Impact-Elastic Wave CT Technology to Detect Internal Defects of Concrete Dams

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Abstract. The elastic wave CT of massive concrete dam generally utilizes the elastic wave traveling time on each ray in the detected section of the measured structure to invert the distribution of the elastic P-wave velocity on the section. At present, there are mainly two detection methods. The first one is the upstream side (underwater) excitation and the downstream side receiving, and the second type is the downstream side excitation and the upstream side (underwater) reception. The second method that the hammer directly hits concrete to stimulate the elastic wave can be called concrete dam impact-elastic wave CT technology. This paper introduces the on-site inspection of the internal defects of RCC gravity dam using the SPV system of Olson Instruments based on impact elastic wave CT technology. Since the sensor string as an elastic-wave signal receiving sensor can be put directly into the reservoir water on the upstream surface of the dam, the detection speed is faster and the result is more reliable. The system can objectively and accurately reflect the internal mass distribution of massive concrete dams after water storage, which is worthy of promotion.

1. Introduction  
The elastic wave CT of massive concrete dam generally utilizes the elastic wave traveling time on each ray in the detected section of the measured structure to invert the distribution of the elastic wave velocity on the section. Since the P-wave (i.e. longitudinal wave or compression wave) in the elastic wave has the fastest propagation speed in concrete and the most accurate traveling time, in general the elastic wave CT uses the P-wave to invert the distribution of the P-wave velocity on the section. The elastic wave CT of massive concrete dam can be divided into ultrasonic CT and acoustic CT.

The frequency of the ultrasonic wave is above 20 kHz. Due to its high frequency, low energy, and fast attenuation, the rays cannot effectively penetrate the massive hydraulic concrete structures with large thickness (especially concrete dams) and are not suitable for full-section CT scanning.

For full-section inspection of larger concrete dams, it is necessary to make use of acoustic wave CT with high energy and strong penetrating power. The frequency of sound waves is generally around 1~5 kHz, which is lower than that of ultrasonic waves. As seen from the current development state of dam CT technology, there are mainly two types of detection methods in which the upstream side (underwater) excitation is received on the downstream side and the downstream side excitation is received on the upstream side (underwater).
2. Introduction to the excitation reception of acoustic wave CT

2.1. Upstream excitation and downstream reception
Explosive excitation is carried out under water of the dam upstream, and the elastic wave signal penetrating the cross section of the dam is collected by a receiving sensor installed on the downstream surface. The biggest disadvantage of this method is that the receiving sensor need to be arranged on the dam downstream surface along the depth of the detecting section, and the sensor must be fixed on the downstream surface and coupled well with the concrete, which is difficult to implement in the field. Because of the slow speed and low efficiency, this method is not suitable for comprehensive and rapid detection of dams.

2.2. Downstream excitation and upstream reception
Excitation is carried out on the downstream side of the dam without water, and receiving sensors are arranged underwater on the upstream side. The acoustic sensors are generally arranged by cascade connection. During the on-site inspection, the sensor string is placed down from the top of the dam and placed at the corresponding position of the detection section as needed. When the vertical sensor string on the upstream surface is close to the dam surface, water is used as a coupling agent to receive the elastic wave signal that penetrates the dam from the downstream surface. The excitation source in this way can also be divided into two types: ① the elastic wave generated by an artificial impact hammer. The elastic impact of the impact hammer during excitation generates elastic waves in the concrete, and the sensor built in to the impact hammer is converted into a pulse electrical signal. The signal is transmitted to the data acquisition terminal through the cable to record the start time of the elastic shock. ② Gravity self-propelled electromagnetic exciter. The elastic wave is generated by the electromagnetic coil driving the built-in small impact hammer to strike the concrete surface.

2.3. Advantages and disadvantages of the two methods
Upstream excitation and downstream reception method that the hammer directly hits concrete to stimulate the elastic wave can be called concrete dam impact-elastic wave CT technology. The stability and repeatability of the excitation signal generated by the impact hammer on the concrete surface downstream of the relatively dry and flat dam are better than those of the explosive source excited under the upstream water surface. Since the sensor string as an elastic-wave signal receiving sensor can be put directly into the reservoir water on the upstream surface of the dam, the detection speed is faster and the result is more reliable.

3. CT detecting equipment
The China institute of water resources and hydropower research has introduced the SPV system from Olson Instruments of the United States shown in Figure 1, which is currently representative impact-elastic wave CT detection equipment for concrete dams. Freedom Seismic PC data acquisition terminal of the system can be installed with more than two 24-bit A/D digital data conversion cards. Each card can be configured with more than 12 channels. Each channel has a sampling rate of 2 kHz to 200 kHz with three kinds of magnification signal gain. The total length of the cable is 180 meters. There are 20 high-sensitivity sensors with a spacing of 1m. The sensor frequency response range is 3Hz - 15 kHz.

4. On-site inspection of RCC gravity dam

4.1. Project overview
The Baishi RCC gravity dam is located on the main stream of the Daling River in the western part of Liaoning Province. The maximum dam height is 50.3 m and the dam crest length is 513 m. During the construction period, a horizontal crack occurred respectively in the normal concrete protective layer of 110.75 m in the upstream and 112.25 m in the downstream elevation. The crack with a depth of about
2.5 m~3 m on the downstream surface is more obvious. The operator sets the two seams as permanent dam retaining seams to facilitate observation of their changes. The crack diagram is shown in Figure 2.

4.2. Line layout
Due to the severe drought during the detection, the water level of the reservoir was only 115.5 m, which was lower than the normal water level of 127.0 m. The 3th and 4th dam sections were selected for testing in combination with actual conditions. Field test is shown in Figure 3. Affected by the topography and siltation at the bottom of the reservoir, the water depth of the upstream at the detection section was not enough to completely immerse the 20 water acoustic sensor string linearly arranged at intervals of 1 m. The top water acoustic sensors on the upstream side of two sections were all under water 1m (EL114.5 m), of which 14 ones were arranged in the 3th section and 16 in the 4th section. 18 excitation points were arranged from the elevation of 118.55 m to 103.84 m on the downstream side of the two detection sections. The typical line layout of elastic wave CT is shown in Figure 4.

4.3. Analysis results
A 40×40 computational grid was used for CT imaging analysis. The CT image analysis results of the 4th and 3th detection sections are shown in Figures 5 and 6. In the CT images of the two sections, an approximate horizontal P wave low velocity zone appears in the elevation of the downstream side of the dam from 113 m to 115 m. The depth of the low-speed zone of 3th dam section is about 4m, which is the most conspicuous. The P wave velocity is basically in the range of 3600 m/s to 3800 m/s, which is significantly lower than other parts of the section. Due to the "color blindness" effect of the elastic wave CT, the actual P-wave velocities at the two strip-shaped P-wave low-speed regions are much lower than those shown in the image, which is judged to be the horizontal reserved crack at the elevation of 112.25 m on the downstream side of the dam body shown in figure 3. There are two
reasons why this seam is slightly higher in the CT image by 1–2 m. First, some errors are existed in the method of the positioning automatic impactor using the meter ruler to measure. Second, the elevation of the horizontal preset crack may vary slightly there.

Figure 5. CT image analysis result of the 4th detection sections (Maximum: 5141 m/s; minimum: 3681 m/s; average: 4370 m/s).

It can also be seen from the CT images of the two sections that, the P-wave velocity distribution of the concrete inside the dam is relatively uniform, generally with the P-wave velocity of 4300–4400 m/s. The local low-velocity zone at the upper and lower boundaries of the section is mainly caused by the lack of elastic wave rays and the error in the analytical results. From the current operating conditions, the gravity dam does not have obvious deterioration of concrete durability.

5. Conclusion
The concrete dam internal defect detection system based on impact-elastic wave CT technology has strong applicability on site, operational convenience and fast detection speed. The test results are repeatable. The system can objectively and accurately reflect the internal mass distribution of massive concrete dams after water storage. At present, the internal quality inspections of the four reservoirs have been carried out with remarkable results. In the future, impact-elastic wave CT technology will be more applied in the quality inspection of concrete dams in China.

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