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Taka-aki Mizutani
Port and Harbor Research Institute, Japan

Ikuo Towhata
University of Tokyo, Japan

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MODEL TESTS ON MITIGATION OF LIQUEFACTION-INDUCED SUBSIDENCE OF DIKE BY USING EMBEDDED SHEET-PILE WALLS

Taka-aki MIZUTANI
Research Engineer
Port and Harbor Research Institute

Ikuo TOWHATA
Professor
University of Tokyo

ABSTRACT

Several earthquakes in the 1990's revealed the problem of significant subsidence of river dikes induced by subsoil liquefaction. Although soil improvement is the most reliable solution to avoid the onset of liquefaction, the substantial length of liquefaction-prone dikes together with the economical reasons does not allow this solution. It is aimed, therefore, to mitigate the subsidence to a certain extent so that a fatal flooding is avoided. The present study examines the possibility of installing sheet pile walls at toes of river dikes. Shaking table tests were conducted for this purpose and the effects of sheet pile walls were studied. Moreover, a combination of walls and drains for quick dissipation of excess pore water pressure was investigated.

INTRODUCTION

A review of liquefaction-induced damage of a variety of facilities demonstrates that the essence of damage is the unacceptable extent of deformation and displacement that remain after earthquakes. For example, subsidence and tilting of buildings in Niigata (Yoshimi and Tokimatsu, 1977) and Dagupan City of the Philippines (Acacio et al., 2000) was a problem because the magnitude of subsidence and tilting exceeded the limit of acceptance. Similar points can be made of floating of embedded facilities such as lifeline pipes and underground tanks. The essence of the problem has been the excessive magnitude of upward displacement, which is namely the floating. Accordingly, recent efforts to avoid liquefaction-induced damage are divided into two categories which are prevention of liquefaction by means of soil improvement and mitigation of liquefaction-induced deformation as well as displacement.

The seismic stability of river dikes has not been seriously discussed conventionally. This is because the aim of dikes is a prevention of flooding during the high level of river water, while prevention of earthquake-induced damage has been out of scope. In particular, the probability of the simultaneous occurrence of high water level and strong earthquake shaking appears to be extremely low. Hence, a quick restoration of any earthquake damage before flooding comes has been considered more practical than seismic reinforcement.

The principle of quick restoration was found to be a problem by several earthquakes in 1990's. The most important example among them was the damage of Yodo River dike in Osaka City during the 1995 earthquake in Kobe area; see Fig.1. Besides the elongated period of restoration, the most important issue was the fact that the water level at this site was affected by the sea tide which became high two times a day. Furthermore, the ground surface behind this dike was lower than the water level. Hence, it was found possible that significant distortion of this dike can easily induce fatal flooding of river water at the time of high tide. Apparently, there is no time to restore a damaged dike before a daily high tide comes. This experience, therefore, triggered to develop a mitigative measure which helps avoid significant subsidence of river dikes due to subsoil liquefaction.

Fig. 1. Distorted shape of Yodo River dike (by Fudo Construction Company).

MITIGATIVE EFFECTS OF EMBEDDED SHEET PILE WALL

Fig.2 examines the variation of the extent of subsidence of the

Yodo River dike along the left bank. The damage concentrated in the Torishima area which is shown in Fig.1. Former studies by the Ministry of Construction showed that the thickness of liquefiable subsoil along the river channel was approximately 10m (quoted by Towhata and Matsuo, 1996, and Kogai et al., 2000). This figure demonstrates at the same time the variation of the length of the embedded sheet pile which was installed under the toe on the river side of the dike. Since this sheet pile wall was intended to reduce the seepage flow of water under the dike, their length was not necessarily as long as 10m to reach the bottom of the liquefiable deposit. It is interesting that the length of sheet pile wall in the damaged Torishima site was shorter than those in damage-free areas. This finding motivated the present study on the use of sheet pile walls for damage mitigation.

It should be further pointed out in Fig.2 that the Torishima dike had no fill on the river side, while other undamaged sites had wider attached fills. It is likely that the weight of the fill improved the slope stability of dikes, leading to negligible distortion of dikes in other areas.

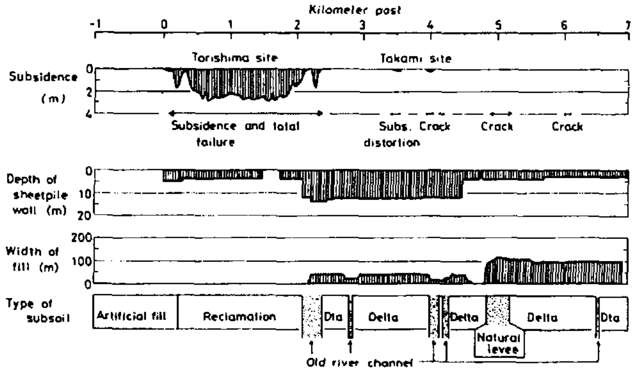

Fig. 2. Correlation between extent of subsidence of Yodo River dike, length of sheet pile wall, and width of fill (Kogai et al, 2000).

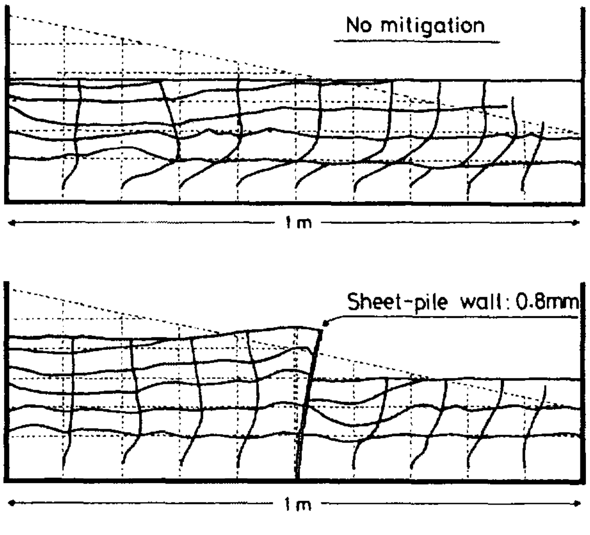

Fig. 3. Shaking table tests on mitigative effects of embedded sheet pile wall on lateral flow of liquefied sandy slope (Kogai et al., 2000).

It is supposed in this study that subsidence of a dike is chiefly caused by lateral flow and loss of sand underneath which is liquefied upon shaking and becomes extremely soft. This idea will be verified later on by shaking table tests (Figs 5 and 6). It is hence reasonable that subsidence is mitigated by preventing lateral migration of liquefied subsoil by installing embedded sheet pile walls. The mitigative effects of an embedded wall on flow of liquefied soil were studied by Kogai et al. (2000) as well as Towhata et al. (2000). Fig.3 compares two shaking table tests in which a model of submerged slope was shaken to trigger liquefaction. The first model without an embedded wall generated flow failure and its surface finally became level. In contrast, the second model with an embedded sheet pile wall had its deformation reduced by the wall. It is found by comparing the ultimate distortions in Fig.3 that the extent of lateral displacement was reduced to less that 40% by the bending stiffness of the embedded wall. The present study intends to apply this finding to mitigation of subsidence of a river dike.

The use of sheet pile walls for seismic reinforcement is not a new practice. Nozawa and Nasu (1985) installed sheet pile walls at the toe of railway embankments. They aimed to thereby prevent the onset of liquefaction. Although mitigation of displacement was out of their scope, this is the first practice of this type. Due to the relatively low cost of construction, as compared with soil improvement, the use of sheet pile wall is attracting engineering concern; for example, Tanaka and Kita(1995), Adalier et al. (1998), and Park et al. (2000) among others. Moreover, the installation of sheet pile walls does not cause undesired ground vibration and noise. The installation of sheet piles into subsoil, however, needs a sufficient working space.

METHOD OF SHAKING TABLE TESTS

Fig.4 illustrates a soil container which was shaken in its horizontal longitudinal direction. The length and the width of the sandy deposit were 200cm and 40cm, respectively. Two end walls were equipped with foam rubber in order to mitigate the interaction with sand. A loose deposit of Toyoura sand had a thickness of 40cm and was placed on a denser deposit at the bottom. The whole sandy deposit was submerged in water with the water surface at the ground surface as well.

A model of a river dike of 10cm in height was constructed at the surface by using a gravelly material. This material was advantageous to sand because, being free of meniscus force, it did not absorb water and, hence, was unlikely to liquefy. It was better than clay, furthermore, because, having no cohesion, it was able to deform under the reduced stress level in 1-g model tests. On the other hand, the earliest stage of testing found that individual gravels sank into liquefied subsoil and made the subsidence of the model dike unable to be measured. Therefore, a wire net was placed beneath the dike model so that subsidence of gravels might be prevented, while not affecting the drainage boundary conditions through the net. The following studies will work on the subsidence at the bottom of model dikes because the subsidence at the top was subjected to uncertainty due to the compaction of a gravel dike whose density was difficult to control.

The model sandy deposit was prepared by the method of wet tamping. This method was able to make the relative density of sand as low as 0 to 20% which was necessary to make dilatancy of sand negative under the low pressure level; keeping the dilatancy negative similar to the insitu prototype situation under higher stress level. The relative density of dense sand at the bottom was 80%.

The horizontal shaking was a harmonic one with a specified acceleration amplitude and, in most tests, 10Hz of frequency. The duration of shaking was 14 to 24 seconds. Thus, the total number of shaking cycles was remarkably larger than that of the real earthquake loading.

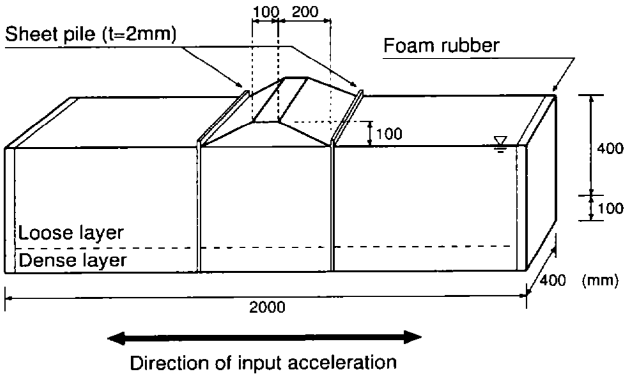

Fig. 4. Model soil container for shaking model tests.

BEHAVIOR OF DIKE MODEL WITHOUT SHEET PILE WALL

Fig.5 manifests the post-shaking configuration of a model. The relative density in the liquefiable layer was 20%, while shaking had 0.25g of amplitude and 10Hz of frequency. The duration of shaking was 14 seconds, inclusive of the initial increasing of the intensity of shaking for two seconds and another 2 seconds for ceasing the shaking. Since no sheet pile wall was installed, the observed deformation and the subsidence were the maximum possible one. The square grids made of black dyestuff in the vertical cross section in this figure helped understand the nature of the overall deformation. The figure indicates that the subsidence of the dike model was maximal at its center and decreased towards the toes of slopes. Moreover, the lateral displacement in the liquefied subsoil attained the maximum extent at the elevation of one third from the bottom, while the displacement was minimal at both top and bottom of the liquefiable layer. This mode of displacement is in contrast with those which were observed in flow failure of slope models where the lateral displacement increased towards the surface.

It was considered to be likely that the deformation of subsoil as shown in Fig.5 was affected by the wire net at the bottom of a dike. The net was able to reduce the lateral extension of subsoil due to its tensile rigidity. It is interesting, however, to refer to the deformation in Fig.6 for which no wire net was installed. The small lateral displacement near the top was similar to what was observed in Fig.5. Therefore, it was concluded that the observed

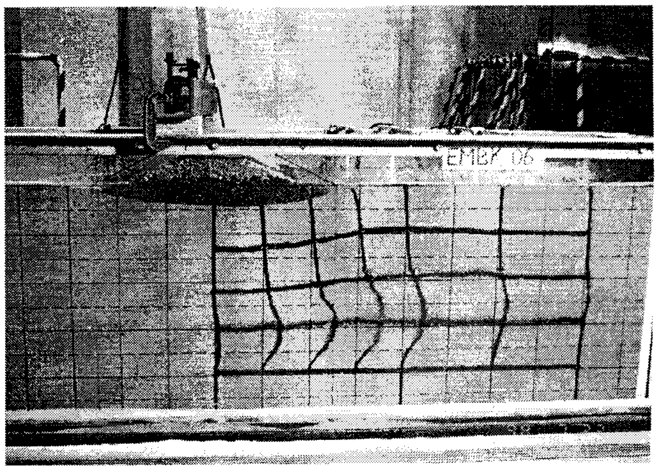

Fig. 5. Deformed shape of model without sheet pile wall.

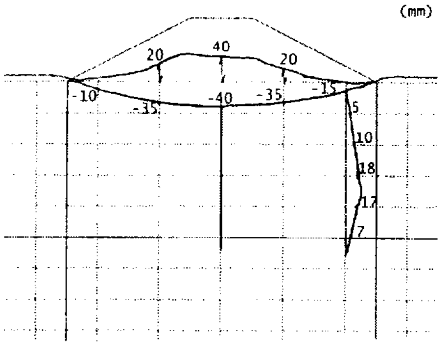

Fig. 6. Deformation of subsoil and dike without wire net.

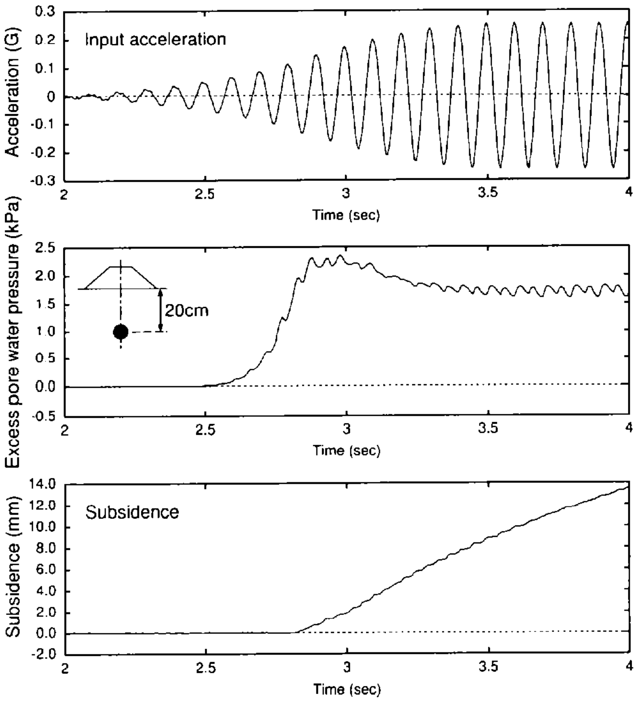

Fig. 7. Time histories of base shaking, pore water pressure, and subsidence of dike in the early stage of shaking.

mode of displacement, being maximal in the middle elevation, was inherent to this type of situation.

Fig.7 illustrates the time histories of base input shaking, excess pore water pressure at 20cm beneath the bottom of the dike model, and the subsidence at the bottom of the dike as well. Data only before the first four seconds are employed. Be noted that the highest excess pore water pressure was attained at around 2.9 seconds of time when the input acceleration exceeded 0.1g. The highest excess pore water pressure of 2.3kPa was comparable with the initial effective overburden pressure produced by 10cm of gravelly dike and 20cm of submerged loose sand. The minor decrease of pore pressure after 3 seconds is probably related with shear deformation and dilatancy of surrounding sand. The subsidence started nearly at the same time as the highest pore pressure and continued without fluctuation very much.

Fig.8 illustrates the vertical variation of the amplitude of response acceleration beneath the dike. The acceleration in this figure was normalized by the response at the base. There is a noticeable difference in the response between 2.5 seconds and 7.5 or 12.5 seconds. This is a consequence of excess pore water pressure development which did not yet start at 2.5 seconds (see Fig.7). The high pore water pressure softened the subsoil and reduced the acceleration near the surface.

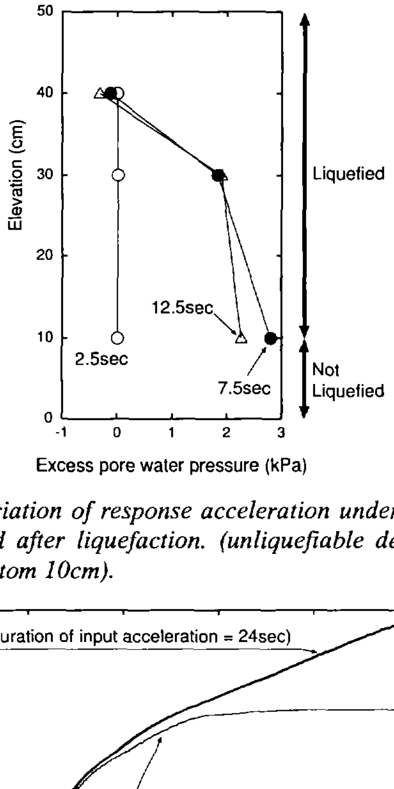

Fig. 8. Variation of response acceleration under dike before and after liquefaction. (unliquefiable dense sand in bottom 10cm).

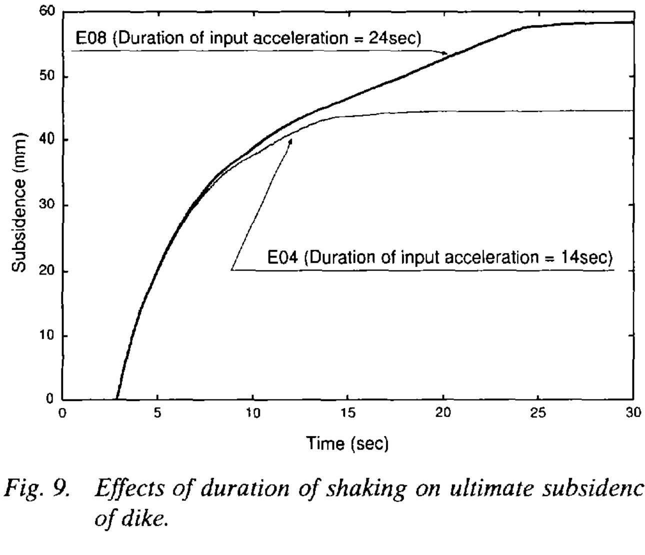

Fig. 9. Effects of duration of shaking on ultimate subsidence of dike.

Fig.9 compares two tests in which the duration of shaking was increased from 14 to 24 seconds. The development of subsidence was terminated when shaking was switched off in both tests. In other words, the ultimate subsidence was increased by shaking the model for a longer period of time. It is reasonable to say, therefore, that the accurate prediction of subsidence and, in a more general sense, liquefaction-induced ground deformation needs the time effects to be taken into account. It seems that this goal is achieved by running dynamic analyses in the time domain; a static deformation analysis is not relevant.

BEHAVIOR OF DIKE MODEL REINFORCED BY SHEET PILE WALLS

Models of sheet pile wall were made of aluminum plates which measured 2mm in thickness. The bending stiffness of this model wall was determined so that noticeable bending strain would occur under the action of earth pressure during tests. Two sets of sheet pile model was made of aluminum plates and installed at the toes of slopes on both sides of a dike model. The bottom tip of the wall was fixed to the bottom of a container so that neither rotation nor lateral translation might occur. Although it is an attractive idea to connect the top of walls with each other in order to further suppress the lateral distortion of the wall and liquefied subsoil, it was not conducted in the present study. This is because the current situation of river engineering is not likely to allow a tie rod to penetrate through a dike body, possibly making flooding water to flow along it during a future high level of water.

Fig.10 demonstrates the post-shaking configuration of a model in which a model dike was reinforced by sheet pile walls. The thickness of liquefied deposit was 40cm with 20% relative density and the shaking had 0.25g in acceleration and 10Hz of frequency. The long duration time of shaking for 24 seconds

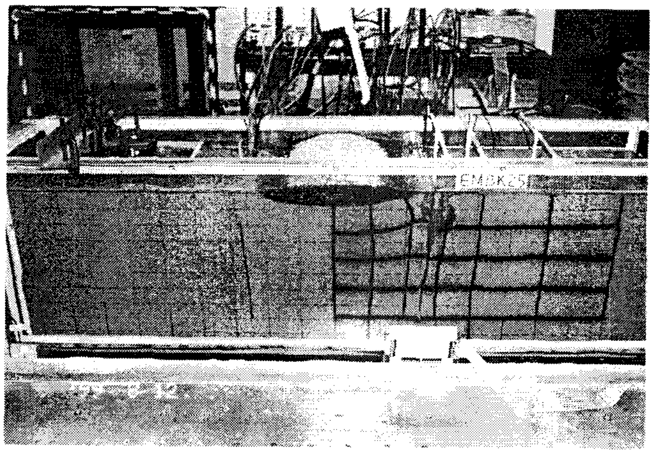

Fig. 10. Distortion of model with installation of sheet pile walls.

means that the model had a sufficient time to attain the maximum possible deformation.

It is found by comparing Fig.10 with Fig.5 that the extent of lateral displacement was reduced by sheet pile walls, suggesting the reduced subsidence of the dike model as well. An interesting difference in Fig.10 from the soil distortion in Fig.5 is that the elevation of the maximum lateral displacement was raised towards the surface. The distortion of a grid of colored sand reveals a noticeable upward flow near the upper half of the sheet pile. Thus, it is inferred that boiling of sand and water occurred along the wall near the toe of the dike.

Fig.11 compares the time histories of subsidence of two model dikes; the one without sheet pile walls in Fig.9 and the other with walls in Fig.10. Test conditions were maintained identical in these experiments except the use of sheet pile walls. Apparently, both the rate of development and the ultimate magnitude of subsidence were mitigated by the use of sheet pile walls. The ultimate subsidence suggests that the use of sheet pile walls reduced the subsidence by nearly 40%. To make this comparison more practice-oriented, the subsidence should be picked up after 20 cycles of strong shaking. This means that the subsidence data should be picked up after 2 seconds of strong shaking (10 cycles per second) plus another 2 seconds for increasing the shaking intensity to the specified level; in total 4 seconds of shaking. In this respect, the subsidence at 7 seconds were used for comparison, and the reduction of 60% was found. It appears, therefore, that sheet pile walls can mitigate the subsidence of a river dike.

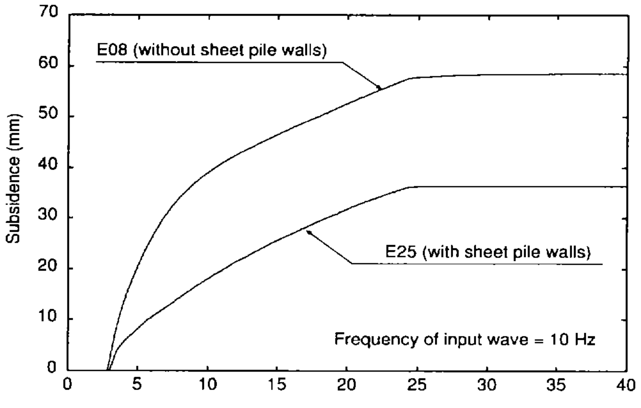

Fig. 11. Effects of installation of sheet pile walls on subsidence of dike.

A noteworthy finding is illustrated in Fig.12 for two tests in which models were shaken at a reduced frequency of 3Hz, while other conditions were held identical; 40cm thickness of liquefiable soil with 20% of relative density, 0.21g of base acceleration, and duration of shaking for 24 seconds. Different from the definite influence of sheet piles under 10Hz shaking (Fig.11), the lower frequency of shaking, thus, does not support the mitigative effects of sheet piles.

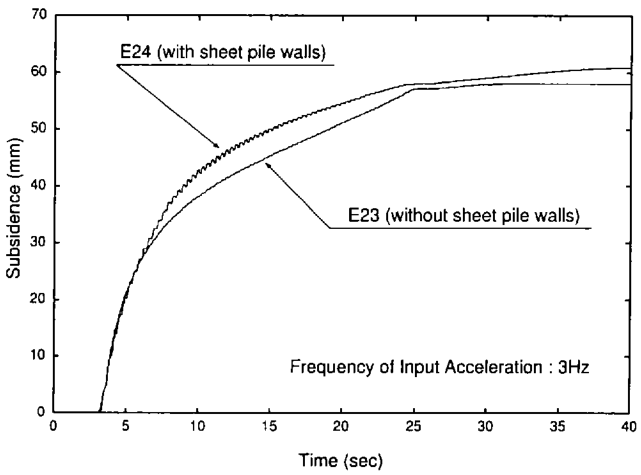

Fig. 12. Shaking tests at reduced 3Hz.

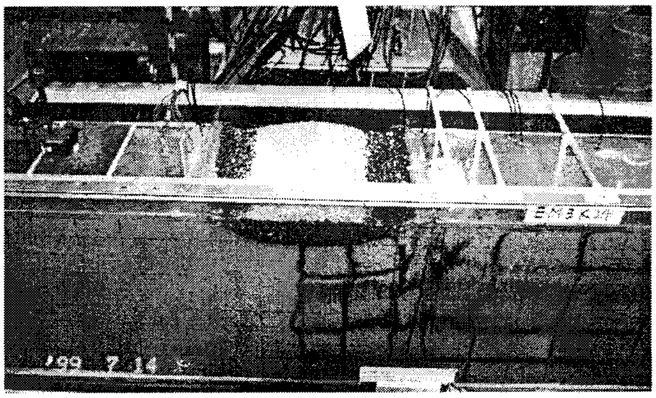

Fig. 13. Consequence of 3Hz shaking in model with sheet pile walls.

This poor behavior of sheet pile walls under lower frequency of shaking was taken seriously, although 3Hz in a reduced size of a model might be too low and less important. Fig.13 displays the post-shaking appearance of the model. Apparently, the extent of distortion was substantial in spite of the installed sheet pile walls. In particular, the upward flow of sand near the top of a sheet pile wall was remarkable. Since a large amount of sand and water was lost from this place, the noticeable subsidence of a dike model occurred. Most probably, the shaking frequency of 3Hz was close to the resonant frequency of the sheet pile wall after subsoil liquefaction. Hence, the displacement amplitude at the top of the wall became very big, relative to the displacement of the toe of the dike, and a crack opened repeatedly during shaking. Consequently, the extensive flow of soil and water occurred from the proximity of the top of the wall and a dike subsided significantly. It is thus necessary to reduce the magnitude of boiling from the toe in order to make the sheet pile walls more effective.

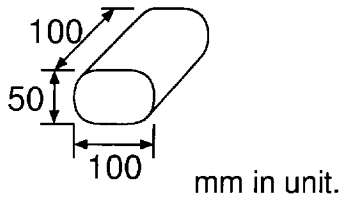

Fig. 14. Configuration of plastic pervious bag containing gravel.

The undesired boiling near the top of sheet pile walls was reduced by placing along the toe of the dike many bags with gravel inside. Fig.14 illustrates the shape of a plastic pervious bag. Fig.15 illustrates the time history of subsidence of a dike model whose sheet pile walls were improved by placing gravel bags. The mitigative effects are promising. Be noted that cohesive material should not be used in place of gravel because open cracks is possible in clay and allows free drainage from the subsoil. It is likely that the surface unliquefiable soil in real situations plays the same role as gravel bags in the present study.

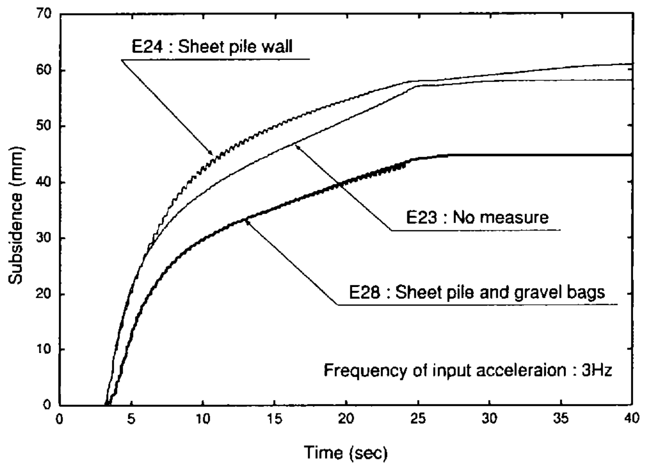

Fig. 15. Reduced subsidence of dike under 3Hz shaking after placing plastic gravel bags.

INSTALLATION OF SHEET PILE WALLS FROM TOP OF DIKE

The most important goal of sheet pile installation in a river dike is to maintain the height of the embankment. From this view point, the installation of sheet pile walls at the toe of slopes may not be the best choice. It appeared more promising to install walls from the shoulder of slopes; see Fig.16. The connection of the tops by tie rods could reduce the lateral distortion of sheet piles and was expected to drastically mitigate the subsidence of the protected top of a dike.

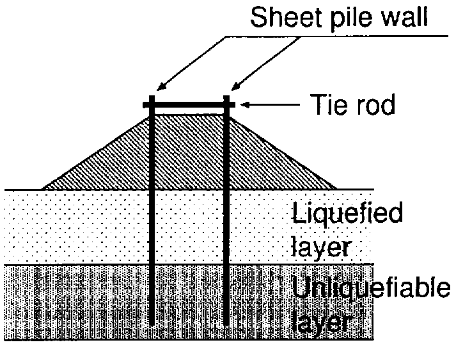

Fig. 16. Schematic vies of installation of sheet pile walls at top of dike.

Fig.17 illustrates the ultimate distortion of a model. A substantial subsidence occurred in the dike because, firstly, the unprotected slopes of the dike subsided and disappeared and, upon the loss of earth pressure from the slope, secondly, the sheet pile walls distorted outwards laterally to a substantial extent. Consequently, the central part of the dike subsided. Fig.18 compares the time histories of subsidence for three cases. Although the central installation of sheet piles exhibits better performance of a dike, the extent of reduced subsidence is similar to the case of toe installation with gravel bags. It appears advisable, therefore, to install one more set of sheet pile walls at the toes in order to further protect the slopes of the dike as well.

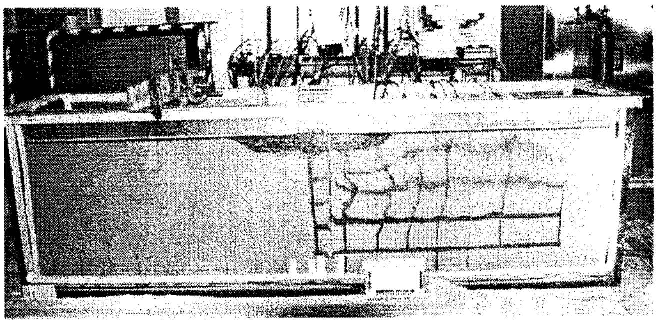

Fig. 17. Post-shaking configuration of dike with central installation of sheet piles.

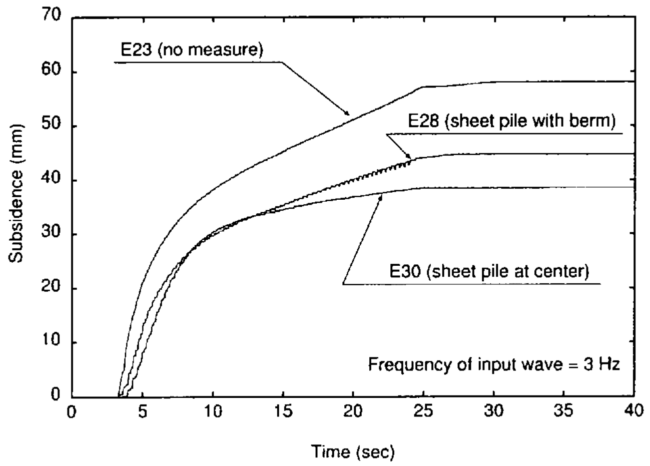

Fig. 18. Time history of subsidence with central installation of sheet piles and tie rod connection at top.

COMBINATION OF SHEET PILE WALLS AND DRAIN PIPES

Since the large deformation of liquefied subsoil is a direct consequence of high pore water pressure and loss of rigidity, it seems promising to accelerate the rate of dissipation of pore water pressure. This measure can make short the duration of high excess pore water pressure, and, as a result, the sandy deposit does not have sufficient time to develop large deformation. With such an expectation, the sheet pile walls were combined with vertical drain pipes which were placed close to sheet piles. Two locations of drains were studied; inside of sheet piles (same side as dike) and outside (opposite from dike and under free field).

Fig.19 compares the time histories of excess pore water pressure at 10cm below the center of a dike for three kinds of test; with normal sheet piles, with sheet pile equipped with drains inside and outside. Only the transient component of pore pressure was employed in this illustration, while the fluctuating component was removed. There was no mitigation in the maximum pore water pressure whether drains were installed or not. This is probably because of the limitation of 1-g shaking table tests with water as the pore fluid. The influence of the installed drains and the induced lateral seepage flow were erased by the overwhelming effects of the vertical flow. Thus, the increase of effective stress by the use of drains was not validated under the dike.

On the contrary, near the top of a sheet pile, the installation of drain pipes inside the sheet pile effectively reduced the excess pore water pressure (Fig.20). Since this portion of subsoil was the channel of undesirable boiling of sand and water (see Figs.10 and 12), the low pore water pressure in this portion means prevention of boiling. It was expected that the reduced volume of boiled water leads to smaller extent of subsidence of dike. This point is illustrated to some extent in Fig.21 in which the subsidence with drain pipes inside the sheet pile walls achieved the least extent of ultimate subsidence. It is noteworthy, however, that the observed subsidence in the early stage of shaking (5 to 10 seconds of time) was greater when drains were installed than that with sheet piles but without drains. This reversed effect of drains is interpreted that the drain increased the amount of seepage flow from the subsoil beneath the dike; this caused greater subsidence of a dike model. It deserves, thus, a special attention that subsidence of a dike is contributed by consolidation of subsoil as well as its lateral distortion. Only the latter component is efficiently mitigated by the use of sheet pile walls.

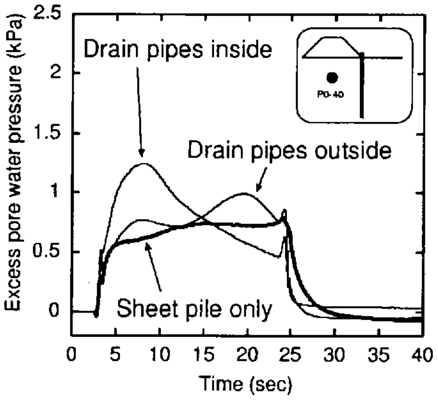

Fig. 19. Time history of excess pore water pressure under dike affected by drain (shaking at 10Hz).

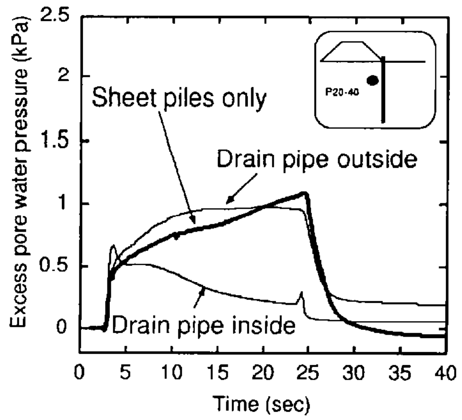

Fig. 20. Effects of drains on time history of excess pore water pressure near sheet pile (shaking at 10Hz).

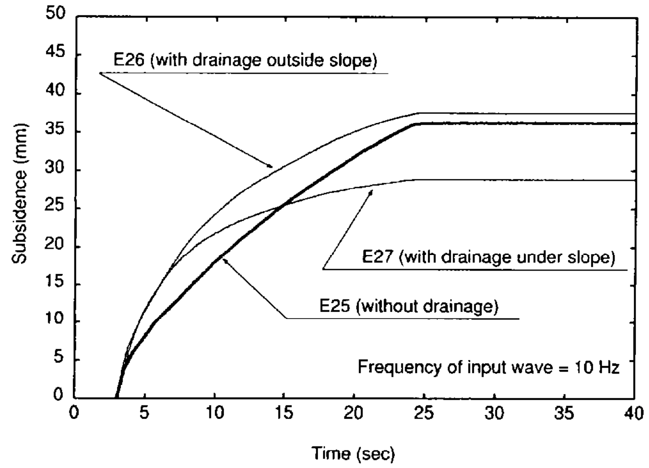

Fig. 21. Comparison of time history of subsidence of dike with and without drain pipe effects (shaking at 10Hz).

OVERALL COMPARISON OF OBSERVED SUBSIDENCE

The present study has investigated the mitigative effects of a variety of sheet pile installations. They are assembled and examined in this section. Since the duration of shaking in this study caused more than 100 cycles of shaking, it is likely that the observed ultimate subsidence appears to exceed the realistic subsidence. It was decided, therefore, to pick up in this section the subsidence after 10th, 20th, and 30th cycles of strong shaking.

Fig.22 illustrates the results. Firstly, when no sheet pile was installed (tests E08 and E19), the subsidence was maximal for any number of cycles. The looser density of sand slightly increased the subsidence. For both test conditions, an installation of sheet pile walls reduced the subsidence to approximately 50% (E25 and E20). A thinner thickness of liquefiable layer (E09) or lower magnitude of shaking (E11) is accompanied by smaller subsidence. When the fixed boundary condition of sheet pile wall at the bottom was loosened to some extent (E14), the subsidence increased slightly; suggesting the importance of a stable base layer. When the walls were fixed to the side walls of a soil container (E18), the subsidence was further reduced. On the contrary, a use of drain pipes inside or outside of sheet pile walls (E26 and E27) increased slightly the

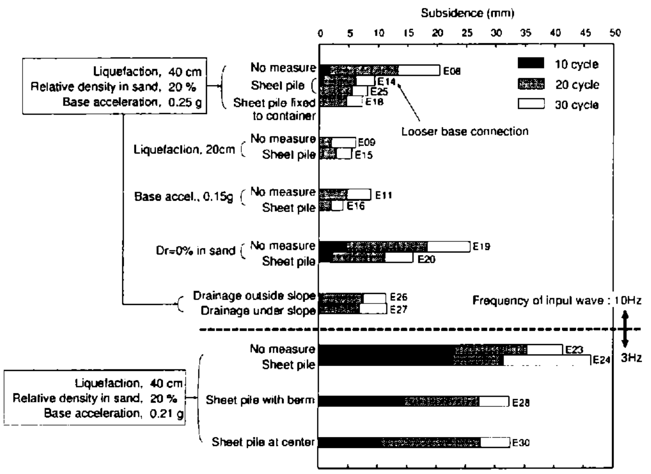

Fig. 22. Overall comparison of mitigative effects of sheet pile walls with different conditions.

subsidence, as compared with E25). This is probably due to progress of consolidation.

Shaking at 3Hz exhibits greater magnitude of subsidence; see bottom of Fig.22. This hazardous situation can be solved to some extent by using sheet pile walls with attached fill or installing walls from the shoulder.

CONCLUSIONS

Shaking table tests were conducted in 1-g gravity field on mitigation of subsidence of a river dike induced by subsoil liquefaction. The tested sandy deposit was made very loose in order to account for the effects of low overburden pressure in the reduced size of model. The major conclusions drawn from this study are summarized in what follows.

1) The experienced damage of Yodo River dike suggests that installation of sheet pile walls as well as placement of additional fills is promising.
2) Sheet pile walls reduces the subsidence to a certain extent.
3) By using sheet pile walls equipped with drain pipes under the slope of dike (inside of sheet pile wall), the subsidence is further reduced.
4) When shaking of sheet pile walls is increased possibly by resonance, a large amount of sand and water is boiled out, leading to increased magnitude of subsidence of dike.
5) This adverse situation can be mitigated by using drain pipes as stated above and/or placing additional gravel fills at the surface.
6) Installation of sheet pile walls from the top of a dike is not so efficient. It seems necessary that additional walls be installed at the toe of a dike.
7) Last but not least, the results of the present study is valid not only to river dikes but also to other types of embankment resting on liquefiable subsoil.

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