Application research on surface wave technique in crack depth detection of hydraulic concrete

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Abstract: Crack has a strong influence on the integrity, impermeable property, durability and bearing capacity of hydraulic concrete buildings. Although ultrasound is the main nondestructive testing method of concrete crack depth at present, a large amount of engineering applications demonstrate that it is not suitable for the crack depth detection of the hydraulic structure concrete. This paper illustrated the basic principle of detection of concrete crack depth by surface wave technique and verified the feasibility of surface wave technique to detect crack depth by two engineering examples, including steady-state surface wave method and transient-state surface wave method. The practical results show that surface wave is a rapid and effective nondestructive testing method in the detection of crack depth of concrete, which will have a good application prospect.

1. Introduction

During the construction and operation period, the hydraulic concrete buildings, such as dam, aqueduct, water gate and tunnel, would have cracks occurring, which has a strong effect on the integrity, impermeable property, durability and bearing capacity of hydraulic concrete buildings. Crack is one of the important factors to assess the structural safety of hydraulic concrete buildings. The research report [1] concerning the working state of dam made by International Commission on Large Dams (ICOLD) in year 1988 points out that most of the constructed concrete dams of the world have the cracks. In the concrete dams in China and foreign countries, there are many examples that the cracks affect the operation and benefits. The Chencun gravity-arch dam[2-3], Panjiakou Dam[4] in China and Zeuzier Dam[5] in Switzerland are forced to limit the operation of water level due to the occurring cracks, whose engineering safety and benefit are influenced severely. Therefore, it is necessary to detect the cracks as well as master the fracture situation and relevant parameters, thus judging the dangerous degree of hydraulic building and studying the related repair and reinforcement measures.

Presently, ultrasonic depth-measuring method is the main non-destructive testing method of concrete crack depth and there are lots of researches concerning it. However, a large amount of engineering applications and practice prove that using ultrasonic depth-measuring method to detect the crack depth of hydraulic structure concrete has certain limitation [6]: a. ultrasonic depth-measuring method could not detect the deep cracks since ultrasonic decays quickly in concrete and its received signal is difficult to process with high frequency and small energy. Currently, the maximum detection depth of ultrasonic depth-measuring method is about 0.8 m. (Test code for hydraulic concrete SL
352-2006 stipulates that the depth of the detected concrete structure via ultrasonic depth-measuring method is not larger than 50cm); b. the transmission of longitudinal wave (also named, P wave or compression wave, its vibration direction is the same as the transmitting direction of wave) is influenced easily by closure crack or filler in crack, such as dregs, mud and water. Therefore, the ultrasonic longitudinal wave directly passes through the cracks and interblends the diffraction signal, causing large errors in the test results; c. ultrasonic method only could be applied in the situation that is no concrete iron or there is little steel reinforced concrete. If the structure has concrete iron perpendicular to crack and its arrangement is dense, this method could not be used.

2. Basic principle of surface wave method to detect the crack depth of concrete

During the process of excitation on the surface of an ideal semi-infinite elastic body, the ingredients of elastic wave with rich frequency were generated, mainly including P wave, S wave and R wave. R wave (also called Rayleigh Wave) is one kind of surface wave that transmits along free surface of elastic medium. Its vibration locus of particle is an oval rotating counterclockwise. The long axis of oval is perpendicular to the transmitting direction and its short axis is parallel to the transmitting direction. The vibration amplitude decreases rapidly with the increase of depth under the surface. The allocation proportion of elastic wave component generated by shock excitation is 6.9% of P wave (longitudinal wave), 25.8% of S wave (transverse wave or shear wave), 67.3% of R wave. The energy of R wave is largest and its attenuation is smaller than P wave and S wave, whose signal is easy to collect. R wave is combined by P wave and S wave vertically polarized. Different with ultrasonic longitudinal wave, the mass point of R wave does the elliptic vibration. The transmitting properties of R wave depend on the shear properties of medium materials, which is more sensitive to cracks. R wave could properly reflect the developing degree of concrete crack depth since its transmission is less affected by filler in crack, concrete iron and water.

In the propagating process, the geometric attenuation and material attenuation of R wave occur and its amplitude could be kept unchanged by system correction. However, when meeting cracks, the transmission of R wave is intercepted to some degree and the wave energy as well as amplitude would decrease after passing through the cracks. Therefore, the crack depth could be calculated based on the variation of wave amplitude before and after crack. As shown in Figure 1, the larger energy declines, the deeper cracks are.

According to different excitation methods, the surface wave method to detect the crack depth could be divided into transient-state surface wave method and steady-state surface wave method. Steady-state surface wave method uses electromagnetic or piezoelectric steady-state vibration source to excite steady-state surface wave with fixed frequency, whose detecting arrangement and principle are shown in Figure 2. However, transient-state surface wave method exerts a transient shock excitation on the detecting medium surface, thus producing elastic wave with certain frequency range, including P wave, S wave and R wave. R wave with different frequencies bangle together and transmits on the surface of medium, whose detecting arrangement and principle are shown in Figure 3. Limited by the excitation energy of percussive hammer, the crack depth detected by transient-state surface wave method is within 2 meter.
Figure 1. Basic concept diagram for testing crack depth by surface wave method

Figure 2. The layout and schematic diagram of crack depth measured by steady state surface wave method

Figure 3. Transient surface wave method to detect concrete crack depth layout

3. Examples of engineering application

3.1 Detecting concrete crack depth by steady-state surface wave method

3.1.1 Engineering background
The roller compacted concrete gravity dam of Shuangfeng Temple located in Chengde city, Hebei province, China. During the construction in September 2015, its 12# bottom hole dam section was found that there were many cracks in its intermittent warehouse surface (its elevation was 377.1m). By detecting the width and depth of cracks, the crack situation of intermittent warehouse surface in 12# bottom hole dam section was mastered, which provided scientific reference to the repair and reinforcement of dam body. Moreover, 7 representative crack depth were detected by steady-state surface wave method and the crack in #12-12 was measured by drilling direct measurement method, both of which was to verify the reliability of the results of steady-state surface wave method.

3.1.2 Detection scheme
When detecting on site, the high power steady-state surface wave actuator was adapted as the exciter, whose excited frequency was in the range of 2000Hz to 200Hz. The distance between seam sensor as
well as seamless sensor and actuator was 40 meter, all of which located in one straight line, perpendicular to the direction of the crack.

During the process of detecting, the frequency of actuator decreased from 2000Hz to 1000Hz with a speed of 100Hz, and declined from 1000Hz to 200Hz with a speed of 50Hz. There were 27 frequencies. Each frequency had recorded the signals received from the seam sensor and seamless sensor and analyzed amplitude ratio of seam signal or seamless signal, thus forming the ratio curve between half-wave length and seam signal amplitude/seamless signal amplitude. Based on the theoretical analysis, the crack depth was judged, combined with the detected results.

3.1.3 Detected results and analysis
The detection results were shown in Table 1. From the detected results, it is known that the crack depth of 12# dam section is relatively large, whose depth reaches 280cm. Actual depth of #12-12 cracks measured by riding seam coring is 65cm while the crack depth of nondestructive testing by surface wave method is 60cm. The fractional error between surface wave method and drilling direct measurement method is 7.8%. The crack depth of steady-state surface wave method is smaller than the actual crack depth. From drilling core sample, it is seen that the lower seam surface of crack basically stays at a closed state, resulting in surface wave penetrating closed surface and the less detected value obtained by surface wave method.

| crack number | crack test results | core verification results (cm) |
|--------------|--------------------|--------------------------------|
|              | width(mm) | depth(cm) | crack depth | core sample length |
| #12-2        | 0.2       | 170       |             |                  |
| #12-3        | 0.2       | 150       |             |                  |
| #12-4        | 0.6       | 150       |             |                  |
| #12-5        | 0.4       | 280       |             |                  |
| #12-7        | 0.4       | 220       |             |                  |
| #12-12       | 0.1       | 60        | 65          | 100              |
| #12-13       | 0.1       | 80        |             |                  |

Figure 4. The core sample of the dam was drilled from the crack

3.2 Concrete crack depth detection via transient-state surface wave method

3.2.1 Engineering background
Shisanling Pumped Storage Power Station is the first large pumped-storage power station established in north area of China. The upper reservoir of power station adapts anti-seepage structure of reinforced concrete slabs. The thickness of slab is 30cm, the standard width is 16cm, the total area is 175,000 m². The concrete slabs of upper reservoir was completed in early June 1995. In the general investigation, a total of 2144 cracks were found before water storage, with a total length of 16468m. Within the whole cracks, there were 136 cracks whose width was greater than 0.2mm and its total length was 1194m, occupying 7.25% of the total length of the crack. There were 2008 cracks whose width was less than
0.2mm and its length was 14274m, taking up 92.75% of the total length. To track and understand the distribution and development of cracks in the concrete slabs of the upper reservoir, the cracks in the upper reservoir concrete slab above the water level of 556.0m were checked in 2005, 2010 and 2012 respectively and the classical cracks depth was detected.

3.2.2 Detection scheme
To know the crack depth situation of concrete slab, ten cracks including six transverse cracks, two longitudinal cracks and two oblique cracks were selected. The SCE-MATS-S concrete multifunction instrument based on transient-state surface wave method was used. There were detecting points for each crack and L₁=20cm, L₂=25cm. To verify the reliability of nondestructive testing results of crack depth, four classical cracks and core samples were drilled, thus measuring crack depth.

3.2.3 Detection results and analysis
The detected results concrete crack depth are shown in Table 2. And from Table 2, it is found that the actual depth of four cracks is in the range of 9.5cm ~ 16.0cm; the crack depth of the nondestructive testing by surface wave method is in the range of 9.1cm ~ 15.4cm; the fractional error between surface wave method and drilling direct measurement method is in the range of 3% ~ 6.7%, which is within the error range of engineering requirements. The crack depth detected by transient-state surface wave method is smaller than the actual crack depth. The reason for that is that the lower part of the crack basically is in the closed state, leading to the results that surface wave could penetrate the closed surface and the detected value by surface wave method is smaller.

| crack number | crack trend      | length (m) | width (mm) | crack depth (cm) | core verification results (cm) |
|--------------|-----------------|------------|------------|-----------------|-------------------------------|
|              |                 |            |            |                 | depth | core sample length |
| SF34-1       | transverse cracks | 16.0       | 0.2        | 13.1            | 13.5   | 18.0               |
| SF31-1       | transverse cracks | 11.0       | 0.2        | 8.8             | —       | —                  |
| SR23-4       | longitudinal cracks | 2.6       | 0.4        | 15.4            | 16.0   | 18.0               |
| SR11-4       | transverse cracks | 2.6       | 0.2        | 17.8            | —       | —                  |
| SR51-5       | transverse cracks | 3.2       | 0.25       | 15.4            | —       | —                  |
| SR69-1       | transverse cracks | 4.6       | 0.25       | 9.1             | 9.5    | 23.0               |
| SR71-5       | longitudinal cracks | 4.3       | 0.2        | 14.2            | —       | —                  |
| SF55-1       | transverse cracks | 4.5       | 0.2        | 11.2            | 12.0   | 23.0               |
| SR105-8      | oblique cracks   | 2.4       | 0.3        | 14.7            | —       | —                  |
| SF09-1       | oblique cracks   | 2.1       | 0.25       | 10.5            | —       | —                  |
Figure 5. The core sample of concrete slab was drilled from the crack

4. Conclusions
During the construction and operation, the hydraulic and hydroelectric engineering are influenced by all kinds of factors and it is common that the cracks occur in concrete. The cracks of concrete influence not only the functions of structure, but also the durability and safety of engineering. Before evaluating the safety of engineering and dealing with the concrete cracks, it is necessary to detect the crack depth of concrete accurately. Due to high accuracy and rapid speed, the surface wave method could detect the concrete crack depth precisely. Therefore, the surface wave method applied to detect the crack depth has a bright application prospect.

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