On-line Response Tests on Case History of Earthquake Induced Deformation of River Dykes Founded on Saturated Sandy Deposits

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ABSTRACT

River dykes and road embankments are frequently damaged during earthquakes. The liquefaction of foundation, the behavior of which is not yet well realized, is considered to be the main cause of the damage. Based on the results of past studies, the foundation of an embankment was divided into three zones to examine the failure modes. One-dimensional on-line earthquake tests, which were conducted by a combination of element tests and computer earthquake response analyses, were performed for such zones of actual river dykes damaged during earthquake. The cumulative horizontal displacement values obtained by the tests were compared with the measured embankment-crest settlement data, which showed that the liquefaction sliding failure under the toe of slope of such an embankment is found to be the most detrimental of all failure modes.

INTRODUCTION

Numerous river dykes and road embankments suffered severe damages in the 1994 Hokkaido-Nanseioki Earthquake and the 1995 Hyogoken-Nanbu Earthquake. Since rivers' dykes extend for long distance, some degree of failure may be allowed unless the rivers overflow. It is, therefore required to establish a method for predicting the magnitudes of deformation of river dykes subjected to earthquakes. The liquefaction of foundation soil is considered to be the main cause of the damage of dykes.

Based on the results of the past studies, the foundation of an embankment was divided into three zones to examine the failure modes. Looking at the failure of embankments of the Shiribeshi-Toshibetsu River struck by the 1994 Hokkaido-Nanseioki Earthquake, the authors performed one-dimensional on-line suede-dynamic response tests which were a combination of element tests and computer earthquake response analyses under the boundary conditions of failure modes in the three zones of each embankment. The crest settlements of the river embankments, measured in the field, and the cumulative horizontal displacements of their foundations obtained by the on-line earthquake response tests were compared to find which failure mode contributes most to such crest settlement.

CLASSIFICATION OF FAILURE MODES

According to the study by Koga and Matsuo with a shaking table (1990), different typical modes of earthquake behavior were observed in three zones; i.e., a zone directly under an embankment, a zone under the toe of slope, and a zone of the horizontal ground. In the horizontal ground, the excess pore-water pressure ratio rose close to 1.0 to cause liquefaction in the ground. In the zone directly under the embankment, although the excess pore-water pressure ratio rose to less than 0.6, residual deformations in both the vertical and horizontal directions were built up. In the zone under the toe of the slope, though the pressure ratio did not reach 1.0, the deformation in the horizontal direction was large, forming a circular slip surface. Thus three liquefaction failure modes were identified in the horizontal ground (Zone I), circular slip under the toe of slope (Zone II), and shakedown directly under the embankment (Zone III). Fig. 1 shows the failure modes, condition of elements, effective stress paths, and stress-strain relations.

To verify the validity of the above zoning and classification of the failure modes, on-line earthquake response tests were carried out.

OUTLINE OF ON-LINE EARTHQUAKE RESPONSE TEST

Fig. 2 outlines the concepts of the on-line earthquake response test (Kusakabe et al. 1990). A lumped mass ground model is used and the earthquake ground motions are input to the base

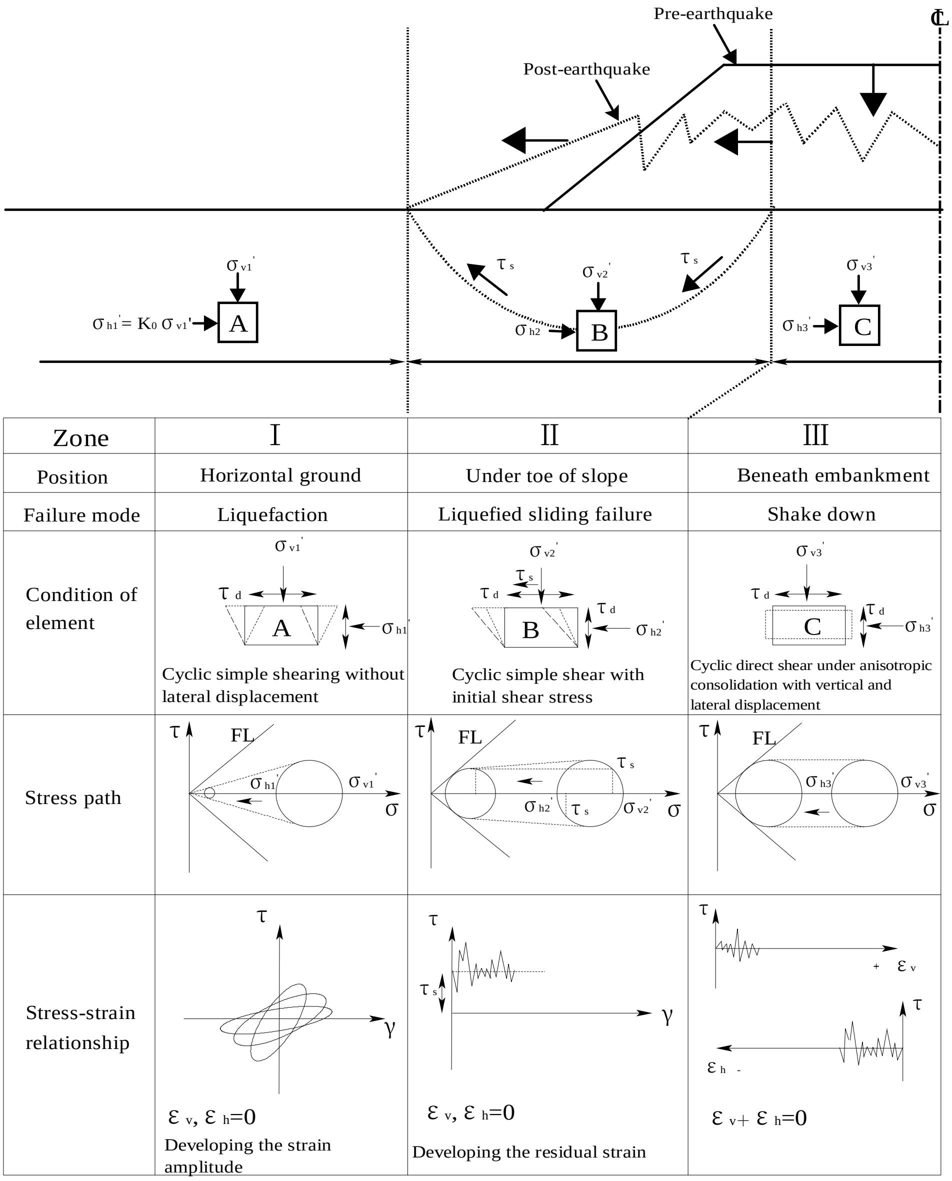


Fig.1. Classification of failure modes

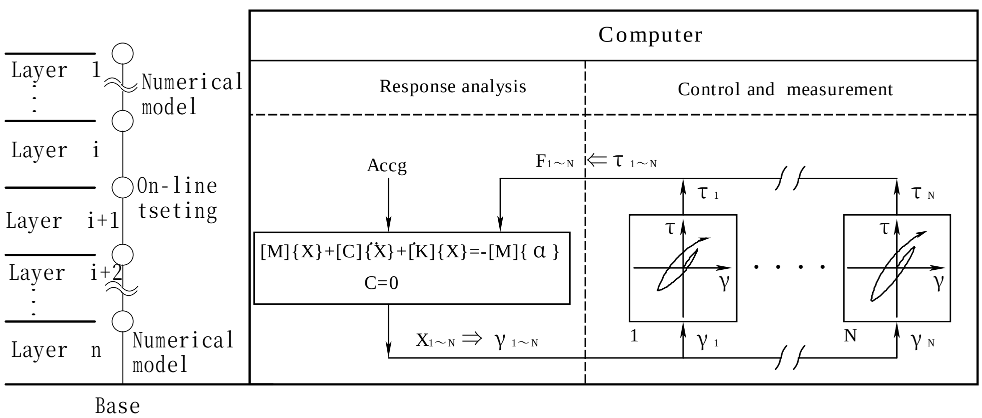


Fig.2. Conceptual fiow for on-line testing

of the layers to be examined. The equation of motion of the lumped mass model is solved by a computer to find corresponding displacements in the ground. Then, shear strains equivalent to the corresponding displacements are applied to specimens under computer control to measure shear stresses automatically. These shear stresses are then used for the calculation of the corresponding displacements for the next step. This process is repeated for the duration of an earthquake. In this way, the continuously changing non-linear shear stress response in the ground during an earthquake is obtained directly from element tests on specimens which are processed on-line by a response-analyzing system to simulate the behavior of the ground. For cyclic loading tests, the simplified simple-shear test developed by Kusakabe (1999) is available.

TEST RESULTS

The embankments of the Shiribeshi-Toshibetsu River struck by the 1994 Hokkaido-Nanseioki Earthquake developed, at their top surfaces, crest settlements of over 2 meters. Fig. 3 shows the cross section (No. 1 section) of the most severely damaged embankment. Soil investigation carried out after the earthquake revealed the *N* values of the alluvial sand layers As_1 and As_2 to be as low as 3~7, suggesting their susceptibility to liquefaction during the earthquake. In this study, therefore, the layers As_1 and As_2 were treated as the on-line layers the other layers were treated as non-linear elastic bodies. Fig. 4 shows that each zone of the two-dimensional section was replaced by a one-dimensional lumped mass model. A static circular slip analysis was performed to calculate the average initial shear stress acting on and around the toe of the slope due to the dead weight of the embankment. This was applied to the model in advance of the testing. The Toyoura sand used had a relative density such that the liquefaction strength curve overlapped that of the in situ undisturbed sand. The other conditions for the tests and analyses were also set up based on the results of the soil investigation. The acceleration waveforms recorded by the Suttsu Observatory were modified taking into account the damping over distance to obtain the earthquake motion, which was an input to the bottom of layer Ac_2.

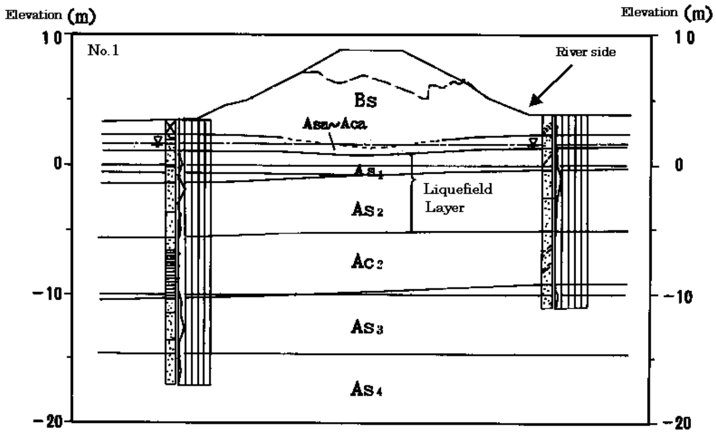


Fig.3. Section of damaged river dyke

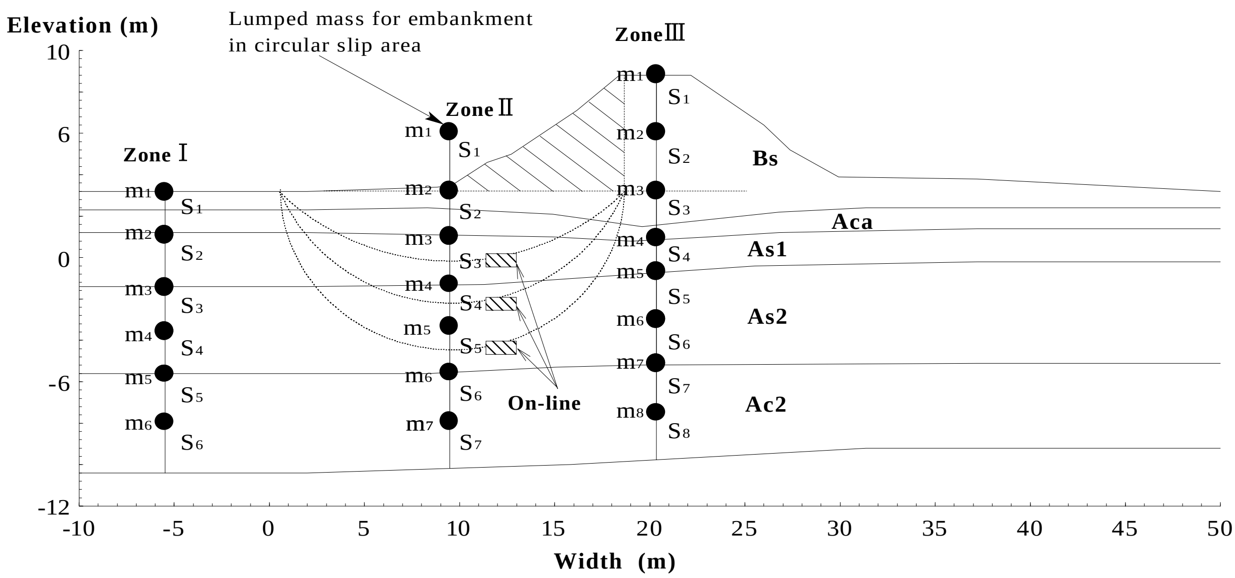


Fig.4. Section of damaged river dyke

Fig. 5 and Fig. 6 show the effective stress paths and the stress-strain relationships, respectively, of the on-line layer As_2. In Zone I, the effective stress became almost zero and the shear modulus decreased rapidly, indicating the occurrence of liquefaction. In Zone II, the effective stress did not reach zero due to the initial shear stress but reached a steady state when it approached the phase-change line. Simultaneously, the shear strain began to develop rapidly, indicating the occurrence of sliding failure with a liquid flow. In Zone III, the effective stress decreased by only 30% or so and reached a steady state without reaching the phase-change line, and although vertical strain of a few percent developed, this hardly increased after the effective stress had reached a steady state.

Figs. 7(a) and (b) show the calculated magnitudes of settlement of the embankment in Zones II and III. The magnitude of the settlement for each layer was calculated by multiplying the strain obtained in tests by the thickness of the layer, and all the settlement magnitudes of the layers were summed to obtain the magnitude of settlement of the embankment. In Zone II, the shear displacement calculated by multiplying the residual shear strain in the soil by the thickness of the soil layer was regarded as equivalent to the crest settlement of the embankment, assuming that sliding failure carried the soil within the circular slip surface uniformly. In Zone III, the settlement was calculated from the vertical strain in soil multiplied by the thickness of the soil layer. Zone I does not appear here because no residual shear strain or vertical strain occurred. It is apparent from these figures that large settlement occurred in the on-line layers in both Zones II and III. The Zone II settlement increased rapidly about 10 seconds after the startup to over 60 cm, whereas Zone III exhibited a settlement growing rapidly in the first 10 seconds or so, progressing slowly thereafter, and finally reaching a mere 10 cm or so. In Fig. 7(a), the cumulative curves terminate at around 20 seconds after the startup, because the strain-measuring range of the test was limited to 25%. If the test had been continued up to 40 seconds, it would have given even larger settlements.

The above results are consistent with those of the shaking table test mentioned earlier, proving the validity of the classification of the failure modes made in the present study. The Zone II sliding failure which was liquefied exhibited the largest strain and seemed to be the main cause of the heavy crest settlement of the embankment.

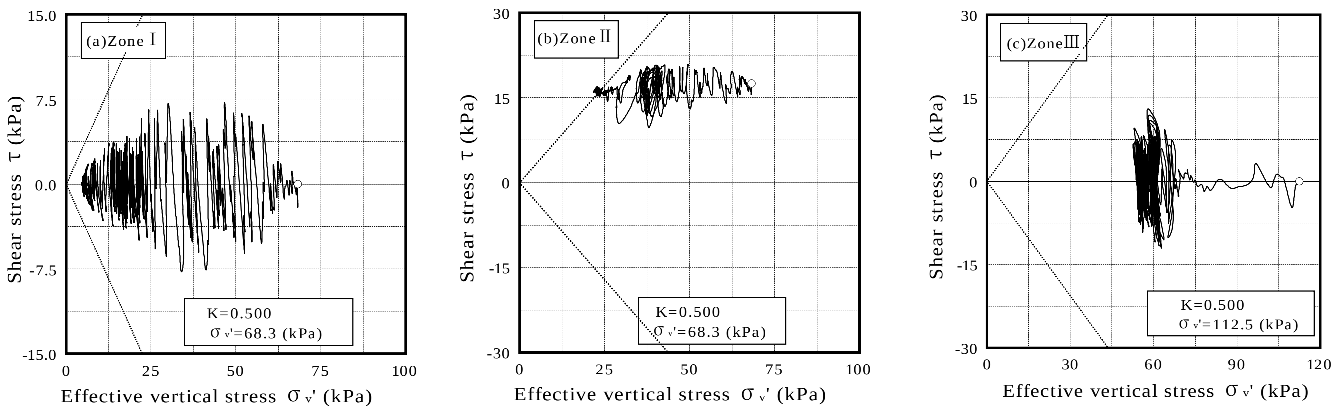


Fig.5. Effective stress paths

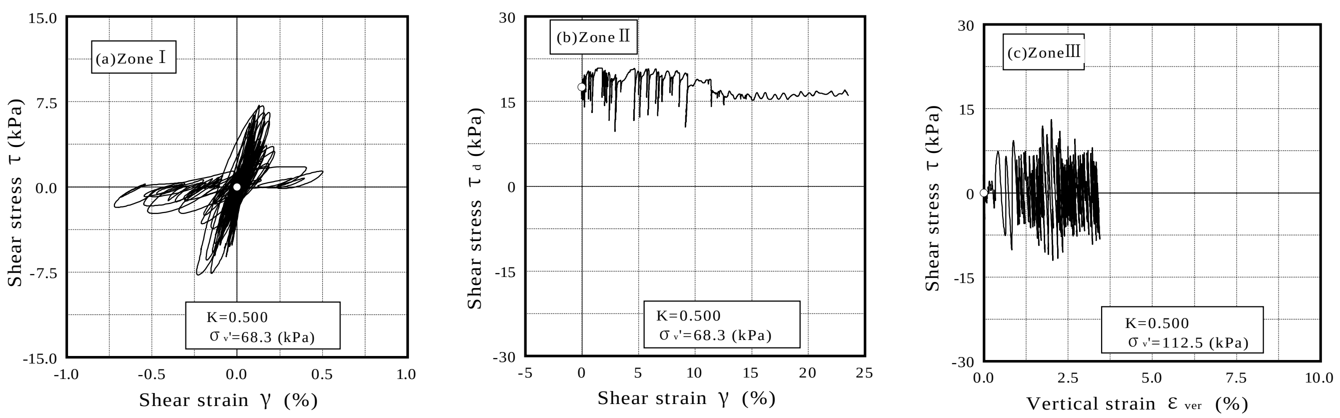
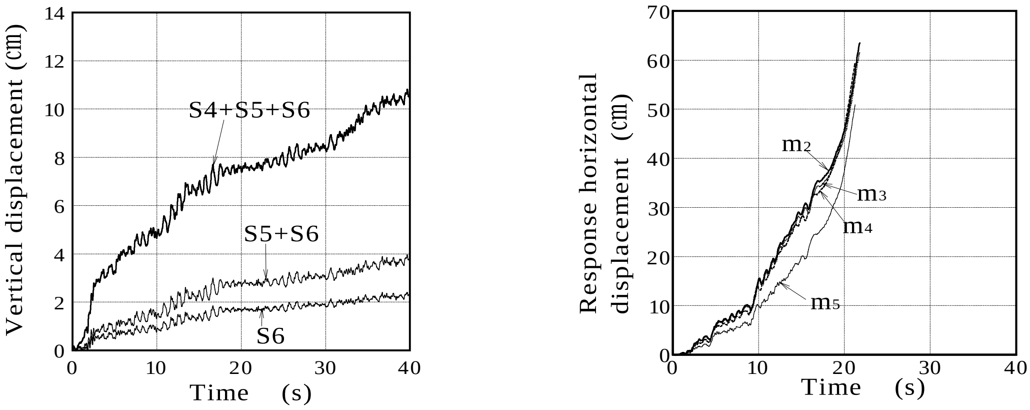


Fig.6. Stress-strain relations

COMPARISON OF DEFORMATIONS

The above tests indicated that the failure mode most detrimental to an embankment was the sliding failure under the toe of the slope (Zone II). Accordingly, further damaged (No. 3 and 5 sections in addition to No. 1 section) and undamaged (No. 2 and 4 sections) embankments of the River were chosen, and on-line earthquake response tests for their Zones II were carried out. In Fig.8, the cumulative horizontal displacements obtained by the tests are compared with the crest settlements of the embankments measured in the field. Although the displacements obtained from the tests are not in very good agreement with the measured values of settlement, the former reflect the trends for the latter. One factor contributing to the underestimation of the settlement by the tests would be that the survey of the ground deformation was carried out several days after the earthquake, allowing later subsidence due to the dissipation of pore water pressure, additional permanent deformation over time, and so on. Another factor is that the soil properties of the ground would have changed under the influence of the earthquake hampering the accurate estimation of the input acceleration based on the liquefaction strength and damping over distance. It was assumed in the present study that sliding failure with a circular slip surface occurred in the soil directly under the damaged embankments. However, the embankments should also have been subjected to the effects of the nearby liquefaction. In addition, although no damage was reported for the No. 2 and 4 embankments, the above tests suggested that some horizontal displacement occurred. When these factors are taken into account, it can be said that the cumulative horizontal displacement values obtained by the on-line earthquake response tests are in fairly good agreement with the crest settlement values measured in the field.



(a)Zone Ⅰ (b)Zone Ⅱ

Fig.7. Cumulative settlement

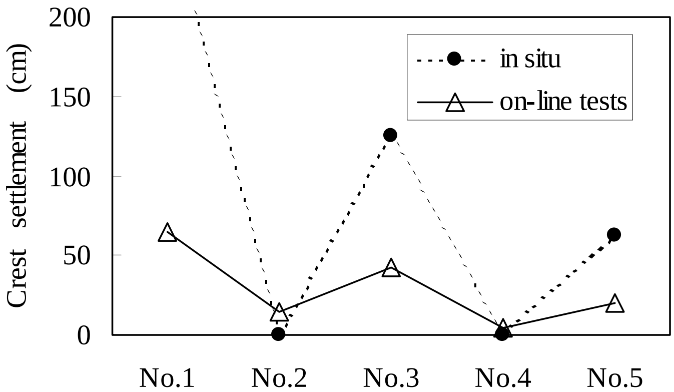


Fig. 8 . Comparison between results of on-line tests and results of measured in situ of crest settlement

CONCLUSIONS

In this study, the foundation of an embankment was, on the basis of the results of past studies, divided into three zones for the examination of failure modes. Liquefied sliding failure occurring under the toe of slope was ascertained as being the most detrimental failure mode, though other modes, should of course, be considered together with it since actual failure involves multiple factors and modes. The approach taken in this study proved itself to be a feasible method for estimating the earthquake crest settlement of river dykes.

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