DISTRIBUTION OF PHYSICAL PROPERTIES IN ROLLER-COMPACTED DAM-CONCRETE CORES ANALYZED BY X-RAY CT

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INTRODUCTION

With regard to the Roller-Compacted Dam-concrete (RCD) placing procedure in Japan, the compaction performed by a vibrating roller after RCD is build up to 75 cm or 100 cm in thickness with several thin layers spread by a bulldozer. This is one of the points where it differs from the Roller-Compacted Concrete (RCC) placing procedure with a thickness of 30 cm. As the thickness of compaction in the RCD method is greater than that in the RCC method, it is necessary to pay special attention to the homogeneity of physical properties in one layer of concrete by the RCD method. However, there have been few studies of these properties.

Here, the segregation of mixed materials and the condition of compaction in cores drilled vertically from an RCD embankment were investigated nondestructively and quantitatively by an X-ray CT method. X-ray CT is a convenient method for nondestructively visualizing internal structures of many types of materials. This method has been used widely since the 1970s for medical diagnosis. The use of X-ray CT has since spread to the industrial field, and this powerful tool can be applied to many types of material, such as soil, rock, and concrete (Otani and Obara, 2003). The X-ray CT method is expected to become a useful diagnostic technique to ensure the safety of large dams.

MATERIALS AND MIX PROPORTION OF RCD

Cementitious material for RCD used in constructing a trial embankment consisted of moderate cement (density 3.21 g/cm^3) and 30% replacement of fly ash (density 2.14 g/cm^3). The physical properties of the aggregate are shown in Table 1. The mix proportion of the RCD for the embankment is summarized in Table 2.

The embankment was constructed such that the thickness of one lift was 100 cm. One lift consisted of five layers, each of which was spread by a bulldozer with a weight of 15 tons. A vibration roller with a weight of 10 tons and a vibrating force of 23 tons was used for compaction of the RCD. Compaction by the vibration roller was performed either 16 or 12 times.

X-RAY CT METHOD

X-ray CT scanner

The X-ray CT scanner used here was a TOSCANER-23200min, as shown in Figure 1, developed for industrial use. The collimated X-ray penetrated from the circumference of the specimen by rotating and traversing the turntable. The detected data were assembled and cross-sectional images reconstructed using an image processing system by the filtered back-projection method. The images were displayed on an engineering workstation. These cross-sectional images around the circumference of the specimen can be used to reconstruct the three-dimensional images. The specification of the X-ray CT scanner is given in Table 3. Medical CT scanners are most commonly equipped with a 140-kV X-ray tube, while the industrial model used here was equipped with a 400-kV X-ray tube, and thus the scanning capacity for industrial use is much higher than that of the medical scanner.

The cylindrical drilled core specimens measured ø20 cm × 100 cm. Specimen A with a compaction time of 16 and Specimen B with a compaction time of 12 were cut into lengths of 50 cm. X-ray CT images were taken every 2 cm along the length of the specimen, and the total number of sections was 50 for each specimen. The method used for cutting and scanning of the drilled core is shown in Figure 2.

Table 1. Physical properties of aggregate.

Item			Density (SSD)	Water absorption	Bulk density	Solid content	Fineness Modulus
Test method			JIS A 1109,	JIS A 1110	JIS A 1104	JIS A 1104	JISA1102
Unit			(g/cm^3)	(%)	(t/m^3)	(%)	
Coarse aggregate	G1	150-80mm	2.68	0.15	1.47	55.1	9.94
	G2	80-40mm	2.68	0.33	1.57	58.7	8.45
	G3	40-20mm	2.68	0.56	1.57	58.9	7.89
	G4	20-5mm	2.67	0.44	1.53	57.5	6.72
Fine aggregate	S	5-0mm	2.65	1.47	1.69	64.7	2.63

Table 2. Mix proportion of RCD.

Max. size of coarse aggregate	VC value	Water-cement ratio	Fine percent	Unit content (kg/m^3)								
				Water	Cement	Fly ash	Fine aggregate	Coarse aggregate				AE Reducer
		W/(C+F)	s/a	W	C	F	S	G1	G2	G3	G4	Ad
(mm)	(sec)	(%)	(%)				0-5mm	150-80 mm	80-40 mm	40-20 mm	20-5 mm	
150	15	95	32	95	70	30	724	389	389	389	388	(C+F) x 0.25%

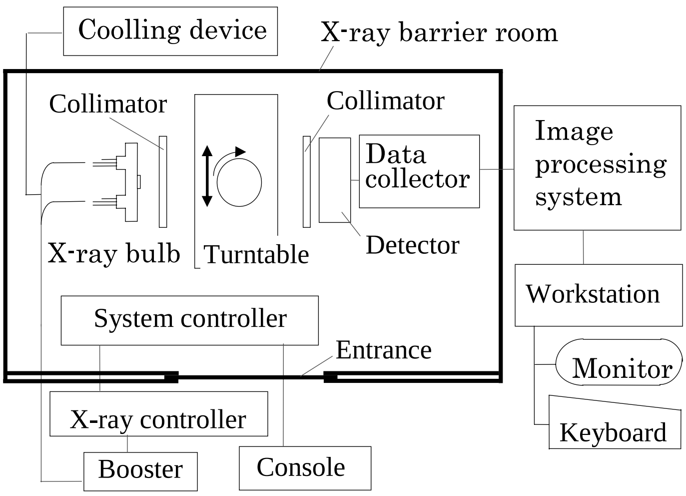

Figure 1. Composition of the X-ray CT scanner.

Table 3. Specification of X-ray CT scanner.

Scan type	Traverse/Rotation
Power of X-ray	300 kV/400kV
Number of detectors	176 channels
Maximum size of specimen	40 cm in diameter, 60 cm in height
	0.5 mm, 1 mm, 2 mm
Thickness of X-ray beam	0.2 mm (diameter of hole) for steel bar 20 mm diameter
Spatial solution	

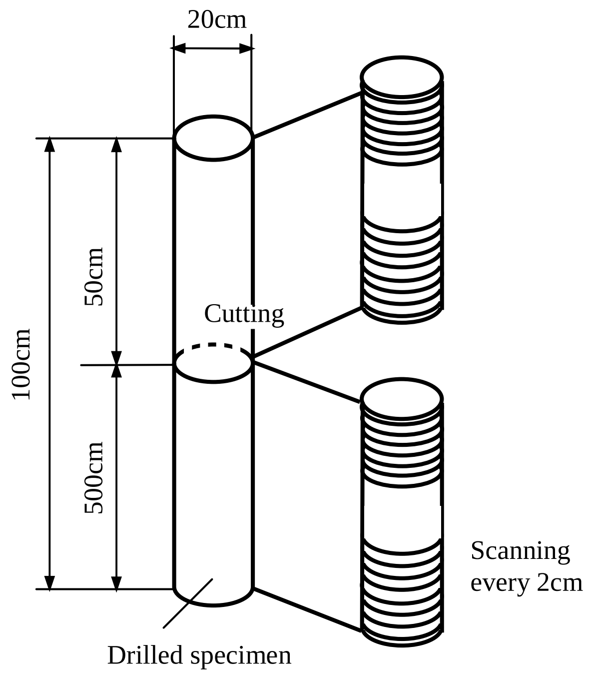

Figure 2. Drilled core and scanning

CT value

The images obtained with the X-ray CT scanner are 512 × 512 pixels and the CT value defined by the following formula is given to each pixel. In this study, the size of each pixel was 0.293 mm × 0.293 mm.

$$\text{CT value} = \frac{\mu_t - \mu_w}{\mu_w} K \qquad (1)$$

where μt : Linear absorption coefficient of X-ray at scanning point
μw : Linear absorption coefficient of X-ray for water
K : Constant for projection

Here, it is noted that the constant *K* was fixed to a value of 1000. Thus, the CT value of air was –1000 because the linear absorption coefficient for air is almost zero, and then the CT value of water is 0.

The CT images are presented in shaded gray or black for low CT values and light gray or white for high CT values. The total number of levels on these colors was 256 as grayscale images. An example of a cross-sectional grayscale image of Specimen A is shown in Figure 3. The white portion is the specimen and the surrounding black portion is air. The inner light gray portion is coarse aggregate, the dark gray portion is mortar, and the black portions are voids. Thus, they can be distinguished visually on the image.

BINARIZATION OF COARSE AGGREGATE AND OTHERS ON IMAGES

The Figure 4 shows the histogram of CT value of Figure 3. The lateral axis represents the CT value and the longitudinal axis is the frequency. The figure shows a normal distribution and does not indicate any particular characteristic for aggregate, mortar, or void. Similar observations were made in all cross-sectional images.

To distinguish aggregate, mortar, and void, and to analyze the characteristics of their distribution within the specimens, binarization of coarse aggregate and remaining components was performed in the original images, as shown in Figure 3. However, the boundary between aggregate and mortar was not as clear as in the CT value data. Therefore, binarization is difficult using existing software, and manual processing was adopted for binarization as described below.

First, the boundary between aggregate and mortar in the X-ray CT image was emphasized by image processing software, so that the boundary becomes clearer. Tracing paper was superposed on the printed image, and the boundary was drawn by hand with a marker pen. The drawn diagram is shown in Figure 5. Second, the data from the diagram were stored on computer with a scanner. Finally, the inner portion enclosed by the boundary was painted black, and the binary image was obtained as shown in Figure 6.

ESTIMATION OF STRUCTURAL CHARACTERISTICS OF RCD

Distribution of coarse aggregate

The black portions represent the coarse aggregate in Figure 6. Therefore, the ratio of the area of black portions to the whole cross-sectional area of the specimen is considered the ratio of coarse aggregate contained in the cross-section. This ratio was defined as the ratio

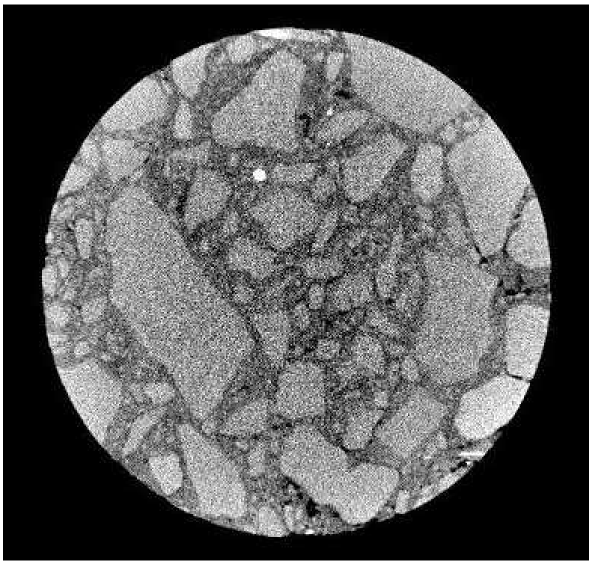

Figure 3. Cross sectional grayscale image of Specimen A.

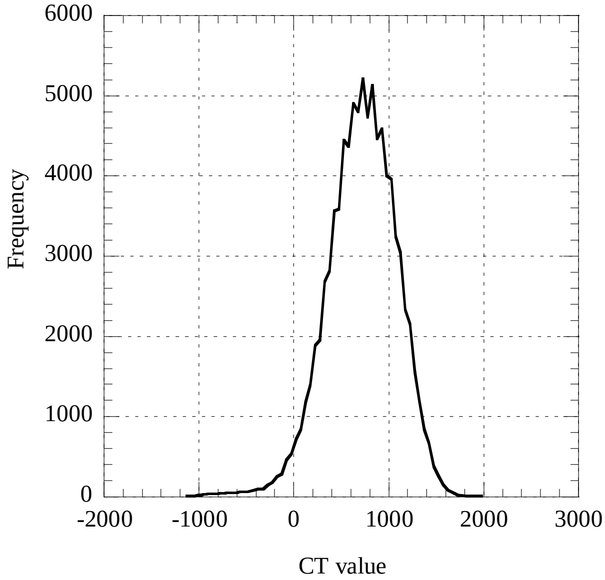

Figure 4. Histogram of CT value of cross-sectional image.

Figure 5. Image of traced boundary between aggregate and mortar.

Figure 6. Binary image by manual processing.

of coarse aggregate, which was calculated in all cross-sectional binary images obtained by manual processing.

The relations between the ratio of coarse aggregate and the depth of both specimens are shown in Figures 7 and 8, respectively. Although the ratio of coarse aggregate for the upper part on the embankment was slightly smaller than that for the lower part in Specimen B, the ratio of coarse aggregate of both specimens is considered to be distributed uniformly with depth. Thus, spread by a bulldozer and compaction by a vibration roller in the RCD method are carried out uniformly without segregation or concentration of coarse aggregate. The theoretical volume ratio estimated from the mix proportion was 59%. On the other hand, the average values of the area ratio of coarse aggregate for Specimens A and B were 56% and 55%, respectively. These values, which were estimated as area ratio in cross-section, were approximately 94% of the theoretical values. Therefore, we concluded that the area ratio of aggregate in cross-section by manual binarization is available for estimating the ratio of aggregate in practice.

Distribution of void

The CT value of coarse aggregate is higher than that of mortar, because the density of the former is higher than that of the latter. Therefore, the CT value of coarse aggregate is distributed in the relatively higher region of the histogram shown in Figure 4. The CT values except those of aggregate are due to mortar and void. Furthermore, as the inside of the void is considered to contain air, its CT value is defined as less than zero.

Then, the histogram of CT values was classified into void, mortar, and aggregate, as shown

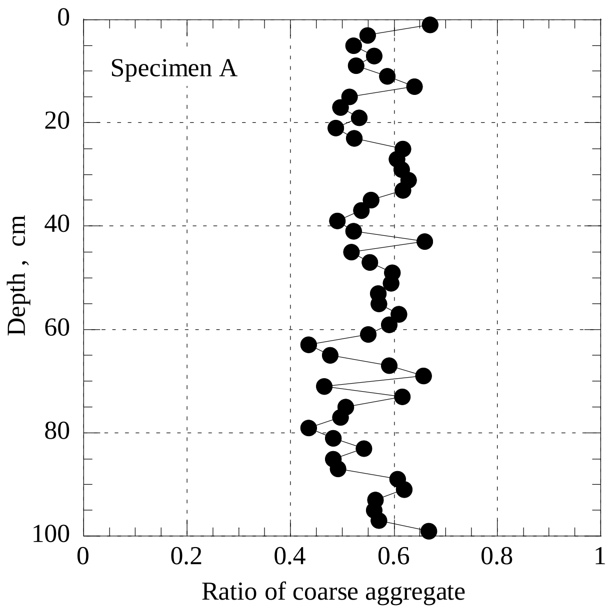

Figure 7. Distribution of ratio of coarse aggregate with depth in Specimen A.

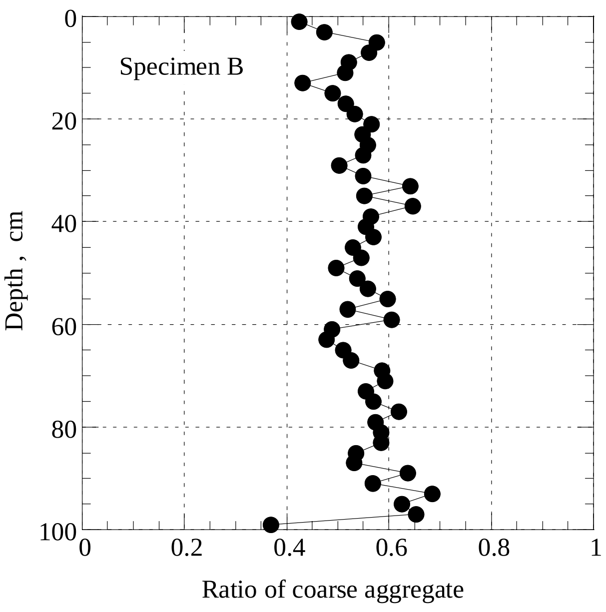

Figure 8. Distribution of ratio of coarse aggregate with depth in Specimen B.

in Figure 9. The area of void was obtained by integrating the distribution function in the range of CT value of less than zero. The whole area of the frequency distribution was also calculated. Therefore, the ratio of void was defined as the ratio of the area of void to the total area of the histogram. On the other hand, as the ratio of coarse aggregate was known, this ratio occupied the whole area of the histogram at higher CT values. The remaining components other than the areas of aggregate and void represent the mortar portion.

The distributions of the ratio of void for both specimens are shown in Figures 10 and 11, respectively. The results showed that the ratios of void of both specimens were 2~4% and 3% on average, despite differences in compaction times. The ratio of void decreased with increasing depth. The voids were considered to move from the lower to the upper parts during compaction by a vibration roller.

Distribution of CT value for mortar portions

The histogram of CT values was classified as shown in Figure 9. The mean CT value of the mortar portion in each cross-sectional image can be estimated. The mean CT values of both specimens are shown in Figures 12 and 13, respectively. Although in Specimen A, the mean CT value in the upper part was slightly lower than that in the lower part, in both Specimens A and B, the mean CT values were scattered uniformly between 450 and 500, and no changes in value dependent on the depth of specimen were seen. Thus, the RCD was mixed uniformly and remained homogeneous during spreading and compaction for building of an embankment.

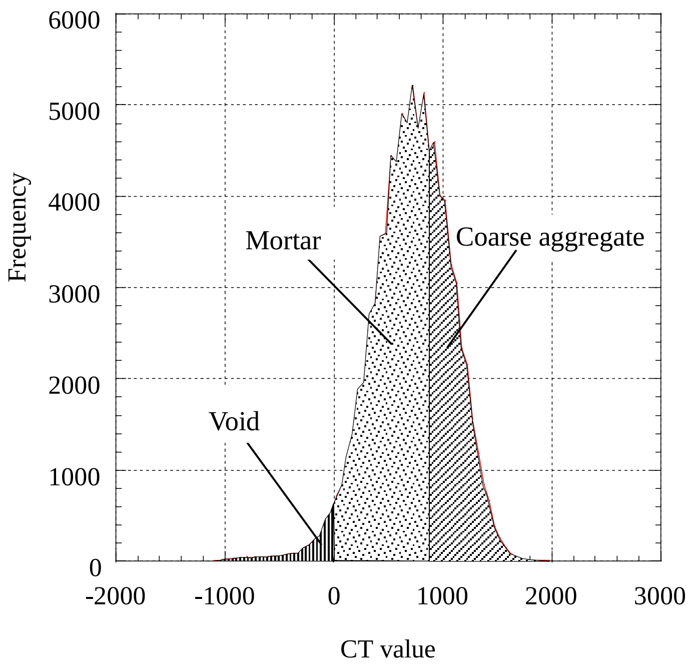

Figure 9. Classification of CT value into coarse aggregate, mortar, and void.

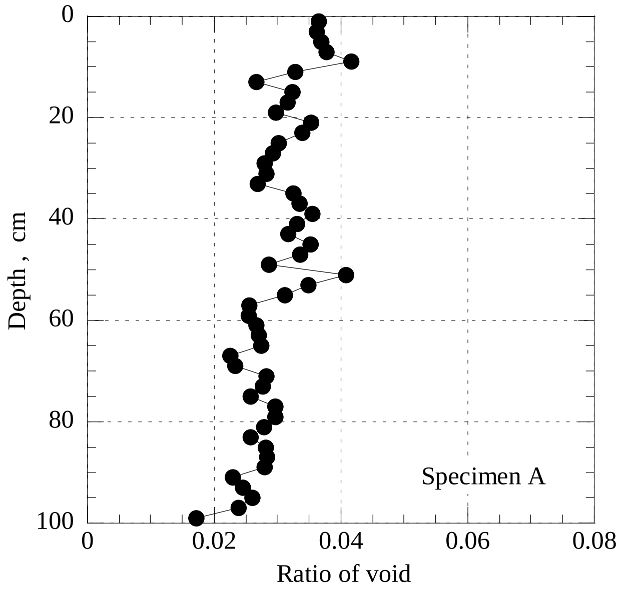

Figure 10. Distribution of ratio of void in Specimen A.

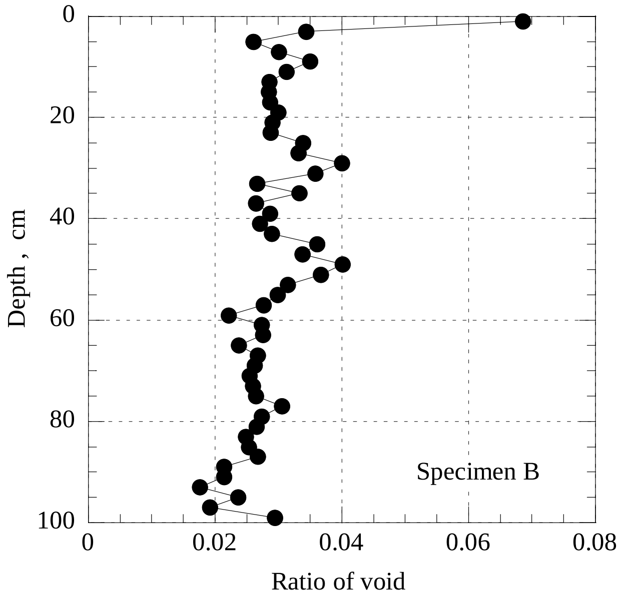

Figure 11. Distribution of ratio of void in Specimen B.

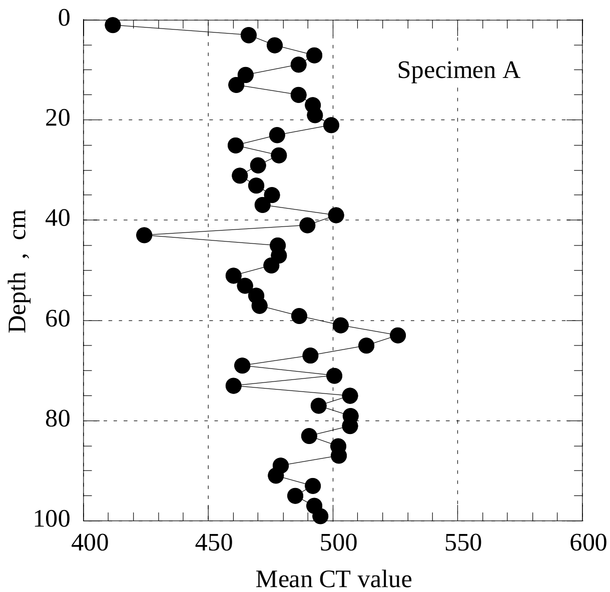

Figure 12. Distribution of mean CT value for the mortar portion in Specimen A.

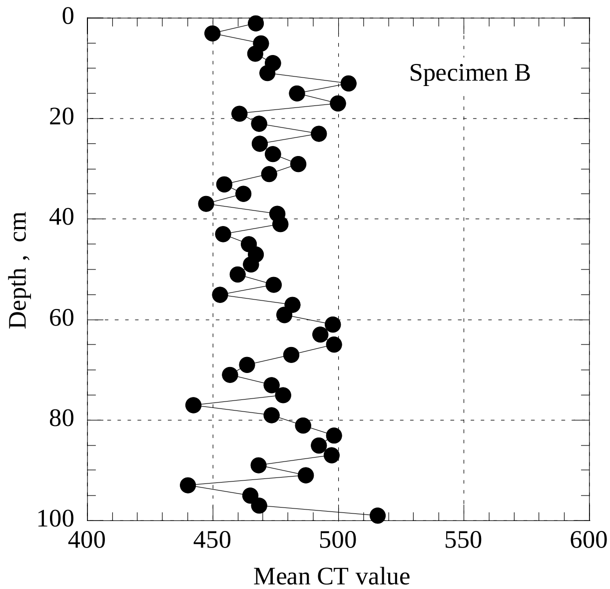

Figure 13. Distribution of mean CT value for the mortar portion in Specimen B.

CONCLUSIONS

To examine the segregation of materials and the condition of compaction nondestructively and quantitatively, an X-ray CT method was proposed. Applying this method to cores drilled from an embankment, the distribution characteristics of coarse aggregate and void within the core were clarified.

The results obtained can be summarized as follows:

1) The ratio of coarse aggregate of the two specimens was uniformly distributed with depth. We concluded that spread by a bulldozer and compaction by a vibration roller in the RCD method were carried out uniformly without segregation or concentration of coarse aggregate.

2) The ratio of void of the two specimens was estimated from the frequency distribution of CT values in the cross-sectional images. The ratio of void was 2~4% and 3% on average despite differences in compaction times.

3) The mean CT values of the mortar portion in each cross-sectional image were estimated from the frequency distribution of CT values. Then, the distribution of mean CT value with depth was analyzed. No changes in mean CT value dependent on depth were found.

4) The above results indicate that the RCD was mixed uniformly and remained homogeneous during spreading and compaction for building of an embankment.

We conclude that the X-ray CT method is effective for estimating the structural characteristics of concrete nondestructively and quantitatively. It will be worth applying the X-ray CT method as a diagnostic technique to ensure the safety of large dams.

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