DAMAGE TO RIVER LEVEES AND REVETMENTS

NAOTOSHI TAKADA1), MASARU NISHII) and MASARU FUKUDA

ABSTRACT
Levees with masonry and concrete-block walls underwent collapse and distortion between the central Kobe and Nishinomiya where the most severe damage was sustained. In a coastal area, levees sustained characteristic deformation of the soft ground. In a reclaimed land liquefaction of the fill brought about excessive deformation in revetments of levees. Levees in the Muko River on the eastern foot of Mt. Rokko suffered from settlement, distortion and cracks. The Ina, Mo, Kanzaki, nakajima, Samondo, Aji and Shorenji Rivers were damaged where a thick soft sandy deposits underlay and old meanders were also found in some locations. In a port area, excessive distortion and cracks occurred in levees, while heavy concrete revetments supported by long piles which resist against the storm surge were little damaged. This paper outlines the structural, geological and geotechnical aspects of earthquake damage to levees in Hanshin region but damage to the Yodo River is excluded.

Key words: deformation, earthquake, failure, levee, river, rivetment (IGC: E6/H7)

INTRODUCTION
There are many small rivers running down the fan from Mt. Rokko to the sea in the area between central Kobe and Nishinomiya in Japan where buildings were severely damaged. Most of them are excavated type rivers having banks of the same height as the surrounding ground, while some are embankment type. These rivers usually have masonry walls. Many of them collapsed or deformed due to the impact of the earthquake. In the coastal area, where the ground is soft, levees deformed in a manner peculiar to soft ground.

There are several large rivers within the Osaka basin, eastern part of Mt. Rokko; including the Muko, Ina, Mo, Kanzaki and Yodo rivers; which have embankment type levees. The Muko river, which runs through a severely damaged area, was damaged throughout its entire length, although its embankments did not seriously collapse. Other rivers on the soft thick alluvial sandy and clayey deposits were also damaged. The largest river, Yodo River, was seriously damaged; the left side levee on the soft sandy deposit near the river mouth failed. Several small rivers between these rivers and some rivers of an old network of the Yodo River in the coastal area, and some branches of the Muko and Kanzaki Rivers were also damaged.

This paper presents the earthquake damage to the levees and revetments of rivers with respect to structural, geological and geotechnical conditions. Damage to the Yodo River is presented elswhere in this special issue of SOILS AND FOUNDATIONS.

OUTLINE OF THE DAMAGE
Figure 1 shows the distribution of rivers and the damage which occurred in the Hanshin region. Levees which were damaged were divided into two types: excavation type and embankment type. The former has the same height as the surrounding ground and the latter has an embankment higher than the surrounding ground. In this figure, the former also includes a levee that has a wide embankment crest exceeding three times the height of the front slope.

The extent of damage was collected based on materials provided by divisions and a branch in charge of both local and central government. Since these materials were prepared for restoration planning, slight damage or damage that requires urgent restoration were not considered. Small streams and ditches, which have pebble stone walls and were used for irrigation of rice paddies, were also reported to have collapsed at many locations, but are not discussed in this paper.

Figure 2 shows a schematic drawing of the subsurface conditions in damaged areas (quoted from Yoshioka et al., 1995 and Iwasaki, 1995 and composed). The foot of Mt. Rokko is an alluvial fan slope which consists of

---

1) Professor, Department of Civil Engineering, Osaka City University, Sugimoto 3-3-138, Sumiyoshi-ku, Osaka 558.
2) Professor, Department of Civil Engineering, Kobe University, Nada-ku, Kobe 657.
3) Chief, Soil Engineering Laboratory Co. Ltd., Yodogawa, Osaka 532.

Manuscript was received for review on August 17, 1995. Written discussions on this paper should be submitted before August 1, 1996 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

241
sandy to gravelly dense deposits, while soft sandy deposits occupy the surface of coastal and reclaimed areas. Muko River runs down the fan deposit between the foot of Mt. Rokko and the Itami diluvial terrace and flows to sea on an alluvial flood plane. Other large rivers, Ina and Kanzaki River systems and Yodo River, were damaged along the alluvial plane where thick soft sandy and clayey alluvial deposits are found.

Small rivers running down from Mt. Rokko have old masonry and concrete-block walls that were not seismically designed. The damage includes: simple collapse; soil flow, collapse of the backfill or back subsoil; sliding along the upper ground surface; settlement with heave of the riverbed. Different movement for different types of structures, such as the revetment and abutment of a bridge, were observed at many locations, resulting in joint openings. In a coastal area and reclaimed land near the shore, the revetments consisting of reinforced concrete walls or steel sheet pile walls suffered from cracks in the concrete facing structure, opening of joints, movement of the crest due to uneven settlement and lateral movement, although the damage was not serious.

Some rivers, Sumiyoshi and Asiya Rivers, having a riverbed higher than the surrounding ground, under which JR line passes, generated collapse of masonry walls, cracks in the embankment and lateral movement of inland ground surface at some locations. In the eastern area of Mt. Rokko, the Muko River suffered from settlement and cracking in the embankment, soil displacement of the back slope, cracking in the high-water riverbed, lateral movement of the ground surface at the toe of the levee at some locations. Rivers Ina, Mo and Kanzaki suffered from settlement of concrete facing of front slopes, lateral movement of low-water revetments, and lateral movement of inland ground surface at some location along the Mo River. Damage to embankments occurred at the locations where old meanders were found. At these locations, sand boils were also observed on the adjacent ground surface.

The Nakajima, Samondo, Aji and Shorenji Rivers, which run to the port area where the ground level is often lower than the sea level, have reinforced concrete revetments with long piles to protect against storm surge. Although little damage occurred to these revetments, settlement of embankment, lateral displacement of back slopes and cracking in concrete facing of high-water riverbed were found at many locations. In some locations, sea water leaked at high tide through the damaged levees.

The left side levee of Yodo River failed for a length of 2 km near the river mouth, although no damage occurred in the adjacent lower section because the levee was designed to resist both storm surge and earthquake. Settlement and soil displacement of the back slopes, cracking in the front slopes were found at several locations along the river.

No damage was reported to the gates installed near the mouth of tidal rivers and to the locks at the bridges that cross the rivers at a lower level, although the alignment of the railway for some locks on which the lock-gate travels was adjusted.

FEATURES OF DAMAGES

Rivers from Mt. Rokko

Many swift streams run down from Mt. Rokko. As typical examples among them, Figs. 3, 4 and 5 show cross sections of the Ishiya, Ashiya and Shuku Rivers. Ishiya
River has a riverbed lower than the surrounding ground, whereas the Shuku River has a higher riverbed than the surrounding ground. Ashiya River also has a higher riverbed in some places, and therefore the JR line passes under it. Each has masonry walls with a slope of around 1:0.5. The subsoil conditions in this region consist of sandy and gravelly alluvial fan deposits. In coastal areas, south of the Hanshin Line or National Highway Route 43, soft alluvial sandy deposits occur, while alluvial clayey deposit occurs beneath the soft sandy deposit in the Nishinomiya area.

Damage to river banks can be divided into 4 types of failure as illustrated in Fig. 6. Type 1 is a simple collapse of a masonry wall with backfill (see Photo. 1). This type is most commonly seen in this region. Type 2 is a failure that exhibits a circular slip failure in the upper part of wall (see Photo. 2, JGS, 1996). This is likely to occur in a high wall on a dense soil. Type 3 is a slip failure including the foundation of wall and background resulting in a large mass movement (see Photo. 3). Type 4 is settlement of the river bank accompanying heaving of the river bed (Photo. 4, JGS, 1996). This movement is possibly caused by high vertical acceleration quite peculiar to the present near field strong earthquake. This type is more likely to occur in a soft riverbed with a heavy (reinforced) revetment.

In the coastal area, rivers have revetments consisting of a concrete wall against the storm surge and waves. These walls suffered from uneven settlement, opening of joints, cracking on the concrete facing structures caused by uneven settlement and lateral movement, although the damage was not serious. The concrete blocks in front of the revetment to protect the revetment toe against storm
wave decreased the extent of the damage.

Shuku River, which is a typical example of the type with wide embankments, suffered from collapse of the masonry walls in Type 1, crackings in the crest as shown in Photo. 5. In addition, heave of the riverbed and lateral movement of inland subsoil due to displacement of the toe of the embankment were observed at some locations. Settlement and distortion of embankments generated the difference in level on the road surface at the ends of all the bridges crossing the river.

The Miya River flows through the reclaimed land near an old shore. The revetment of steel sheet pile with tie rods and anchor piles on both sides was deflected by lateral earth pressure increase due to partial liquefaction of the soft sandy fill (Fig. 7 and Photo. 6). This constructed land suffered seriously from uneven settlement due to liquefaction.

Figure 8 shows coincidence between the damaged areas to buildings (Japanese seismic scale of 6 or larger cited from various literature available) and to rivers appeared in Fig. 1.

Muko River

In Fig. 9, the location of Muko River is shown on an old map published in 1885; distribution of damage and important information such as location of sand boil are described on it. The Muko River has maintained its location for more than a century. The average width of the river is 250 m and the riverbed gradient ranges from 1/400 in the upper reach to 1/1000 in the coastal area.

From the river mouth to the Nanbu Bridge 1.8 km up-
stream from the river mouth, the river has reinforced concrete revetments to protect against storm surge and waves as other rivers have. Although sand boils are observed on the neighboring inland ground surface along this section, the levee generated a slight deformation such as movement of the crest due to uneven settlement of the subsoil. The configuration of the levee in the upper reach is illustrated in Fig. 10; the levee crest is 5 to 6 m high from the inland ground surface and 3 m high from the high-water riverbed; the high-water riverbed is wide and is protected by low-water revetment. The levee crests on both sides have a two-lane road, which passes under bridges with sloped embankment.

The damaged areas are mainly in the upper reach from the Hanshin line 2.6 km upstream from the river mouth as shown in Fig. 9. This levee did not collapse completely, but the levee crest settled ranging from 10 to 100 cm. Figure 9 omitted settlement less than 30 cm. When the levee crest was extended from 5 m wide to 7 m to meet a double-lane road, lines of curb blocks were left buried. This possibly caused the crackings easily to occur. The left side levee from 2.7 to 2.9 km from river mouth settled about 50 cm and cracking in the levee crest and the concrete facing on the front slope occurred. Displacement of the back slope toe caused lateral movement of the inland subsoil.

The right side levee from 5.0 to 5.3 km and at around 6.2 km has narrow cross sections because underpass slopes occupy the part of the front slope, thus large settlement and deep cracks occurred (Photo. 7). From 5.1 to 7.7 km on the left side, settlement and cracks occurred in the crest. Many cracks occurred on the front slope where a bridge pier of Meishin Express Way is located.

From 7.4 to 8 km on the right side, large settlement of 100 cm and cracking in the embankment (Photo. 8) and, in addition, many cracks in the high-water river bed along the levee toe occurred. This damage may be caused by the existence of a small stream along the toe of the back slope which can be seen in the old map in Fig. 9. The geotechnical survey indicates that the subsoil beneath the embankment consists of sandy silt with SPT values of 7 in the lower reach and gravelly sand with SPT values of 10 to 17 in the upper reach in this section.

From 8.1 to 8.3 km on the left side, settlement of about 100 cm in the crest occurred with cracks and uneven settlement (Photo. 9). Uneven settlement also occurred on the back slope, and concrete walls of the small stream running along the toe of the back slope were deflected. Cracks occurred in the high-water river bed, and a pier of Kobu Bridge was slightly deflected. Geotechnical survey indicates the subsoil beneath the levee is a soft gravelly sand 5 m thick with SPT values of 2 to 7.

Koni River, a small branch of Muko River having a stream 8 m wide running down from Mt. Rokko suffered extensive damage at the foot of a diluvial terrace: col-
Fig. 9. Present and past hydography of Muko Rivers on an old map indicating damage
lapse of the masonry wall on the right bank and distor-
tion of the left bank. Several buildings including a rein-
forced concrete building on the slope of the left bank
were seriously damaged (Photo. 10).

Another branch of Muko River, Tenjin River, suffered
from distortion of the levees. Geotechnical survey rev-
ealed that the subsoil beneath the levee is a silty sand 1 to
2 m thick with SPT values of about 5 and the embank-
ment 2 m high has SPT values of 2 to 5. These soft soils
lacking in bearing capacity caused the bases of levees to
expand resulting in settlement and distortion of the levee
and decrease in width of the stream (Photo. 11).

Kanzaki and Ina River Systems

Figures 11(1) and (2) show the locations of damage
together with lengths of damaged levees. Damage is con-
centrated in the lower reaches where alluvial soft deposits
are thick. Small branches joining the upper reach of
these rivers were also damaged at several locations.

Kanzaki River

Locations ① to ④, and ⑩ in Fig. 11(1) are in a port
area. Levees here have heavy concrete walls as revetments
with long steel piles to protect against storm surge. These
walls were not damaged, but the high-water riverbed
and/or embankment settled and deflected resulting in
cracking, joint openings and distortion of concrete fac-
ing structure. Figure 12 is an example of damage at the lo-
cation ④ in Fig. 11(1). The concrete wall and embank-
ment were constructed over an old masonry revetment;
settlement of the crest (two-lane road) of embankment
and displacement of the back slope occurred.

Locations ⑤ and ⑥ suffered from settlement of crest
Fig. 11(1). Kanzaki River system and damage

Fig. 11(2). Ina River system and damage
and back slope failures. The revetments of low-water riverbed in the location (6) moved forward (Fig. 13). Location (7) indicates the old Ina River which have been maintained after diversion of the main stream. The steel sheet pile revetment at left moved forward by 1 m; the back fill settled due to liquefaction. The deflection of revetment of the same type at right was small but the back slope 1.5 m high failed due to liquefaction of the adjacent subsoil (Fig. 14). Many tomb stones were displaced and fell down near here. Figure 15 shows the present river location on the old map of 1885. This figure suggests that the damage at locations (6) and (7) was caused by the presence of soft sandy deposits along the old streams.

Tenjiku River runs down from Senri Hill. It runs through the alluvial plane on the raised riverbed 8 m wide to join Kanzaki River. Both front slopes of the levees are constructed as a concrete revetment. At the location (8), surface slide occurred on the back slope 180 m in total length at 4 locations (Fig. 16). Although the revetments in the front slopes were not deflected, leakage occurred where a cement mixing cut-off wall along the toe of front slope was not yet constructed.

Nakajima and Samondo Rivers

Both rivers have similar levees to those employed by the lower reach of Kanzaki River. At location (9) in Fig. 11(I), settlement of the levee crest, distortion of the back slope and cracking on the high-water riverbed occurred for length of 950 m, and the concrete wall supported by steel piles also settled slightly.

Figure 17 shows the configuration of the levee at locations (a) and (b) in Fig. 11(I) together with the feature of damage: settlement of the levees and cracking in the concrete facing on the back slope (Photo. 12). At some locations, heave of subsoil occurred on the back slope toe and leakage of sea water occurred at high tide. Figure 18 shows settlement of the concrete wall for a length of 3.5 km from the river mouth together with the boring logs including SPT values. The maximum settlement of 1.8 m was recorded; the settlement including to some extent previous settlement due to land subsidence. One part, which was newly designed considering stronger seismic motion (Fig. 19), was not damaged. Boring logs in Fig. 18 show that the subsoil consists of soft reclaimed fill, a sandy deposit 6 m thick and of SPT values 2 to 20 and a soft clayey deposit 15 m thick. This sandy deposit is not as soft as suggested by Fig. 20 which indicates the distribution of soft alluvial sandy deposit that may be liquefied by a strong earthquake shock (Shibata and Iwasaki, 1987).

Ina and Mo Rivers

A general cross section of the levee of Ina River is shown in Fig. 21. The levee has a berm on the back slope and a high-water riverbed protected by a low-water revetment. Damage was concentrated on the lower reaches where thick soft sandy deposits are encountered.

At location (1) in Fig. 11(2), the levee 3.5 m high from the inland ground having a crest 8 m wide (two-lane road) is covered by concrete facing and blocks. Settlement of the crest and crackings in the front slope and high-water riverbed occurred for length of 290 m. The revetment of the low-water riverbed was displaced by 15 cm. The back slope was not damaged.

At locations (2) and (3), the levees were deflected accompanied by large cracks 5 to 20 cm wide and 100 to 200 cm deep. According to Fig. 15, this damage occurred at an old stream meander. This suggests the presence of soft soils and discontinuity of the mechanical properties of subsoils.

Locations (4) to (7) generated settlement, distortion of levees and crackings on the slopes and in the high-water riverbed. Sand boils were found on the surrounding ground surface. The levee at location (6) settled 100 cm accompanied by lateral movement of the inland subsoil. The geotechnical survey indicates that the subsoils are
The levee at this location also crosses an old meander. The alluvial deposits (about 15 m thick) consist of a soft sandy deposit 5 m thick and a soft clayey deposit about 5 m thick; the latter varies its thickness and depth below ground surface. The damaged levee 100 m long was temporarily protected by a sheet pile wall and replaced by a new embankment after the subsoil was treated by cement mixing.

At the uppermost reach, the Mo River also suffered from distortion of the back slope for length of 100 m due...
to slip of the widening of embankment. Senri River, which joins the Ina River at the southern end of Osaka Airport, generated collapse and deflection of the revetment at several locations (see Fig. 1).

Fig. 16. Cross section and damage at location ③ in Fig. 11(1)

Fig. 17. Cross section of levee and damage at location ③ and ④ in Fig. 11(1)

Fig. 18. Settlement of revetment and subsurface conditions

Fig. 19. Cross section of levee newly designed against stronger earthquake

Photo. 12. Damage to concrete facing on the back slope

Fig. 20. Section of levee newly designed against stronger earthquake
Aji and Shorenji Rivers

The Aji river was a main tributary stream of the Yodo River before the present lower reach of Yodo River was excavated. According to the old map of 1885, the present Aji and Shorenji Rivers have maintained their locations. This region has a thick alluvial deposit; sandy subsoil is soft with respect to liquefaction as shown in Fig. 20. Levees were designed similarly to those in the port area, and therefore the features of damage are similar. At location (1) in Fig. 23 near the river mouth of Aji River, concrete facing on the high-water river bed generated serious distortion and cracking for the length of 720 m, which was replaced by a new one.

Some levees of the Shorenji river were constructed on old ones which had sunk due to land subsidence from excessive pumping of ground water. The levee at location (5) in Fig. 24 is an example. The back slope was damaged due to settlement of the embankment.

Dohjima and Tosabori Rivers, the upper reaches of Aji River, which are located in the center of Osaka city also suffered from distortion of the revetments for length of 450 m and 350 m at locations (2) and (3), respectively.

CONCLUSIONS

The earthquake generated extensive damage at many locations along levees and revetments irrespective of the size of the river. It is obvious from the geotechnical viewpoint that the earthquake imposed forces on and caused damage to the earth structures that were less well compacted and were founded on soft subsoils. The following conclusions can be made from the data collected and the
site investigations:

1) Damage to old masonry walls was due to a lack of inherent strength, less compacted embankment material and presence of untreated soft foundation subsoils.
2) Damage was concentrated in areas where alluvial sandy subsoils are soft.
3) Damage is likely to occur at a location where the levee crosses an old stream.
4) Less damage occurred to revetments supported by long piles in port areas, although the embankments were often damaged.

ACKNOWLEDGEMENTS

The authors are indebted to the following agencies for their presentation of related materials in preparing this paper: Ina River Construction Office, Kinki Regional Construction Bureau, Ministry of Construction; River Division of Public Works, Osaka Prefectural Government; Nishinomiya Public Works Office, Hyogo Prefectural Government.

The materials presented in this paper were collected and arranged by following members in the river division, earth structure section in the Committee on Investigation of Hanshin-Awaji earthquake in Japanese Geotechnical Society: S. Araki (Dia-consultant Co. Ltd.), M. Ando (Kanko Co. Ltd.), Y. Tanda (Asanuma Cooperation Co. Ltd.), M. Hachiya (Chuo Fukken Consultant Co. Ltd.), N. Yoshida (Kyoto University), K. Yufu (Student, Kobe University).

REFERENCES