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Long-term monitoring of spillway using various NDT techniques-case studies

K-T Hsu¹, C-C Cheng², C-H Chiang², Y-T Ke³ and J-S Cheng⁴

¹Assistant Professor, Department of Construction Engineering, Chaoyang University of Technology, Taiwan

²Professor, Department of Construction Engineering, Chaoyang University of Technology, Taiwan

³Ph. D. Candidates, Department of Construction Engineering, Chaoyang University of Technology

⁴Graduate student, Department of Construction Engineering, Chaoyang University of Technology 168, Jifong E. Rd., Wufong District, Taichung City, 41349, Taiwan

Email: frankhsu@cyut.edu.tw

Abstract. The erosion under a spillway can be a long-term issue that threatens the structural integrity of a water reservoir. The heavy rainfall associated with storms or typhoons could cause a serious flood if the spillways do not function properly. The spillway under investigation was suspected to be defective after they had been commissioned in 1987. Potholes and subsurface cavities were confirmed in the safety assessment using various NDT techniques including ground penetrating radar and impact echo. The engineering team applied the repair project that aimed to remedy the deteriorating concrete structure. The GPR inspection was able to differentiate the repaired region from the cavities under concrete slabs. The results were verified against other measurement data obtained independently. Hence, the GPR technique is effective for quality check of grouting repair of spillways. Repetitive GPR scans were also carried out after the rehabilitation of spillways. Not only the quality of repair can be evaluated, but the scans were also provided as the baseline record for long-term condition assessment of the spillway-reservoir system in the future.

1. Introduction

Taiwan is an island surrounded by sea with high mountains, narrow land, and abundant rainfall. During the flood season, the abundant rainfall often makes the water conservancy structure faces a rigorous test. The erosion under a spillway can be a long-term issue that threatens the structural integrity of a water reservoir. The investigated spillway was suspected to be defective after it had been commissioned in 1987 as displayed in figure 1. After a heavy rainstorm, the piping was founded in soil slop beside the spillway. The serious deterioration was also visible under spillway, which leads to explicit cracks and breaking of the external concrete layer shown in figure 2 and figure 3, but we do not know precisely the erosion area under the spillway. Thus, it is more suitable and effective to apply the non-destructive testing method to detect potholes and subsurface cavities distribution status of the spillway.

The so-called non-destructive testing method (NDT method) is not to destroy the measured object. Instead, it detects the measured object and adopts sound, light, electricity, magnetic and other methods



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through the indirect way to know the relevant information. For the detection of water conservancy structures, a variety of non-destructive detection techniques are suitable to use. For example, ground penetrating radar with electromagnetic wave detection principle is suitable to quickly detect the emptiness of embankment. Visible cracks in the dike penetrating through the thickness is an important indicator to safely assess the embankment. The stress wave detection method using the impact of the spherical ball to examine the depth of surface opening crack can overcome the shortcomings of the insufficient energy in the traditional ultrasound method. The newly developed normalized impact-echo test method can also be carried out to detect the hollow underneath the spillway. As a very small air gap, less than about 0.1 mm, can produce a complete reflection of the stress wave from the boundary [1, 2]. The method is more sensitive than GPR in air void detection. In the present study, the theoretic principles of the three mentioned NDT methods will be briefly introduced, followed by an experiment to classify the GPR response with respect to different air gap distance, and a final site-investigation of a spillway structure using two methods.



Figure 1. The picture and design diagram of spillway which had been commissioned in 1987 in Taiwan.



Figure 2. The picture of the spillway discharge during a heavy rainstorm.



Figure 3. The piping was founded in soil slop beside the spillway after a heavy rainstorm.

2. Nondestructive techniques for spillway monitoring

2.1. Ground-penetrating radar

Propagation of electromagnetic waves through different materials is affected by the dielectric constants (or relative permittivity), which also govern the travelling speed of EM waves. The amplitude reflection coefficient of EM waves across the interface of two materials can be expressed as equation (1). The dielectric constant of vacuum is 1.0 by definition. The dielectric constant of water is about 80 times of that of dry air ($\epsilon \sim 1$). Moisture or void in or beneath concrete can thus be detected since dry concrete has a dielectric constant about 5.

$$R_{1,2} = \frac{\sqrt{\epsilon_{r1}} - \sqrt{\epsilon_{r2}}}{\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}}} \quad (1)$$

Ground-penetrating radar, or GPR, is a device that performs line scans using EM waves of 100MHz – 2GHz in frequency. The receiving antenna picks up signals reflected from the internal discontinuity. The electromagnetic waves travel in a speed of 0.06 m/sec or greater in earth or concrete. A large amount of data is thus obtained swiftly in a single scan. The scanning procedure may include multiple scanning lines for high-risk areas. The recorded data are processed online or offline, such that the difference in travelling time or dielectric constant can be analyzed. Further inspection may be deemed necessary to be executed using other techniques. Cross-reference based on additional information is sometimes required to report severely distressed concrete structures [3].

2.2. Normalized impact-echo spectrum

Impact-echo method, is an acoustic method for nondestructive evaluation of concrete that was developed in the 1980's [4]. In the method, transient stress waves are generated by the impact of a spherical steel ball, 3 mm to 20 mm in diameter, on the surface of the test object. Vertical displacements are recorded by a broad-band displacement receiver consisted of a small, conically-shaped, piezoelectric element cemented to a brass cylinder located on the surface near the impact-position. A portable computer-based data-acquisition system is used to capture the output of the transducer and store the digitized waveforms. The response is analyzed in a spectral form. The depth of an interface is determined from the frequency of the dominant response that corresponds to the multiple reflections from that interface.

For a normal incidence of P-wave (dilatational wave), the amplitude of the reflected P-wave, $A_{\text{reflected}}$, is given by equation (2),

$$A_{\text{reflected}} = A_i \frac{Z_2 - Z_1}{Z_2 + Z_1} = A_i R \quad (2)$$

where Z_1 is the acoustic impedance of the material in which the incident wave propagates, Z_2 is the acoustic impedance of the material in which the refracted wave transmitted through, A_i is the amplitude of particle motion in the incident wave, and R is called the reflection coefficient. Figure 4(a) shows a schematic illustration of phase changes in reflected P-waves for the case that the acoustic impedance of the bottom layer is less than that of the top layer ($Z_2 - Z_1 < 0$). Figure 4(b) illustrates the displacement waveform recorded by a receiver close to the impact point.

For an interface at a depth of T_1 , the dominant frequency (f) in the waveform is given by equation (3),

$$f = \frac{C_{p, \text{plate}}}{2T_1} = \frac{0.96C_p}{2T_1} \quad (3)$$

where $C_{p, \text{plate}}$ is the apparent P-wave speed in a plate and C_p is the P-wave speed in an infinite medium. According to the elastic theory, an impact response ($u(r, t)$) at a point having a distance (r) from the impact point is the result of the unit impulse response ($G(r, t)$) convoluted with the force-time function of impact ($F(t)$) as follows equation (4),

$$u(r, t) = \int_{-\infty}^{\infty} G(r, t - \tau) F(\tau) d\tau \quad (4)$$

Performing the Fourier transform, $F()$ of the both sides of equation (4) and rearranging the equation, one can obtain the Fourier transform of the unit impulse response as it follows equation (5)

$$F(G(r, t)) = F(u(r, t)) / F(F(t)) \quad (5)$$

Equation (5) can be regarded as the *normalization* of the impact-echo spectra with the impact force. The time history of the impact force is essential to normalize the impact-echo spectrum. In impact-echo tests, a steel sphere is used as an impact source and the force-time history when the impact is not available. A simulated transfer function was proposed by Cheng et al. [5, 6] to normalize the impact-echo spectrum. The simulated force-time function is derived from the displacement waveform caused by the arrival of Rayleigh wave (R-wave). The simulated force-time function can be obtained by dividing the displacement waveform of the R-wave with a F_n coefficient [5, 6].

Figure 5 presents the procedure for calculating the simulated transfer function from an impact-echo response. The duration of the R-wave, t_d , is defined by the time window between points A and C in figure 5(a), where point A is the first crest of the R-wave. The fraction of the R-wave beneath the zero displacement (the curve between points B and C) is used as the basis of the simulated force-time function as displayed in figure 5(b). The simulated force-time function is obtained by dividing the waveform in figure 5(b) by F_n . The simulated transfer function is the amplitude of the impact-echo spectrum shown in figure 5(c), this function is divided by the amplitude of the simulated force spectrum plotted in figure 5(d). Figure 5(e) plots the results.

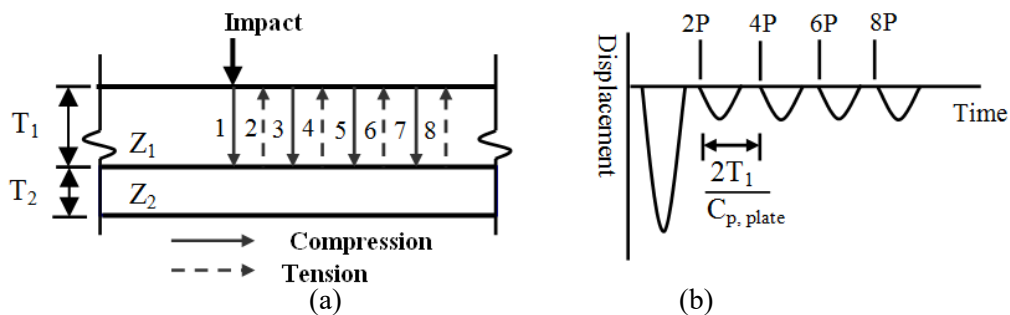


Figure 4. The impact-echo method: (a) phase changes in reflected P-waves; (b) waveform.

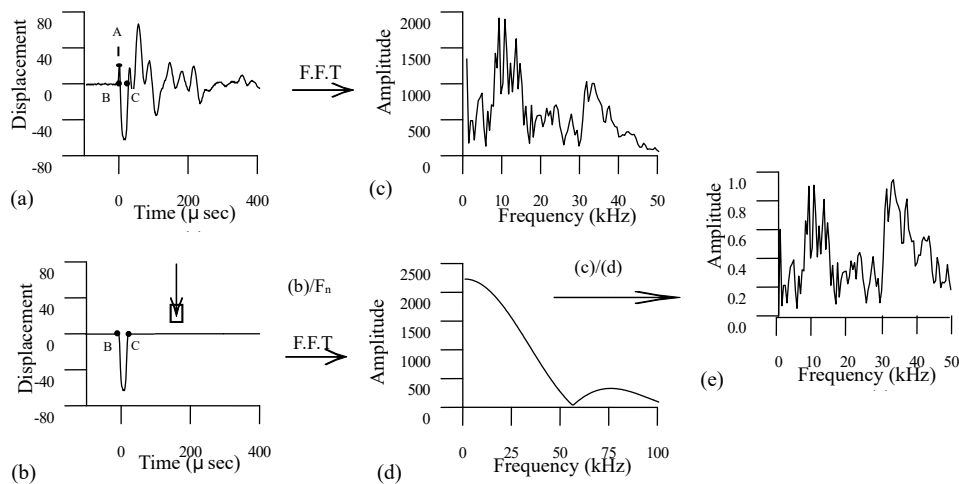


Figure 5. (a)-(e) Procedure to calculate the transfer function from an impact-echo response.

3. Evaluation of the erosion under the spillway by non-destructive testing method

3.1. Field test carried out on the spillway after a heavy rainstorm

After a heavy rainstorm, the piping was founded in soil slop beside the spillway. At the same time, a serious deterioration was visible under spillway which leads to explicit cracks and breaking of the external concrete layer. Thus, the key issue is going to be the evaluation of the distribution of potholes, and subsurface cavities under the spillway for the engineering team to repair the deteriorating concrete structure. NDT techniques that includes ground penetrating radar and normalized impact echo were performed for the safety assessment as shown in figure 6. Figure 7(a) is the result of impact echo waveform recorded by the transducer and normalized spectrum. Figure 7(b) is two-dimensional imaging of GPR profile from the spillway which indicated the erosion area under the spillway (the blue wireframe in the figure). Local penetration drilling test was dealing with the concrete slab of the spillway to confirm the result of two non-destructive techniques which are both indicate subsurface cavities under the spillway as shown in figure 7(c). The field test with non-destructure techniques including ground penetrating radar and normalized impact echo are explained in figure 8. Figure 8 and figure 9 show the distribution of subsurface cavities under the spillway. Therefore, based on the results of the field test, the engineering team designed and executed the repair projects based on the conclusion of the integrity assessment, as shown in figure 10.



Figure 6. The picture of field test with non-destructure techniques after a heavy rainstorm on the spillway.

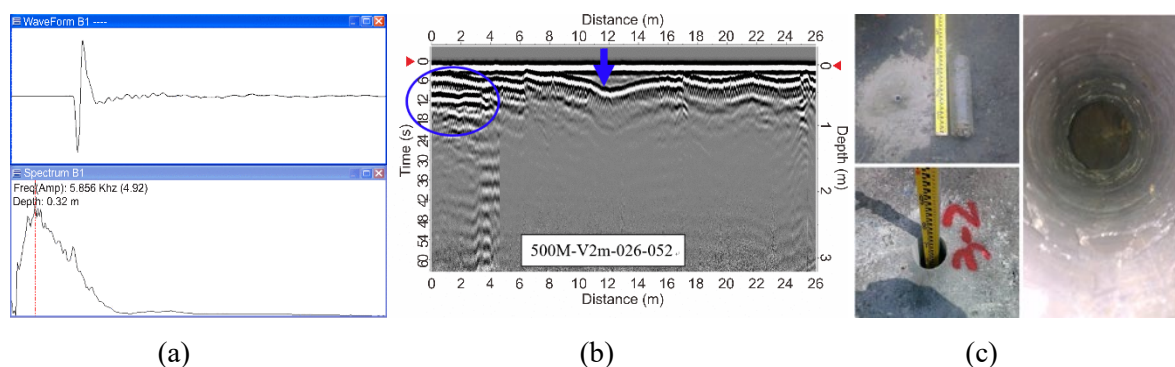


Figure 7. The result of non-destructure techniques on the spillway: (a) normalized impact echo (b) two-deminesional imaging of GPR profile (c) penetration drilling tes ton the concrete slab of the spillway.

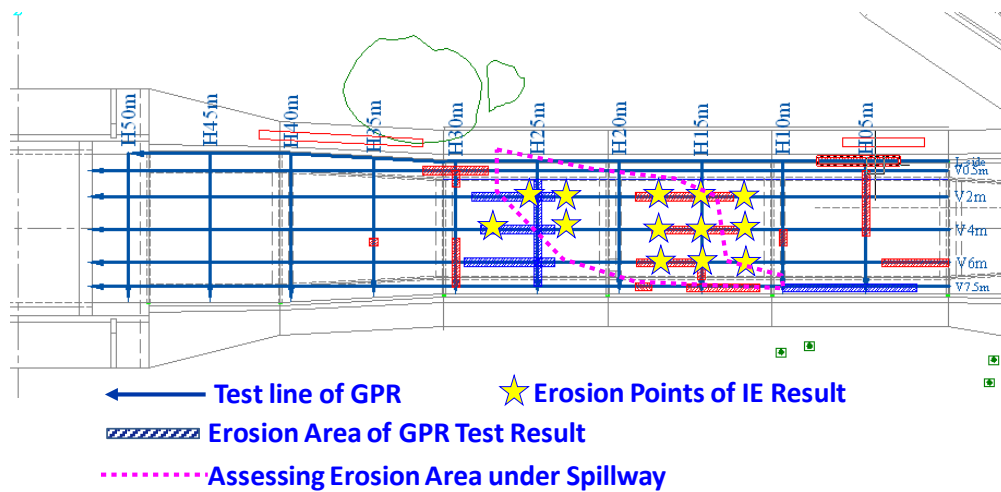


Figure 8. The result of the field test with non-destructive techniques including ground penetrating radar and normalized impact echo.

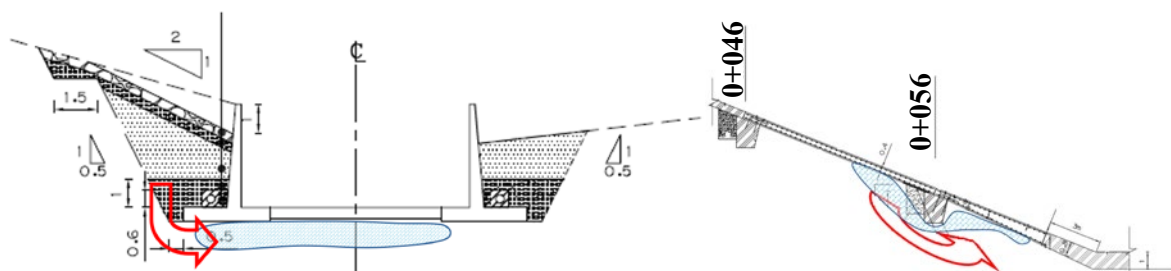


Figure 9. Potholes and subsurface cavities were confirmed in the safety assessment by using various NDT techniques.



Figure 10. The repair project that aimed to remedy the deteriorating concrete structure of the spillway.

3.2. Long-term monitoring of spillway

The repair project that aimed to remedy the deteriorating concrete structure of the spillway. The engineering team designed and executed the repair project based on the conclusion of the integrity assessment. Subsequent GPR inspections have been performed to monitor the integrity of the spillway in a period of 18 months following the repair project. After the completion of the repair project, repetitive GPR scans were also carried out after the rehabilitation of spillways, the integrity of the spillway can be observed in the profile of the penetrating radar as shown in figure 11. Not only the quality of repair can

be evaluated, but the scans also provided a baseline record for long-term condition assessment of the spillway-reservoir system in the future.

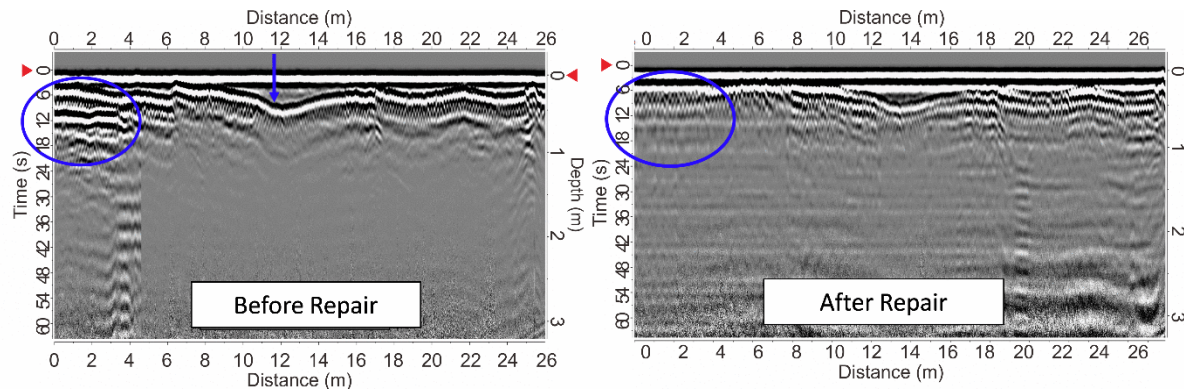


Figure 11. Ground penetrating radar profile of the spillway.

4. Concluding remarks

A variety of non-destructive testing methods are used to detect the erosion of the spillway, including Ground Penetrating Radar (GPR), and normalized IE. In this study, an obvious erosion zone of soil was discovered by the GPR method. Thus, the results from different NDT techniques confirmed each other and provide useful information to plan priority repair. Repetitive GPR scans were also carried out after the rehabilitation of spillways. Not only the quality of repair can be evaluated, but the scans also provided a baseline record for long-term condition assessment of the spillway and the reservoir in the future.

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