Shaking table tests on mitigation of liquefaction-induced subsidence of river dikes

Tests sismiques sur la minimisation de l'effondrement par infiltration des berges de rivière

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ABSTRACT: This text concerns mitigation of significant subsidence of embankments induced by seismic liquefaction of the foundation soil. Since the particular interest lies in the protection of river dikes, a relatively economical mitigative measure is required. It is important, at the same time, that a limited magnitude of subsidence, such as 1 meter, is still allowed in most dikes unless flooding of river water is imminent. With these view points, shaking table tests were run on river dike models with embedded sheet pile walls at the toes. Tests proved that these walls reduce the lateral flow of liquefied subsoil and consequently mitigate the subsidence. An analytical method to predict this mitigative effect was developed which is based on energy principles and experimentally-observed mode of soil deformation. This method is able to give a good prediction despite that it needs only limited soil data as available from conventional in-situ liquefaction studies.

RÉSUMÉ: Ce texte concerne la minimisation de l'effondrement des fondations conséquence de la liquefaction sismique du sol. Depuis que se sont développes des intérêts majeurs pour la protection des berges de rivière, un besoin de mesures ralativement économique semblé requis. En parallèle il apparaît important qu'une tollérance de 1m de magnitudes soit toujours authorisées pour la plupart des berges cn cas d'innondations imminentes. Prenant en considération ces quelques points, des tests sysmiques ont été réalises sur des rives modeles ou avaient ete enfouis des piliers au niveau des fondations. Ces tests ont montres que les murs constitues de ces piliers ont diminue les infiltrations latérales des sous-sols et ainsi diminue les effondrements. Une méthode analytique a été développe afin d'estimer l'influence de ces minimisations; elles sont développees à partir de principes énergétiques et d'études expérimentales. Cette méthode est capable de donner une bonne estimation malgré le peu d'informations disponibles lors d'études in-situ d'infiltration dans ces sols.

1 INTRODUCTION

Seismic liquefaction is one of the geotechnical earthquake hazards to many kinds of facilities. Since the essence of liquefaction-induced damage is the significant residual deformation and displacement, it has recently been attempted to reduce the residual displacement down to an allowable magnitude, while allowing for onset of liquefaction. This mitigative principle is relatively economical as compared with such conventional measures as densification. The present study aims at the application of this mitigative principle to a river dike.

It is intended herein to reduce the liquefaction-induced subsidence of a river dike by installing embedded sheet pile walls beneath the toes of a dike (Fig.1). Since the bottom tips of the walls are fixed in the unliquefiable dense layer at the base, the walls as elastic cantilever beams resist the lateral flow movement of the liquefied subsoil under the dike. Consequently, the subsidence of a dike is reduced.

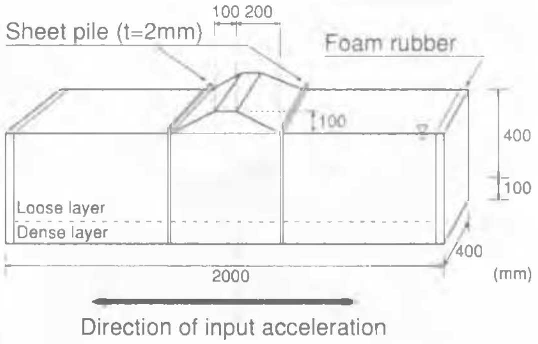

Figure 1. Shaking-table test model of river dike (experiment E25).

The development of a mitigative measure as described above requires two goals to be achieved; the one is an experimental verification of the mitigative effects of sheet pile walls. This goal is attained in the present study by shaking table tests in 1-g field. A similar study has been made by Adalier et al. (1998) and Park et al. (2000). The other goal is special to the present study, which is development of an analytical tool for predicting the reduced magnitude of subsidence of a protected embankment. This goal is achieved by using the method based on the principle of minimum potential energy (Towhata et al., 1999; Kogai et al., 2000).

2 METHOD OF SHAKING TABLE TESTS

Fig.1 illustrates the configuration of a model container which measures 2m in length, 0.4m in width, and 0.6m in depth. The transparent side walls of the container enables to observe the overall deformation of liquefied subsoil which is exhibited by distortion of embedded square grids of colored sand.

The model ground was made of Toyoura sand which was placed at a very loose relative density of 20% by moist tamping. Since the dilatancy of sand, which plays a key role in liquefaction-induced large deformation, is governed by both the level of consolidation pressure and density of sand, this low density of sand under low pressure in a model makes dilatancy equivalent to that of sand of about 40% relative density under in-situ higher pressure. During shaking, the ground water level was located at the ground surface. Being made of gravel with the mean diameter of 3.5mm, the dike model had a height of 100mm with the slope of 2 horizontal to 1 vertical.

The model sheet pile walls were made of 2mm-thick aluminum plates whose bottom was fixed to the bottom of the container. The model of river dike at the surface was made of gravels. A sheet of metal mesh was placed under the dike in order to prevent sinking of individual gravel grains from the dike into liquefied subsoil and to maintain the integrity of the dike model. The base shaking was produced in the longitudinal direction of the model container in a harmonic manner with duration time of 24 seconds.

The major attention was paid to the magnitude of subsidence of a river dike model. Although the subsidence at the top of a dike is important in reality, the present study focuses on the subsidence at the base of a dike where a vertical displacement transducer was placed. This is because the model dike was made of dry unliquefiable gravel whose volume contraction during shaking was not precisely measured. Thus, the base subsidence is designated as the dike subsidence in this text.

3 TESTS WITH EMBEDDED SHEET PILE WALLS

The mitigative effects of sheet pile walls are illustrated in Fig.2 where time histories of subsidence of dike model with and without sheet pile walls are compared. After 24 seconds of shaking, the residual subsidence was reduced to 60 % by installation of sheet pile walls. Be noted that subsidence ceased when shaking was switched off.

Furthermore, the subsidence after 2 to 3 seconds of shaking, which is equivalent to a realistic number of cycles of 20 to 30 under 10Hz shaking, the subsidence was reduced to about 50% or less. The residual distortion of the model is illustrated in Fig.3 for the case with sheet pile walls. Apparently, the subsidence of a dike was induced by vertical compression of the liquefied subsoil which in turn spread laterally and pushed the sheet pile wall. Moreover, the distortion of square grids shows that liquefied subsoil moved up towards the surface along the deformed sheet pile wall.

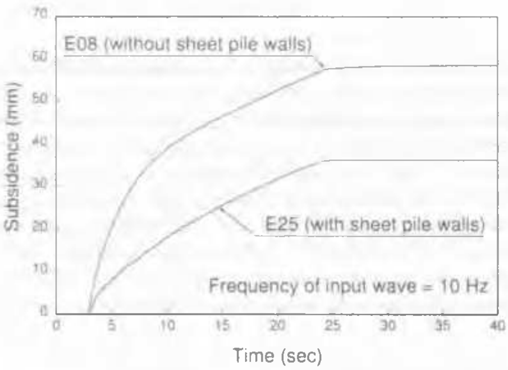

Figure 2. Effects of embedded sheet pile walls on time history of subsidence of dike model (amplitude of base shaking =0.25g with 10 Hz).

The mitigative effects were unexpectedly poor when the shaking frequency was reduced to 3Hz; see Fig.4. The cause of this unsatisfactory results under lower shaking frequency was investigated in Fig.5. It was found therein that, since the amplitude of shaking of the top of sheet pile wall was increased from 5mm in 10Hz shaking to 35mm in 3Hz shaking, a greater size of ground opening was produced between the wall top and the body of the dike. Therefore, a substantial amount of sand was boiled out of ground through it. Therefore, the extent of boiling along the wall was more substantial in Fig.5 than in Fig.3. Thus, the mitigative effects on subsidence attained by the installed sheet pile wall was canceled by additional sand boiling. A measure to reduce the undesired boiling was studied by firstly placing additional berms at the top of sheet pile walls (Fig.6). Being made of gravel, the unliquefiable berms made boiling phenomenon difficult to occur. Thus, as illustrated by test E28 in Fig.7, the residual subsidence of a dike undergoing the critical 3Hz shaking was reduced by 20%.

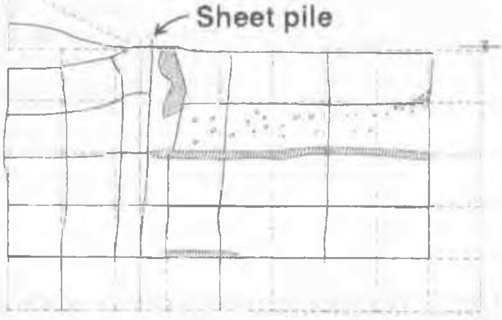

Figure 3. Residual deformation of liquefied subsoil with sheet pile walls (10Hz in Test E25).

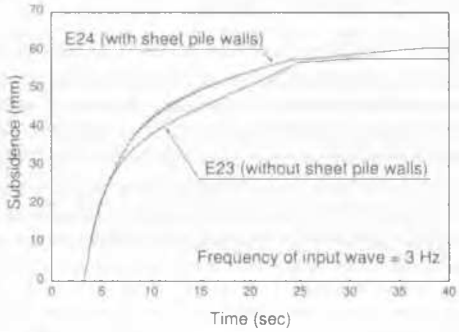

Figure 4. Unsatisfactory effects of embedded sheet pile walls on time history of subsidence of dike model (amplitude of base shaking =0.25g with 3 Hz).

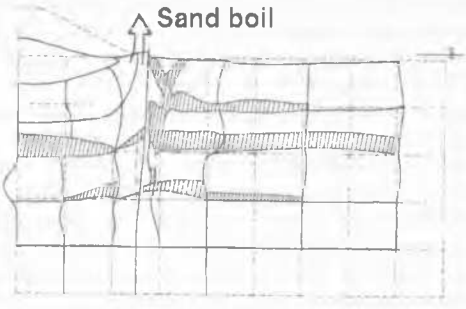

Figure 5. Residual deformation of liquefied subsoil with sheet pile walls (3Hz in Test E24).

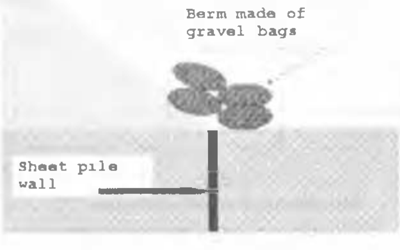

Figure 6. Placement of gravel berm around the top of a sheet pile wall.

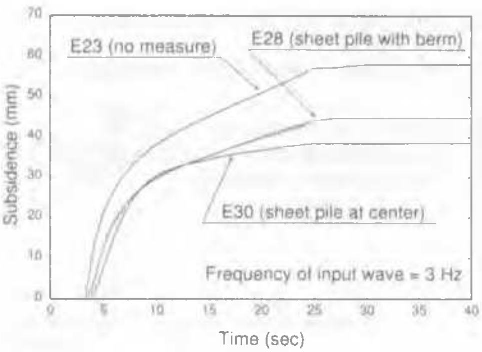

Figure 7. Mitigative effects on subsidence of dike undergoing 3Hz shaking attained by placing gravel berms or sheet pile walls at shoulder.

Another attempt to further mitigate the subsidence of a dike was to change the location of sheet pile walls from the toes of the slopes to the top shoulders. It was expected that connecting the tops of two shoulder walls by a tie rod could tightly maintain the central body of the dike. Although the side slopes were not protected by walls anymore, the sufficient height of the dike at the center could be maintained so that the risk of flooding might be avoided. Fig.7 demonstrates that the subsidence of the dike base was reduced even under 3Hz shaking (E30 test) as expected. However, the deformed shape of the model in Fig.8 manifests that the subsidence at the top of a dike was extremely large, and that the slope was lost completely. This means that the loss of slope drastically reduced the earth pressure on the slope side of the wall, which therefore distorted outwards and caused significant subsidence in the soil, beneath the crest of a dike, sandwiched between two walls. Such a large distortion is difficult to be repaired due to existence of standing sheet pile walls.

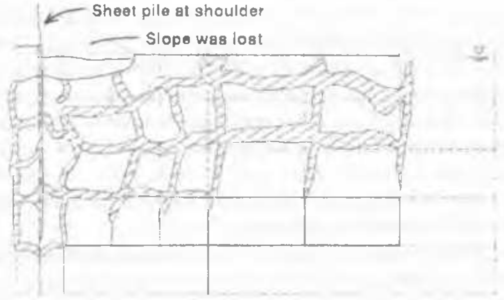

Figure 8. Significant distortion of dike model with sheet pile walls at shoulders.

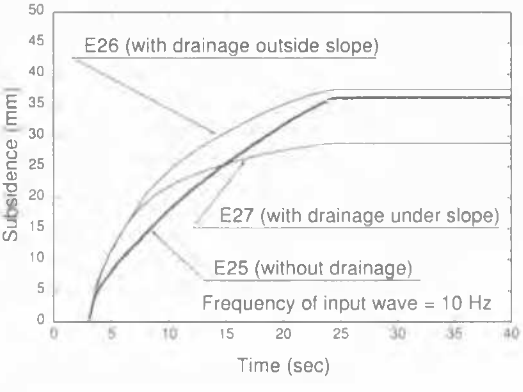

Figure 9. Effects of drainage pipes attached to sheet pile walls on magnitude of dike subsidence (10Hz shaking).

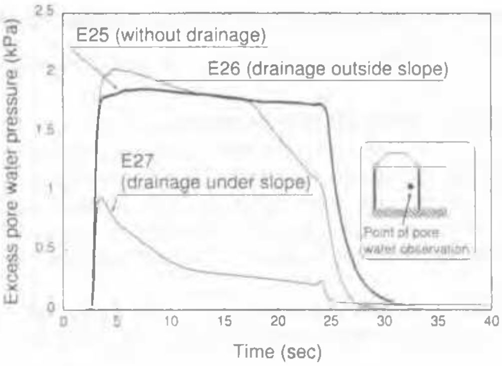

Figure 10. Time history of excess pore water pressure under dike slope as affected by drainage pipes (oscillating component of record was removed).

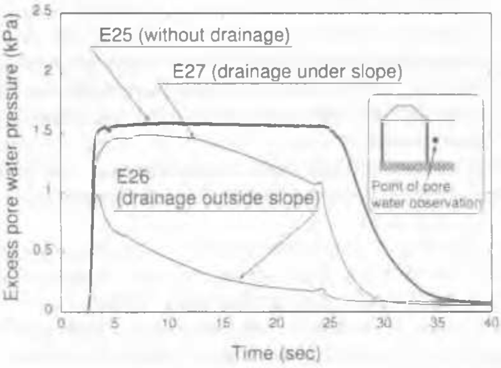

Figure 11. Time history of excess pore water pressure outside of wall as affected by drainage pipes (oscillating component of record was removed).

4 EFFECTS OF DRAINAGE PIPES NEXT TO SHEET PILE WALL

A use of sheet pile walls with drainage pipes is an interesting attempt. Reducing excess pore water pressure in sandy deposit around walls is able to keep the effective stress high together with the soil rigidity during shaking. This idea was employed in the present study to prevent the undesired boiling-induced deformation near the sheet pile walls as reported in Fig.5. Many drainage pipes were made of metal mesh and embedded beneath dike slopes vertically along sheet piles. The recorded time history of subsidence is shown by E27 in Fig.9. When drainage pipes were installed on the opposite side of the walls from the dike (outside of walls) (E26 in Fig.9), the mitigative effects was poor. This indicates that the mitigative effects were generated not by the increased rigidity of soils supporting the walls from the outside but the increased rigidity of soil which prevented boiling of sand under the slope. This point is further supported by Fig.10 in which the development of excess pore water pressure along the possible channel of boiling was dramatically reduced only by the installation of drainage under the slope. In contrast, the pore water pressure outside the wall was most efficiently reduced by installation of drainage outside the wall (Fig.11). The increased effective stress there, however, did not reduce the subsidence as shown by E26 in Fig.9 because boiling under the slope was not mitigated. Thus, the combination of sheet pile walls and drainage pipes under the slope more effectively reduced the ultimate subsidence from 58cm in E08 of Fig.2 to 29cm in E27 of Fig.9. It is noteworthy, however, that drainage accelerated the rate of consolidation in the early stage of shaking; compare E25 and E27 in Fig.9.

5 PREDICTION OF SUBSIDENCE

An analytical method to predict liquefaction-induced deformation of subsoil has been developed by Towhata et al. (1999) as well as Kogai et al. (2000). In contrast to nonlinear finite element approach, this method is characterized by the following features;

- the amount of computation is drastically reduced by the useof deformation mode which is observed in many model tests,
- consideration is made of large displacement of subsoil which affects geometrically the force equilibrium and magnitude of displacement,
- since undrained deformation is assumed to liquefied sand, the calculated subsidence of ground surface should be added by the consolidation settlement of, for example, 3% of the layer thickness in order to obtain realistic subsidence,
- a limited number of input data is required only of the configuration of ground, depth of liquefaction layer, and the rigidity of the surface unliquefied layer as estimated by, for example, SPT-N; there being no need for undisturbed soil sampling and laboratory shear tests for nonlinear soil parameters, and
- the depth of liquefaction is determined independently by employing a conventional SPT-based method for liquefaction potential.

The capability of the method to predict liquefaction-induced displacement has been demonstrated by class-A predictions as carried out in VELACS Project (Towhata, 1994).

Calculation was made of the maximum possible subsidence of a tested dike, assuming undrained behavior of sand as stated above, and compared with observation (Fig.12 and 13). The maximum possible subsidence means the force equilibrium state after which no more distortion is possible. Generally, the agreement is good between calculation and observation when the state of flow continued for a long time. By adding to calculated subsidence the consolidation settlement of, for example, 3% of 40cm layer thickness, the agreement is improved. Overestimation is apparent, in contrast, for cases of smaller thickness of liquefiable layer, lower magnitude of shaking, or shorter duration of shaking, because, in those cases, the duration of high excess pore water pressure ceased rather quickly and the state of liquefaction did not last for a sufficiently long time. Thus, the observed subsidence did not have sufficient time to attain the extent close to the maximum possible subsidence.

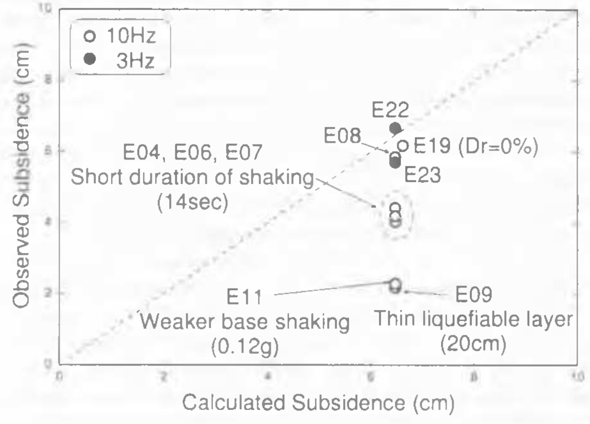

Figure 12. Comparison of dike subsidence between observation and calculation; no sheet pile installation. .

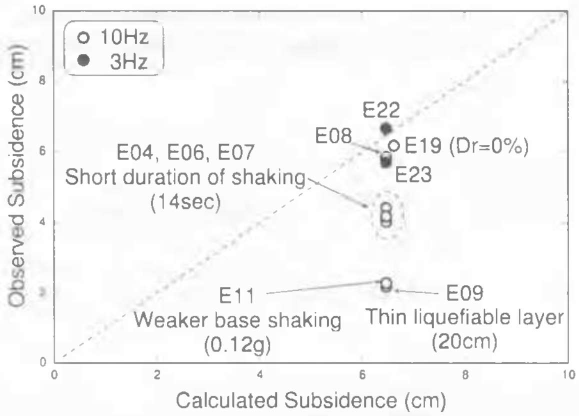

Figure 13. Comparison of dike subsidene between observation with and without drainage.

6 CONCLUSION

A series of shaking-table model tests was conducted on the mitigative effects of embedded sheet pile walls on subsidence of a river dike. Test results reveal that combination of sheet pile walls with a berm of gravel is the most effective measure. A use of drainage pipes under the slope is further promising. Analytical prediction of subsidence is possible, on the other hand, by using a limited amount of input data.

REFERENCES

Adalier,K., Elgamal,A.-W., & Martin,G.R. 1998. Foundation liquefaction countermeasures for earth embankments, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 124(6), 500-517.

Kogai,Y., Towhata,I., Amimoto,K., & Hendri Gusti Putra. 2000. Use of embedded walls for mitigation of liquefaction-induced displacement in slopes and embankments, *Soils and Foundations*, 40(4), 75-93.

Park,Y.H., Kim,S.R., Kim,S.H., & Kim,M.M. 2000. Liquefaction of embankments on sandy soils and the optimum countermeasure against the liquefaction, *Proc.12th World Conf. Earthq. Engrg*, Auckland, Paper number=1170.

Towhata,I. 1994. Review of Prediction 'A' on Model 11, *Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems*, Vol.2, p.1607-1612, Balkema.

Towhata,I., Orense,R.P. & Toyota,H. 1999. Mathematical principles in prediction of lateral ground displacement induced by seismic liquefaction, *Soils and Foundations*, 39(2), 1-19.