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Abstract

In this study, we report the damage characteristics of conduits in irrigation earth dams based on the surveys conducted on four dams with different conduit types (cast-in-place and precast types) and diameters (600–1000 mm). The damage condition (cracks, leakage, and joint separation) and the deformation of conduits were observed using a self-propelled measuring system with an inertial measurement unit (gyroscope and accelerometer) and a CCD camera. Results reveal that cracks were scarce in conduits, and most conduit deformations were accommodated by the joint separation. In particular, in the precast conduits, because the number of joints per unit length was more, the deformation tended to be allocated to several joints. Moreover, settlements of conduits were not simply convex in accordance with the overburden pressures but were significantly affected by intake structures and structural cutoff walls. Although, in the future, it is necessary to develop conduits with joints having both high sealing performance and flexibility, the results obtained from this study will provide important knowledge for this development.

Keywords: Earth dam, Intake work, Differential settlement, Earthquake

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Abstract

In this study, we report the damage characteristics of conduits in irrigation earth dams based on the surveys conducted on four dams with different conduit types (cast-in-place and precast types) and diameters (600–1000 mm). The damage condition (cracks, leakage, and joint separation) and the deformation of conduits were observed using a self-propelled measuring system with an inertial measurement unit (gyroscope and accelerometer) and a CCD camera. Results reveal that cracks were scarce in conduits, and most conduit deformations were accommodated by the joint separation. In particular, in the precast conduits, because the number of joints per unit length was more, the deformation tended to be allocated to several joints. Moreover, settlements of conduits were not simply convex in accordance with the overburden pressures but were significantly affected by intake structures and structural cutoff walls. Although, in the future, it is necessary to develop conduits with joints having both high sealing performance and flexibility, the results obtained from this study will provide important knowledge for this development.

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1. Introduction

Conduits are installed transversely through earth dams and these significantly affect the stability of the earth dams. The piping along conduits may cause internal erosion of embankments and produce embankment failure during earthquakes or heavy rainfalls. Hori et al. (2002) examined such damage characteristics caused by heavy rainfall for small earth dams, and reported that many embankments broke due to piping failure along conduits. Nakashima and Mohri (1999) investigated damages from the 1997 typhoon Rosie to small earth dams in Yamaguchi Prefecture and Shimane Prefecture in Japan. They reported that five of the seven breached embankments were caused by piping along their conduits. In addition, Hori (2005) examined cases of piping failure beside ancillary works in earth dams breached by heavy rainfalls, stating that in many cases, the failure surfaces were V-shaped above the conduits and also corresponded to surfaces previously excavated for conduits replacement. For piping failure along a reinforced concrete pipe due to heavy rainfall before an embankment construction is completed, Sherard et al. (1972) mentioned proposed two possibilities. First, the occurrence of differential settlement and decreased lateral earth pressure due to usage of low compressive material for backfilling the base excavated over the entire conduit length. Second, the likely occurrence of drying shrinkage cracks in the ground surface around the conduit is because of lengthy exposure during the installation and backfilling of the conduit.

Regarding damages to earth dams caused by conduits during earthquakes, Moriya and

Kawaguchi (1970) investigated 93 earth dams damaged by the Tokachioki earthquake in 1968. They reported that some damage was associated with intake works comprising inclined sliding gates on the upstream face and horizontal conduits. Considering leakage from conduits triggered by earthquakes, Tani and Hasegawa (1987) reported leakage from conduits in two small earth dams damaged by the Nihonkai-Chubu earthquake.

A cutoff wall is required as a countermeasure against leakage in the current guideline for the construction of small earth dams in Japan (MAFF, 2015). However, Sherard (1984) noted that cutoff collars and structural cutoff walls are likely disadvantageous to soil compaction with heavy rollers because of protrusion into the surrounding dam embankment. In addition, the author suggested the inclination of the side face of the conduit and filter at the downstream of the conduit as countermeasures of piping.

Ngambi et al. (1997) conducted in-situ measurements and numerical analysis for reinforced concrete conduits, indicating the horizontal earth pressure on the side face of the conduits drastically decreased with increasing vertical earth pressure on the upper surface of the conduits. In addition, to prevent piping failure, they suggested placing compressive materials on the upper face of conduits, inclining the side faces of conduits, and installing filters downstream of conduits. Fujita et al. (2008) conducted model tests on seepage failure along conduits embedded into a model ground subjected to local settlement, revealing that a pipe with flexible joints follows the local settlement with resistance against piping.

Elaborate surveys have been performed for earth dams severely damaged by earthquakes and heavy rainfalls. However, for earth dams without visible damage, the condition of the conduits remains essentially unreported.

In Japan, concrete pipes covered with reinforced concrete (Fig.1 (a), referred to as a cast-in-place conduit) are most commonly used as conduits in earth dams. In recent years, precast conduits, which are connected with PC steel bars or bolts through rubber sealing, are increasingly utilized to shorten the construction duration (Fig.1(b) and (c)). However, differences in structural types might affect damage and deformation of conduits. Moreover, although the settlements of conduits may be convex in accordance with overburden pressure, an intake structure connected at the upstream end of conduits and a structural cutoff wall also influence the deformation characteristic of conduits.

In this study, the results of damage investigation for conduits embedded in four earth dams in Hyogo Prefecture in Japan are reported. The conduits investigated are of different types (i.e., cast-in-place and precast types) and diameters (600–1000 mm). A self-propelled measuring system using an inertial measurement unit (gyroscope and accelerometer) and a CCD camera were employed for acquiring data of the vertical displacement and pictures of the damage condition (cracks, leakage, and joint separation). In particular, the effects of the following: (i) the differences in structural types (i.e., cast-in-place and precast types), (ii) a structural cutoff wall and an intake structure, and (iii) earthquakes on the damage or deformation characteristics of conduits are examined.

2. Damage survey

2.1. Investigated earth dams

In this study, four earth dams in Hyogo Prefecture in Japan were investigated. The conduits in Dams A and B are cast-in-place while those in Dams C and D are precast (Table 1). The renovation of Dam A is the oldest of the four dams and it was exposed to the 1995 Southern Hyogo Prefecture Earthquake, whereas Dams B, C, and D were renovated after the earthquake. The service life of reinforced concrete structures is generally over 40 years. The damage survey was conducted in 2017, and all the conduits are sufficiently younger than their service lives. Regarding the consolidation settlement, because the embankment height did not change significantly before and after retrofitting, the foundations must have been in over-consolidated state and the settlement would have been immediately completed. Therefore, the effect of the retrofitting year on the damage is not likely to be significant.

The cast-in-place type conduits involve joints of reinforced concrete on the joints of concrete pipes. Moreover, dowel bars are installed in the conduits to prevent differential settlement between the joints, while a water stop plate installed through two joint filler boards prevents leakage (Fig.1 (a)). Conversely, in precast conduits, different rubber seals are used in type I and II, with blocks connected using PC bars and bolts in type I and type II, respectively (Fig.1(b) and (c)).

2.2. Survey methodology

A self-propelled crawler with an inertial measurement unit (gyroscope and accelerometer, e.g., Shiozawa et al., 2013) and a CCD color camera (720×480 pixels) was moved from the downstream to the upstream ends of the conduits for the investigation. Cracks, leakage points, and joint separations were observed based on images captured by the camera, and the vertical displacements were measured using the inertial measurement unit. The position accuracy of the inertial measurement unit used in this study is 2–3 mm and 3–5 mm for 1-m lateral and vertical movements, respectively.

The camera mounted on a frame in Fig.2 was movable by remote control, with the ability to place the camera head at the center of the pipe (Fig.3 (a)). In addition, the camera also rotates through the remote control, enabling 360° imaging of the pipe's internal face. Thus, at conduits joints, the gap distance of joint separations was evaluated based on pictures of the internal faces (Fig.3 (b)).

To clarify the deformation of the conduits, the vertical relative displacement, which is defined as the difference from the designed value (i.e., initial elevation of the conduits), was calculated as summarized below.

The positions (x, y, z) were obtained based on the movement of the inertial measurement unit moving from the downstream to the upstream side of the conduits. The displacement was calculated as follows:

$$L(x, y, z) = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} \quad (1)$$

where L is the displacement, x_0 , y_0 , and z_0 are the starting positions (i.e., the downstream ends of the conduits). Assuming that the conduits were installed in accordance with the blueprints, the initial elevation of the conduits was calculated as follows:

$$H_b(L) = H_{b0} + i \times L \quad (2)$$

where H_b is the initial elevation of the conduit, H_{b0} is the initial elevation at the downstream end of the conduit, and i is the design gradient. Thus, the elevation of the conduit during the survey was given by:

$$H(z) = H_{b0} + (z - z_0) \quad (3)$$

where H is the elevation of the conduit during the survey. Because the elevation at the downstream end of the conduit during the survey could not be measured owing to time constraints, this was assumed as H_{b0} . Therefore, at the downstream end (i.e., $z = z_0$ or $L = 0$), H is equal to $H_b (= H_{b0})$. Moreover, based on Fig.4, the position changed with rotation of the vehicle. Regarding the position z , this difference was significant and the position was corrected as follows:

$$\Delta z = -r(1 - \cos \theta) \quad (4)$$

$$z = z' + \Delta z \quad (5)$$

where Δz is the correction for position z , r is the distance from the center of the pipe to the inertial measurement unit, θ is the rotation angle, and z' is the position before the correction. Therefore, the vertical relative displacement d_r is obtained from the expression:

$$d_r = H - H_b = (z - z_0) - i \times L \quad (6)$$

As indicated earlier, this relative vertical displacement represents the difference from the designed value (i.e., the initial elevation of the conduit).

3. Survey results

The damage appearance (i.e., cracks, leakage, and joint separations) and conduits deformation in Dams A, B, C, and D are displayed in Figs.5–8. The joint separations are partitioned into four groups based on the gap distances. These include: non-gap (less than 5 mm), small gap (greater than 5 mm but less than 10 mm), medium gap (greater than 10 mm and lower than 15 mm), and large gap (greater than 15 mm). Although there was no particular engineering significance with respect to the interval of 5mm, it was adopted as a reliable threshold value based on the scale interval of the camera (10 mm). The conduit deformation is the relative vertical displacement calculated using equation (6). The measurement using the inertial measurement unit was not performed for Dam B owing to financial limitations.

3.1. Dam A

Joint separations were observed in five out of eleven joints as illustrated in Fig.5. The joint separation in the upstream end of the conduit was over 15 mm (large gap) as shown in Fig.3(b), and the relative vertical displacement was -38 mm at the same location. These were likely caused by the settlement of the intake structure. In addition, a crack and leakage were present at the connection with the intake structure.

3.2. Dam B

Two medium joint separations of approximately 10 mm (medium gaps) occurred at the center and the upstream side of the conduit, without any crack or leakage as exhibited in Fig.6.

3.3. Dam C

The survey results for Dam C in Fig.7 reveal joint separations of approximately 5 mm (small gaps) at three locations, while leakage emerged at two spots in the downstream side of the core. Moreover, although the base foundation improved, the relative vertical displacement was -30 mm.

3.4. Dam D

Although there was no crack, and no joint separation that exceeded 5 mm (small gap), two traces of leakage occurred, with the relative vertical displacement of 27 mm (Fig.8).

4. Discussion

4.1. Influence of structural types on damage and deformation of conduits

Only one crack, present in Dam A was observed for all dams investigated. This result suggests that the conduit deformation was accommodated by the joint separations for the cast-in-place and the precast conduits.

The cast-in-place conduits in Dams A and B displayed in Figs.5 and 6 exhibit joint separations representing medium and large gaps. Contrarily, in Figs.7 and 8, for the precast conduits in Dams C and D, the joint separations are characteristic of no or small gaps. In particular, in Dam D, because the length of one block is 1 m and the number of joints per unit length is more, no joint separation greater than 5 mm exist. Although the maximum values of relative vertical displacement in Dams C and D are smaller than that in Dam A, the vertical displacements against their total length in Dams C and D are greater than that in Dam A. Therefore, the deformation in the precast conduits is likely accommodated by the several joints. However, in Dams C and D, leakage is present, with sealing still an issue in precast conduits.

4.2. The influence of intake structures and structural cutoff walls on the damage and the deformation of conduits

To elucidate the influence of intake structures and structural cutoff walls on damage and deformation of conduits, the positional relationships between the structural parts and the damage were examined. The

position in Table 2 is the order counted from the structural parts. For example, in Dam D, although damage is observed at joints No 16 and 15, these positions are the first and second from the intake structure, respectively. If the same damage is considered from the structural cutoff wall, the positions are fourth and third, respectively. Therefore, the lower order (i.e., first and second) is termed the “occurrence position.” In addition, if several damages (e.g., leakage and joint separation) occur at the same joint, these are counted separately.

The number of damages and the occurrence positions are presented in Table 2, while the proportions are displayed in Fig.9. From Fig.9, approximately 70 % of the damage concentrates at the first or second joint from structural parts. Therefore, intake structures and structural cutoff walls significantly affect damage and deformation of conduits. In Dam A, judging from the distribution of the relative vertical displacements (Fig.5), the settlement of the intake structure likely occurred. In Dams C and D, the structural cutoff walls probably served as fulcrums (Figs.7 and 8). In particular, in Dam D, the N value of 7 is significantly lower compared with that in Dam C (N value = 41), and the settlement of the intake structure likely caused the positive vertical displacement near the structural cutoff wall. Note that the standard penetration test in both dams were performed directly below the upstream end of the conduits before retrofitting dams, and the above N values were obtained in the vicinity of the core bottom.

4.3. The influence of earthquake on damage and deformation of conduits

As presented in Table 1, Dam A was exposed to the 1995 Southern Hyogo Prefecture Earthquake, which is an earthquake that caused major damage to agricultural facilities (e.g., Hasegawa and Murakami, 1996). Although Dam B which was renovated after the earthquake shows joint separations, no crack or leakage was present. In contrast, in Dam A, the joint separations, crack, and leakage were observed, representing the severest damage for all dams investigated. Therefore, based on these results, major earthquakes may affect the damage and deformation of conduits in earth dams. However, assigning a dominant influence for earthquakes is premature due to scant data.

5. Conclusions

In this study, to clarify damage characteristics of conduits in irrigation earth dams, surveys were conducted on four conduits (ϕ 600–1000 mm cast-in-place and precast conduits) using a self-propelled measuring system including an inertial measurement unit (gyroscope and accelerometer) and a CCD camera. The findings are summarized as follows;

- 1) Only one crack was observed for all dams investigated in this study, with deformation of most conduits accommodated by joints separation. In particular, in the precast conduits, because the number of joints per unit length was more than that in the cast-in-place conduit, the deformation tended to be allocated to several joints.
- 2) The settlements of conduits were not simply convex in accordance with the overburden pressures, but

were significantly affected by the intake structures and structural cutoff walls. In addition, the damage also concentrated near the structural parts.

- 3) Regarding the influence of earthquakes, although investigations were scant, large earthquakes were likely to negatively affect conduits in earth dams.

In the future, the development of conduits with joints having both high sealing performance and flexibility is essential. The results obtained from the present study must provide important knowledge for this development.

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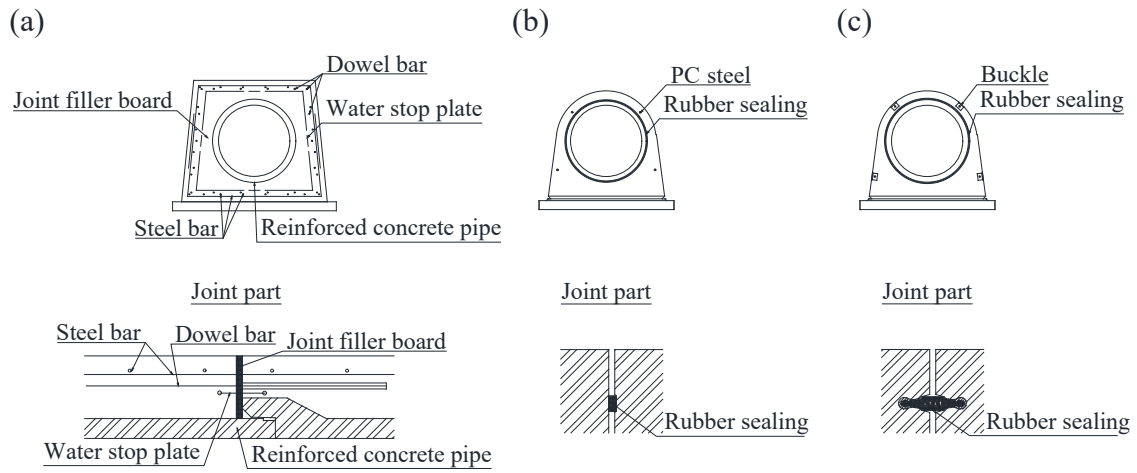


Fig. 1 Cross section of a conduit for a) cast-in-place conduit, b) precast conduits connected with PC bars (Type I), and c) connected with bolts (Type II)

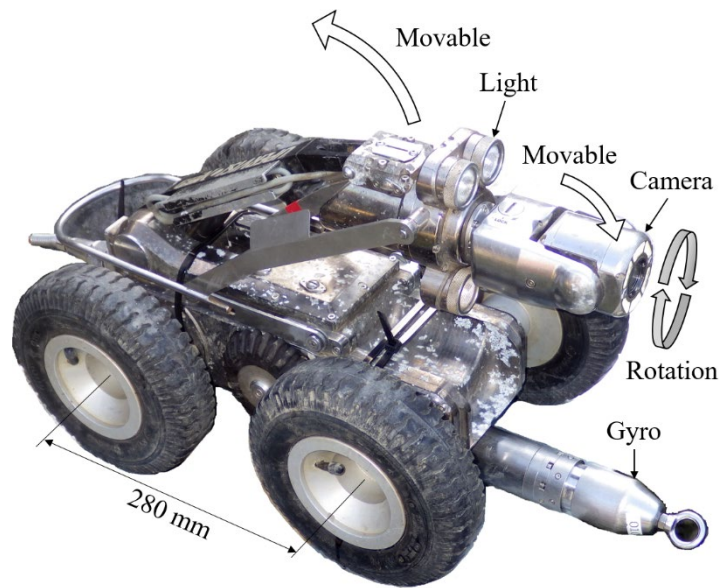


Fig. 2 Photograph of the self-propelled measuring system utilized for conduit examination

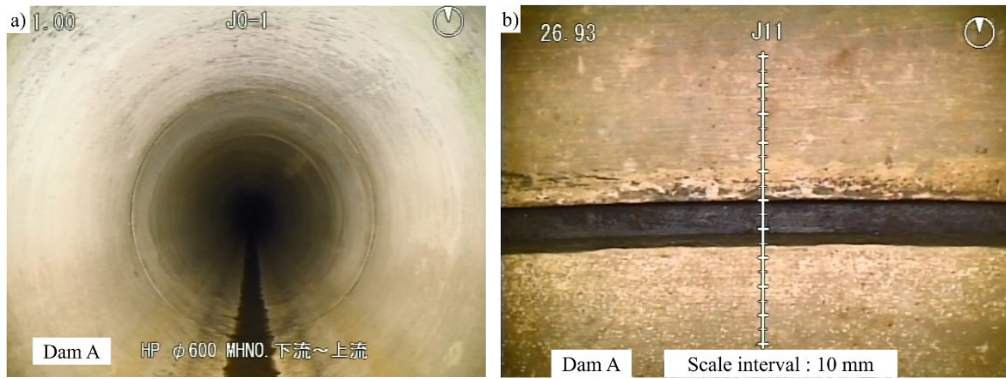


Fig. 3 Photographs taken by the camera of the self-propelled measuring system

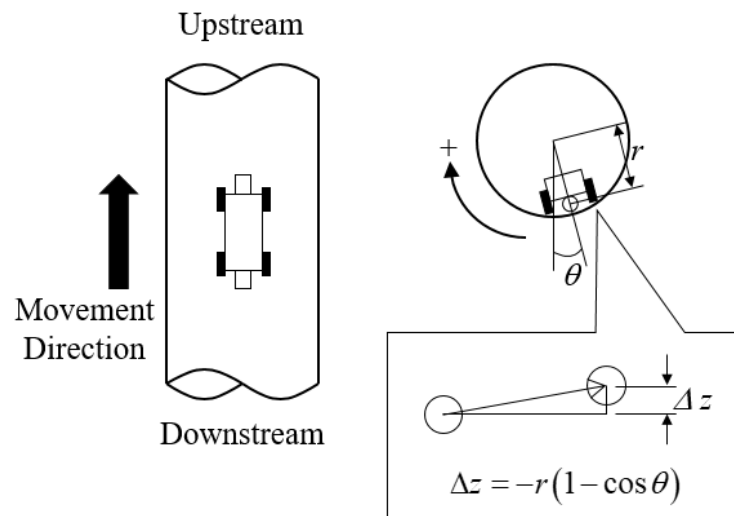


Fig. 4 Illustration of the movement direction of the self-propelled measuring system and the correction of z due to its rotation

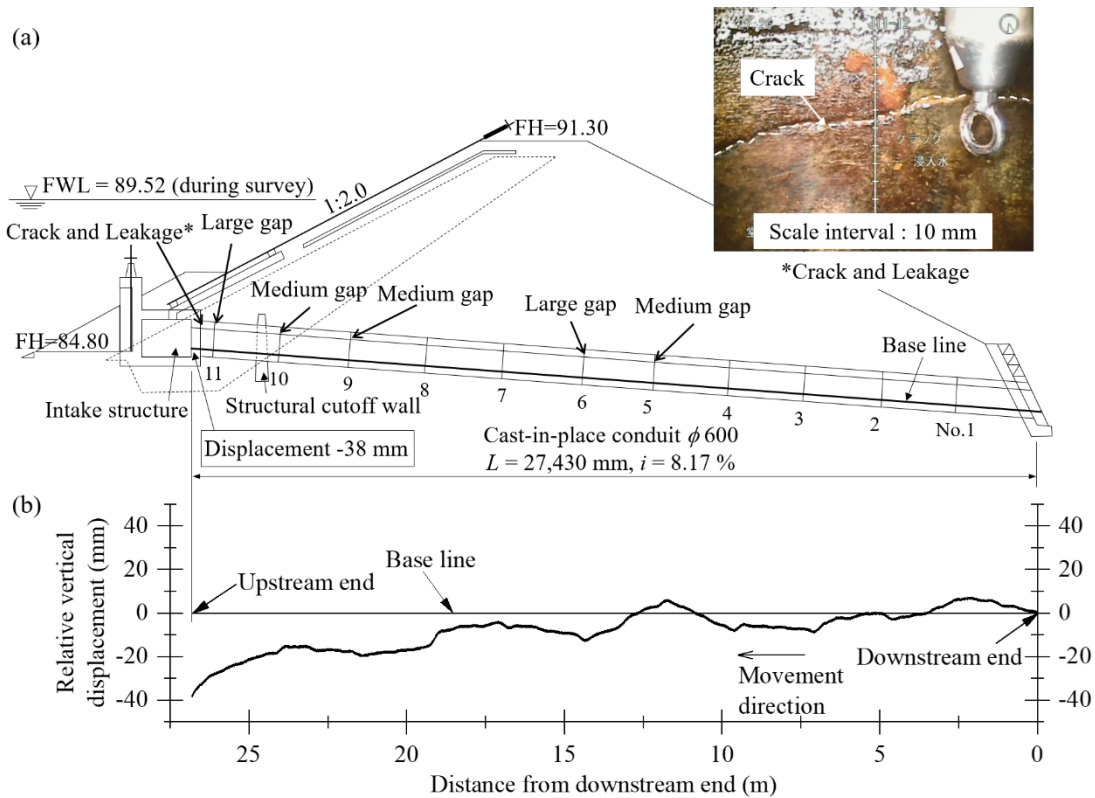


Fig. 5 Survey results in Dam A: (a) the damage conditions (the emergence of cracks, leakage, and joint separations) and (b) the relative vertical displacement

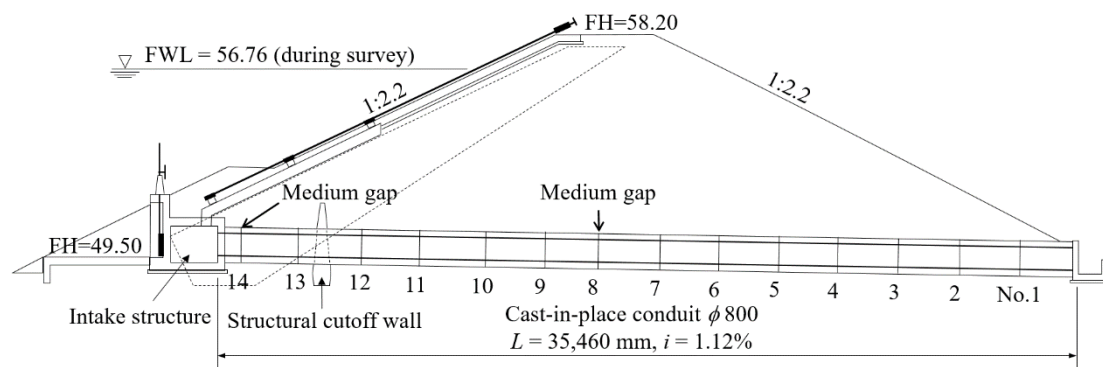


Fig. 6 Survey results in Dam B (the emergence of joint separations)

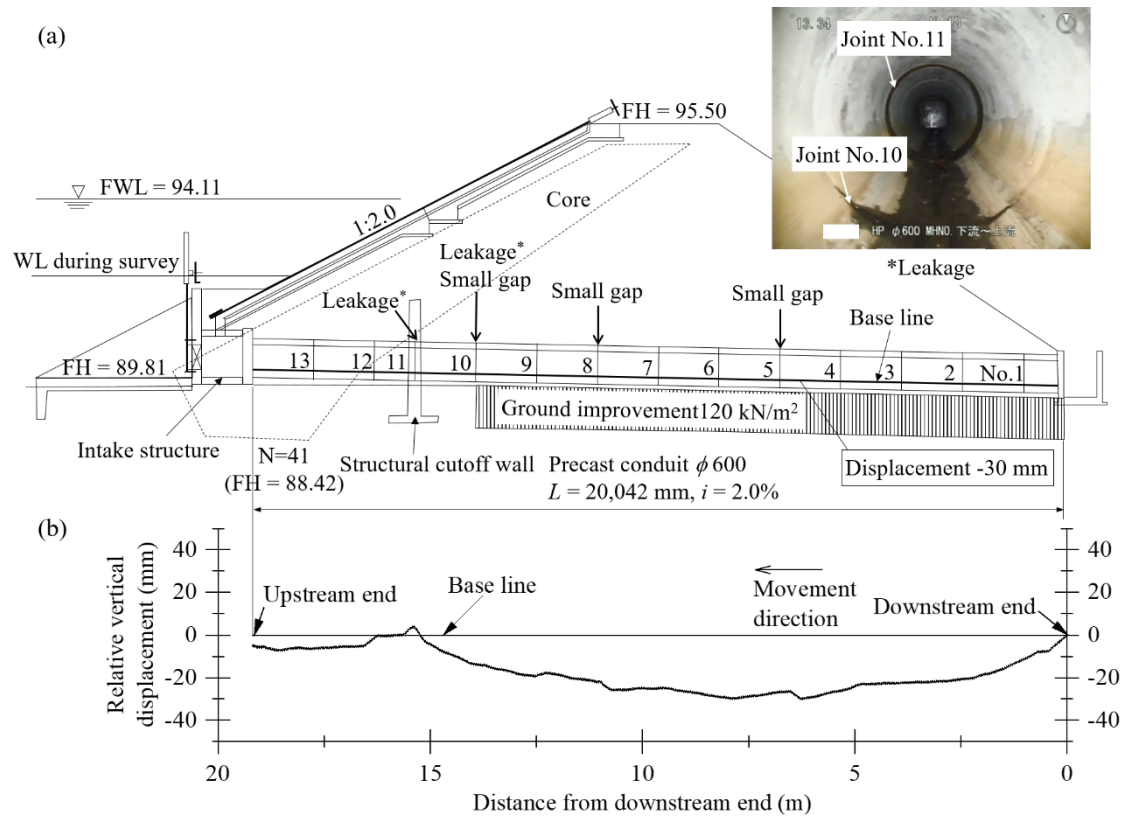


Fig. 7 Survey results in Dam C: (a) the damage conditions (the emergence of leakage and joint separations) and (b) the relative vertical displacement

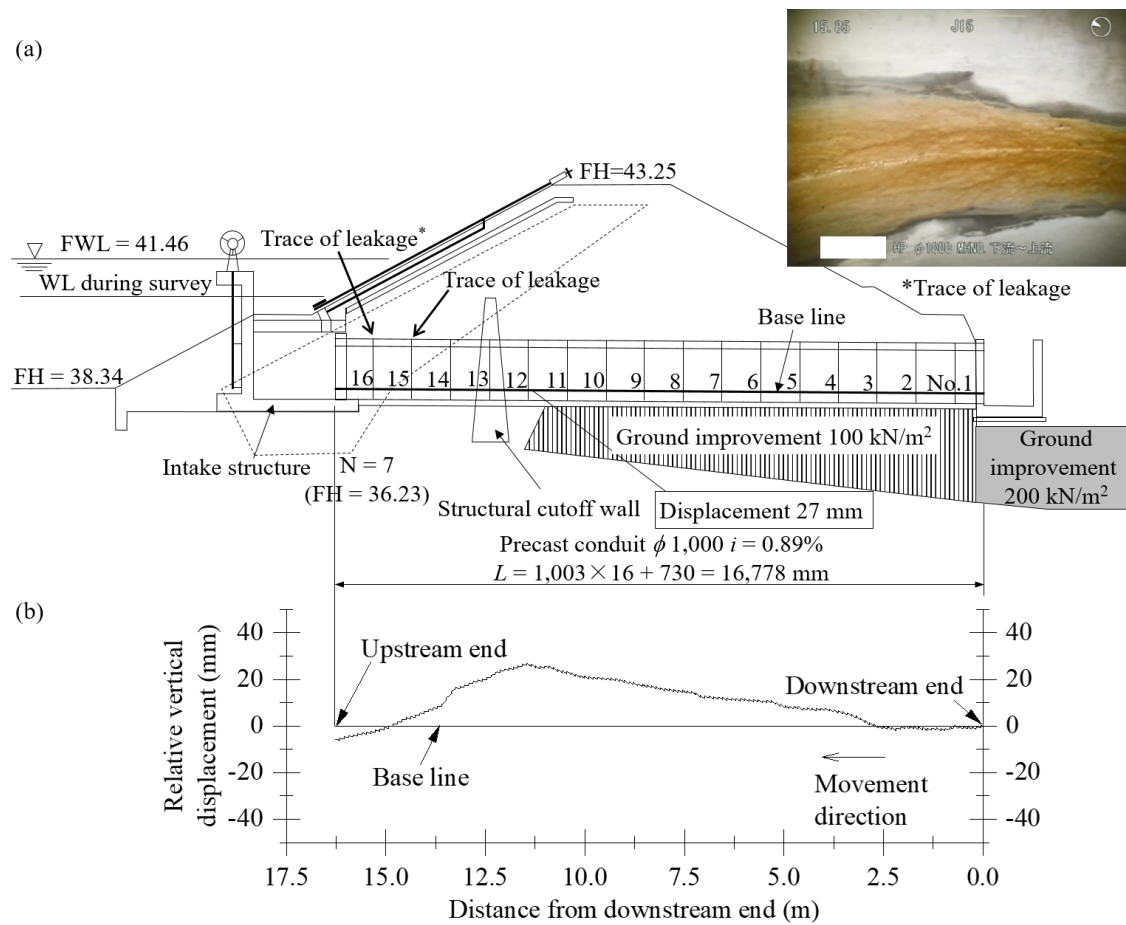


Fig. 8 Survey results in Dam D: (a) the damage conditions (the emergence of leakage) and (b) the relative vertical displacement

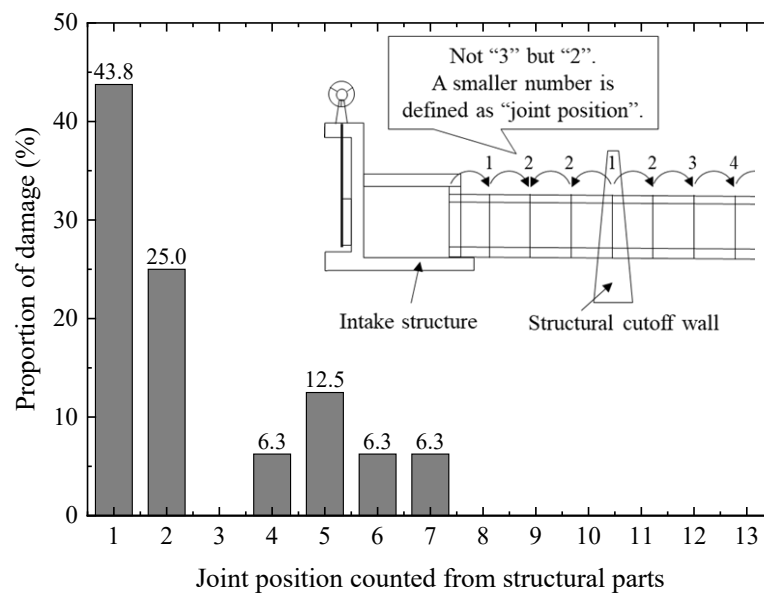


Fig. 9 The proportion of damage at joint positions counted from structural parts

Table-1 Specifications of the earth dams investigated in this study

Designation	Specifications of conduits (Type, diameter: ϕ , total length: L , and gradient: i)	Depth of cover (m)	Retrofitting year
Dam A	Cast-in-place conduit ϕ 600, $L = 26.4$ m, $i = 8.17\%$	6.7	1994
Dam B	Cast-in-place conduit ϕ 800, $L = 35.6$ m, $i = 1.12\%$	7.8	2000
Dam C	Precast conduit ϕ 600, $L = 20.0$ m, $i = 2.0\%$	5.3	2012
Dam D	Precast conduit ϕ 1000, $L = 16.8$ m, $i = 0.89\%$	3.8	2013

Table-2 The number of damages at joint positions counted from the structural parts

Position	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Dam A	4	1	0	0	1	1	0	0	0	0				7
Dam B	1	0	0	0	1	0	0	0	0	0	0	0		2
Dam C	1	2	0	1	0	0	1	0	0	0	0			5
Dam D	1	1	0	0	0	0	0	0	0	0	0	0	0	2
Total	7	4	0	1	2	1	1	0	0	0	0	0	0	16
Proportion (%)	43.8	25.0	0.0	6.3	12.5	6.3	6.3	0	0	0	0	0	0	