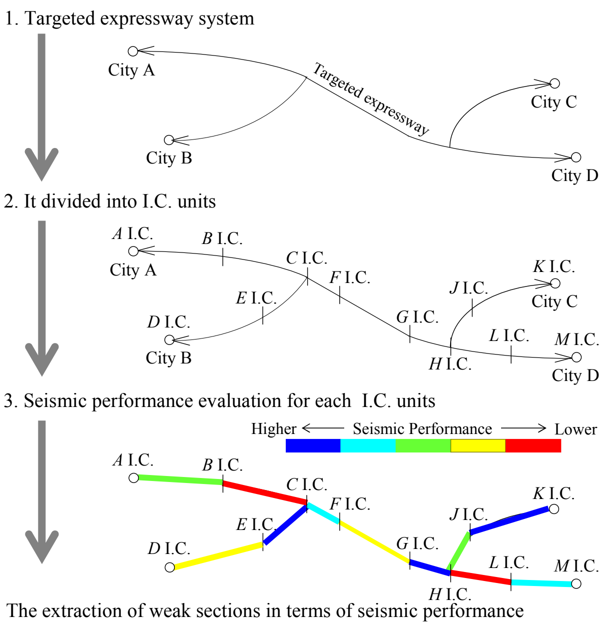

Fig. 1. The outline of the seismic performance assessment of an expressway.

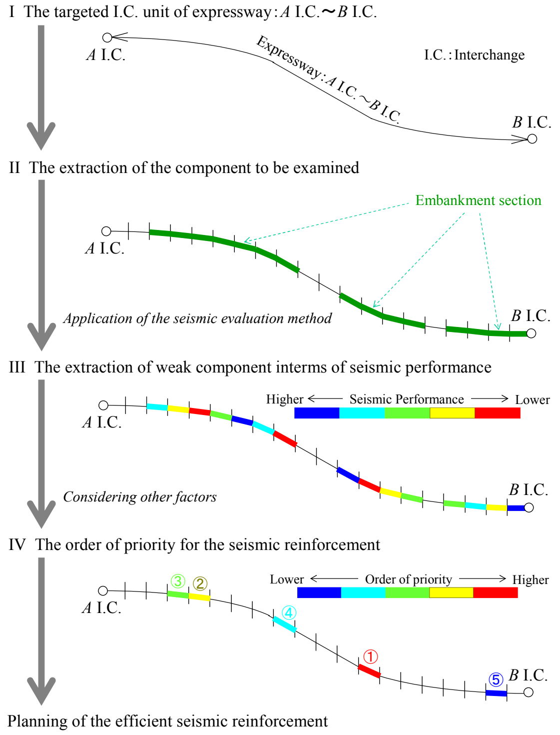

Fig. 2. The outline of the seismic performance assessment for the targeted I.C. unit.

2.2. The Target for the Case Study

The targeted I.C. unit for the case study is shown in Fig. 3. It is a section of the expressway located in a mountainous region in Hiroshima Prefecture. The entire length is 11 km from the SJ I.C. to the SW I.C. The total of embankment section is 4.8 km in this I.C. unit. The seismic stability evaluation for the embankment was carried out for the interval of 100 m, and a total of 48 cross-sections of the embankment were evaluated.

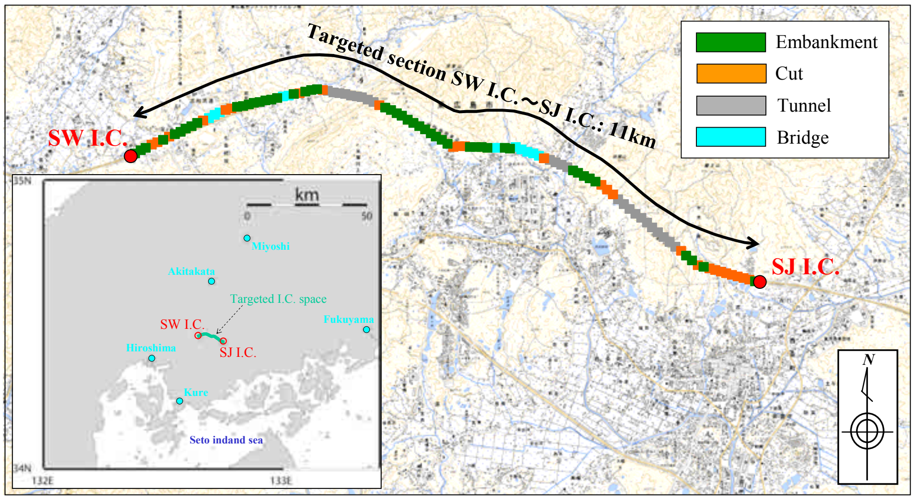

Fig. 3. The targeted I.C. unit for the case study.

2.3. Input Earthquake Motion

One of the difficulties of seismic evaluation for an expressway embankment is that the characteristics of the predicted earthquake motion are different site by site. In this study, the earthquake motions given by an earthquake at some close faults were estimated for each location of the embankments. In other words, the synthesized strong earthquake motions using the statistical green function method (e.g. Kamae *et al*., 1992) were used for every embankment. The details of the strong motion set up are based on Irikura's common method (e.g., Irikura, 2004). However, the validity of the fault parameter set up and the calculation results are beyond the scope of this study, so are not discussed here.

The fault locations around the target are shown in Fig. 4. In this study, these six inland faults were considered as the possible sources of earthquakes. Fig. 4 shows the estimated accelerograms for the scenario earthquakes at the SW I.C.. Though only some examples of the strong earthquake motion was shown here, in this study the strong earthquake motion at all 6 faults for a total of 48 locations were calculated.

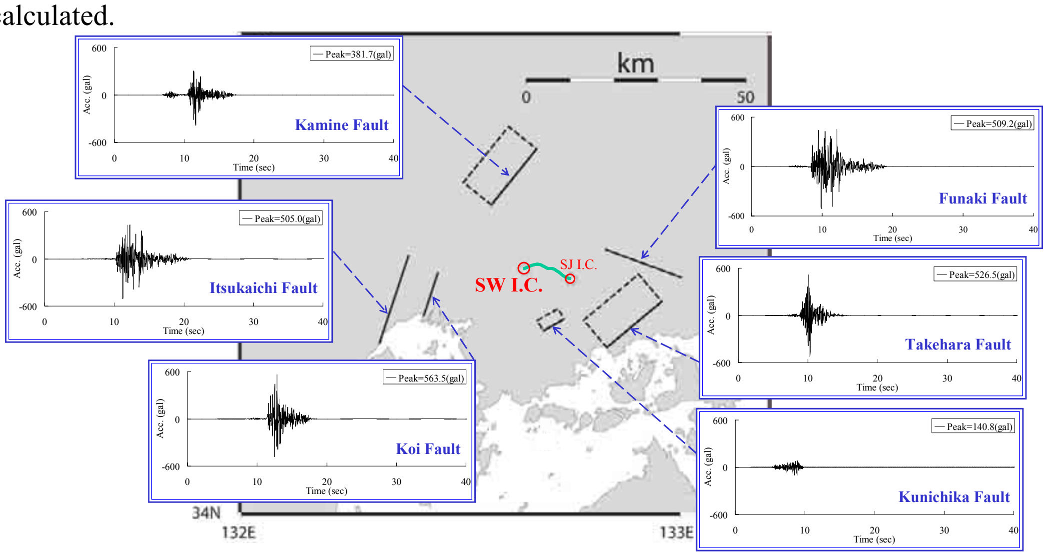

Fig. 4. The estimated accelerogram for scenario earthquakes at the SW I.C..

2.4. Modeling of the Embankment (Step 1)

The vertically heterogeneous model shown in Fig. 5 was made for each site. This model expresses a heterogeneous ground with a horizontal layered system. (e.g. Hata *et al*., 2008a). With the interval of the scale of fluctuation ΔH, the soil strength was homogeneous in the horizontal direction but was heterogeneous in the vertical direction. This model is based on the usual construction process with horizontally layered compaction. There are no in-situ soil test results at the target, and the lightweight dynamic cone penetrometer test (called "PANDA" in the following) (Langton, 1999) was employed as a simple investigating method (Photo 1). An example of the test results is shown in Fig. 6. Next, the ground strength was estimated from the results of PANDA (Apathapaththu *et al*., 2007), where, the degree of saturation S_r= 43% and the wet density ρ_t=1.57g/cm^3 were assumed based on a sample obtained at the site. The heterogeneity of the ground strength was taken into consideration, and the variation coefficients V, which correspond to the degree of the heterogeneity, were supposed as V_c =0.3 in the cohesion c and V_ϕ=0.3 in the internal friction angle ϕ (Hata *et al*., 2005). The correlation coefficient between cohesion c and internal friction angle ϕ was supposed to be -0.5 (Hata *et al*., 2005). Then, the characteristic of the heterogeneity of ground strength was expressed by 2-dimensional normal distribution between cohesion c and the internal friction angle ϕ (e.g. Hata *et al*., 2008a). The scale of fluctuation ΔH for the embankment model was computed using Vanmarcke's method as shown in Fig. 7 (Vanmarcke, 1977).

The embankment was modeled as a SDOF model to evaluate the seismic response. Knowing the natural frequency of embankments is necessary for the modeling, and the outline to calculate the natural frequency of embankments is shown in Fig. 8. Note that the natural frequency of each embankment model was estimated by the equation considering the embankment shape (Hata *et al.*, 2007a; 2007b). Also, knowing the shear wave velocity profile is necessary for the calculation of the natural frequency. Here, the results of PANDA at some site were converted into the data for the N value (called "Converted N value" in the following), and the shear wave velocity V_s was estimated from the converted N value using the empirical relation (e.g., Imai, 1977). The existence of underground water is not considered because groundwater or springwater were not observed in the field investigations.

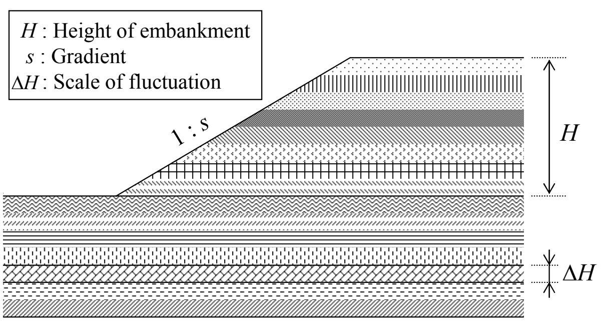

Fig. 5. The heterogeneous ground model.

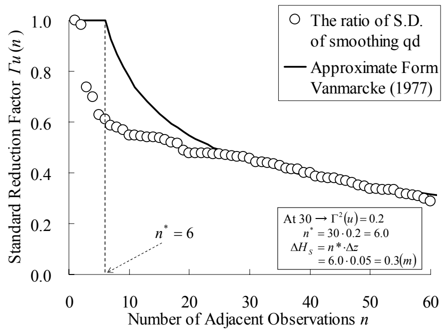

Fig. 7. The calculation of fluctuation height using Vanmarcke's method.

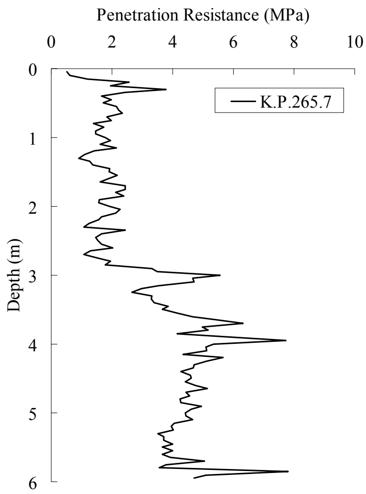

Fig. 6.An example of penetration resistance.

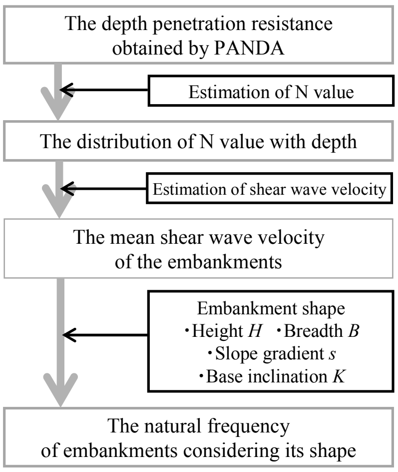

Fig. 8. The estimation of natural frequency of embankments.

Photo 1. The lightweight dynamic cone penetrometer test (PANDA).

2.5. Possibility of Slope Failure (Step 2)

A pseudo-static stability analysis considering the horizontal seismic intensity k_H was employed. To consider the effect of heterogeneity, a Monte Carlo simulation with total iteration number of 1,000 times was used. The pseudo-static stability analysis is based on the Fellenius Method. The horizontal seismic intensity k_H was calculated easily by the following equation with the peak acceleration of the input earthquake motion A_{max} and the acceleration of gravity g. This evaluation usually gives results on the conservative side.

$$k_H = \frac{A_{\max}}{g} \tag{2.1}$$

The safety factor of the critical slip surface was lower than 1.0 means case where that it have the possibility of seismic slope failure. Note, the possibility of seismic slope failure can be judged to be very low for the Kunichika Fault case, since there are no cases in which the safety factor is less than 1.0 with an iteration of 1,000 times.

2.6. Estimation of the Failure Range (Step 3)

A method using the maximum slip surface was adopted for the estimation of the failure range of embankment (Hata *et al*., 2007c). This method is based on the assumption that the sliding failure occurs from the shoulder of the slope to the position of the maximum slip surface. And if the estimated failure range exceeds the allowable limit, the function of the expressway cannot be maintained. Here, a Monte Carlo simulation considering the heterogeneity of the ground strength was employed, and 90% non-excess probability about the horizontal distance at the crest from the shoulder to the maximum sliding circle was defined as the failure range of embankments (Hata *et al*., 2007c). Fig. 9 and Fig. 10 show the failure range of embankment of each component for the Funaki Fault case and Koi Fault case, respectively. The black parts in the Figure show the sections where the failure range of embankments was less than 5.5 m. The white parts in the figures are the parts of cut slopes, tunnels and bridges, where the proposed method cannot be applied. As for the allowable failure range of embankments, though there could be some discussions, in this study, it was assumed as 5.5 m which is equivalent to the width of a driving lane. This means that, even if 1 lane fails, vehicles can use an expressway after an earthquake, since there are total 4 lanes constructed.

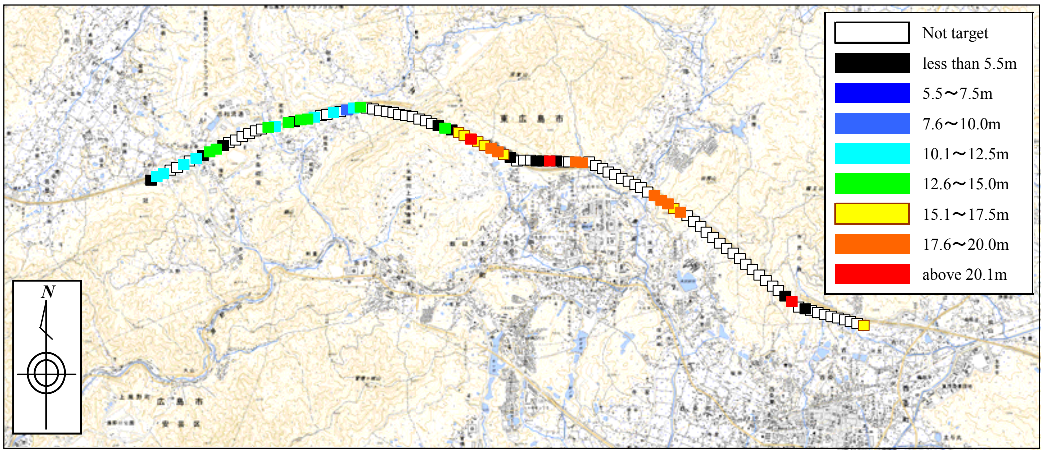

Fig. 9. An example of estimated failure range. (Funaki Fault case)

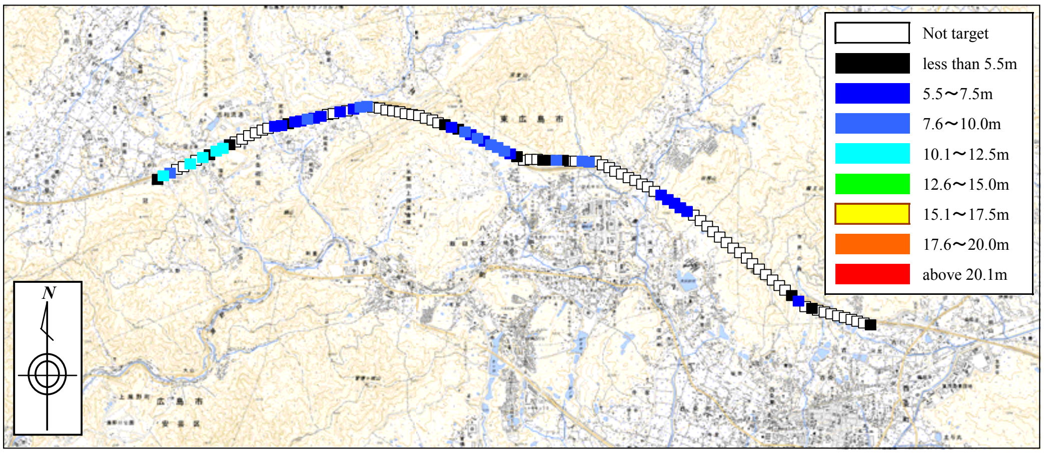

Fig. 10. An example of estimated failure range. (Koi Fault case)

2.7. Estimation of the degree of failures (Step 4)

A Newmark Type Method was adopted for the estimation of the residual displacement of an embankment (Hata *et al*., 2008b). First, the embankment is modeled with a SDOF model. Next, the seismic response of an embankment is calculated. Then, the residual displacement is calculated by using the concept of the Newmark Sliding Block Method (Newmark, 1965). The heterogeneity of the ground strength is considered using the Monte Carlo simulation, and the residual displacement in which standard deviation was added to the mean was defined as the degree of embankment failure

(Hata *et al*., 2008a). Fig. 11 and Fig. 12 show the estimated results for the Funaki Fault case and the Koi Fault case, respectively. The black parts in the figures show the sections where the failure range of embankments was less than 5.5 m, and an evaluation about failure degree is not employed. According to Kokusho (2007), about 0.1 m is reported as an allowable residual displacement for standard use.

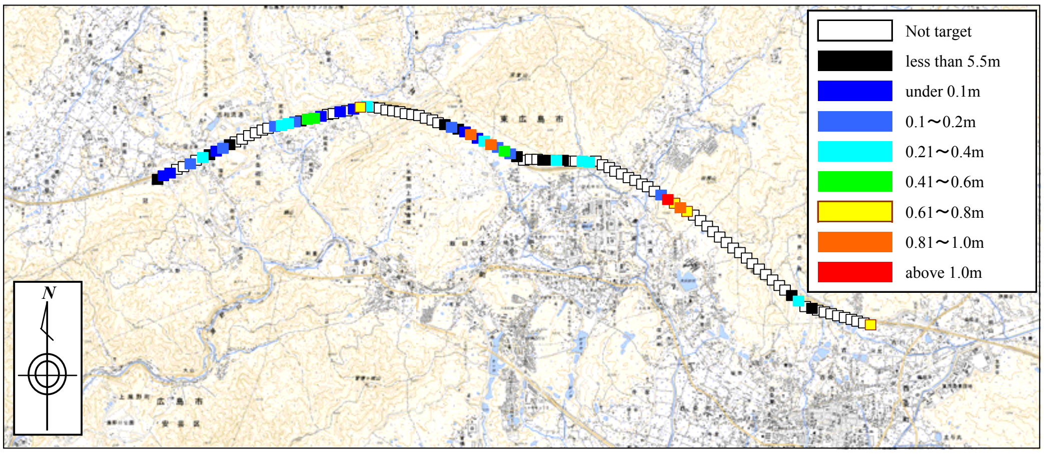

Fig. 11. An example of estimated degree of failure. (Funaki Fault case)

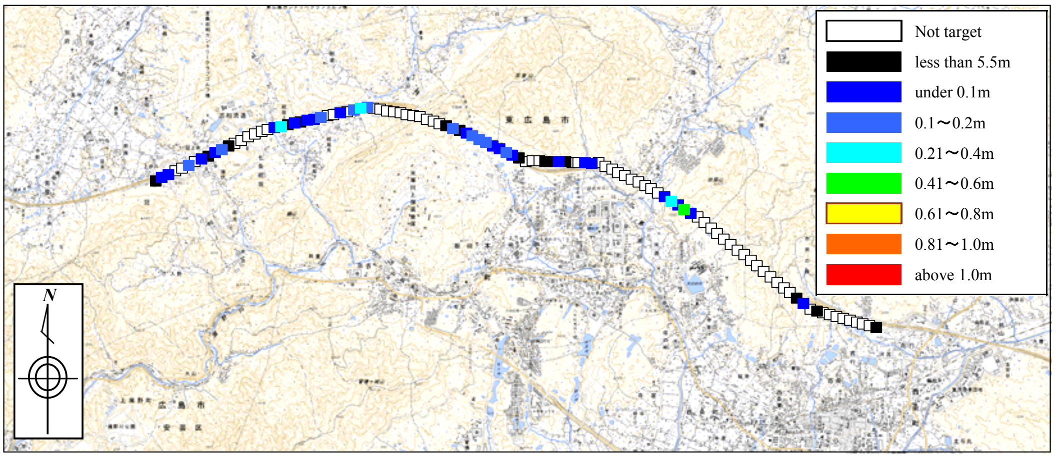

Fig. 12. An example of estimated degree of failure. (Koi Fault case)

3. SUMMARY OF THE PROPOSED SEISMIC PERFORMANCE EVALUATION METHOD

The proposed method consists of 4 steps as shown in Fig. 13. The setup of the input earthquake motion is not the scope of this study, but the proper earthquake motion is supposed to be set up. The fundamental idea of the proposed method is to combine various techniques (for example, the slope stability calculation by the Seismic Coefficient Method and the sliding displacement calculation by the Newmark Method). The method is composed of 3 steps, (1. Measuring the possibility of slope failure, 2. Measuring the range of failure and 3. Measuring the degree of failure).

Withy respect to modeling the ground, the analytical embankment model is based on the limited ground information at the site. It is recommended that engineers estimate the ground strength by using some in-situ tests such as PANDA, because cases in which the ground strengths inside embankments are well-known are rare. The possibility of a slope failure corresponds to a sliding safety factor less than 1.0 should be evaluated using the Seismic Coefficient Method. Although the Fellenius Method with a circular slip was applied in the example, other appropriate methods also can be applied.

A FEM, a DEM, a maximum sliding circle (Hata *et al*., 2007c), and a proposed equation (Hata *et al*., 2007c) can be used for the estimation of the range of embankments failures. When the estimated failure range stays within the permissible range, the function as a lifeline may be maintained.

A FEM, a DEM, the usual Newmark Method (Newmark, 1965), a modified Newmark Method (e.g., Kramer *et al*., 1997), and a seismic response consideration type Newmark Method (Hata *et al*., 2008b) can be used for the estimation of the degree of embankment failure. The residual displacement considering the effect of heterogeneity of the ground strength can be estimated easily without the Monte Carlo simulation if an extra coefficient or reduction factor is used.

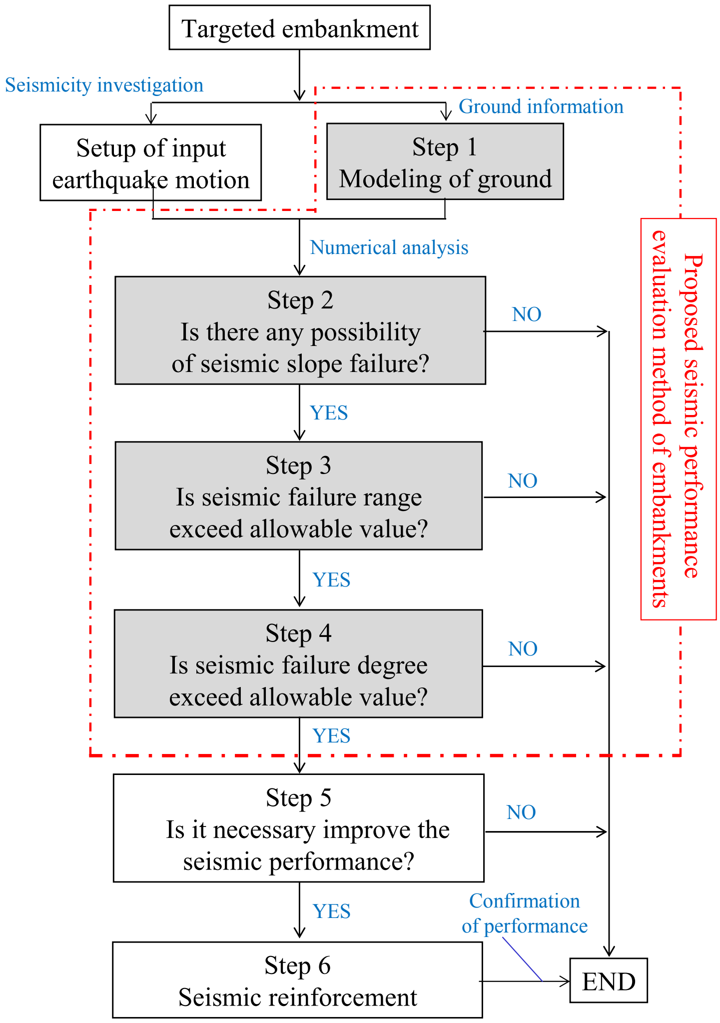

Fig. 13. The flow of the proposed method.

4. CONCLUSIONS

In this study, a seismic performance evaluation method for expressway embankments is proposed. An example of the application of the proposed method to an actual expressway embankment in Japan was introduced. The following conclusions were obtained.

1) In this study, a seismic performance evaluation method for the expressway embankment was proposed. The fundamental idea of the method is to combine various techniques (for example, the slope stability calculation by the Seismic Coefficient Method and sliding displacement calculation by the Newmark Method). The enables us to easily point out the relatively weak sections in terms of seismic performance easily.

2) An example of the application to the actual field was shown.

The proposed method is simple and easy, and suitable for the initial screening purpose. Therefore, the section where the evaluated seismic performance is poor should be checked by more detailed examination as the next step.

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