Tracing developing deterioration zones in a damaged dam by using elastic wave tomography

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Abstract. In this paper, the concrete gravity dam built 40 years ago was partially damaged by the M=7.3 Chi-Chi Earthquake in central Taiwan in 1999. The elastic wave tomography method was applied to identify the safety conditions of the repaired dam in 2010. The resulting velocity profiles showed that the total structure conditions were accepted as a good to questionable condition. The filled materials and cracks existed in some dam components. Seven years later, the updating tracing investigation revealed that the previous detrimental zones were spatially extended and associated with time. These testing results were also consistent with the findings from the ground penetrating radar inspection.

1. Introduction

Non-destructive testing is a non-intrusive method for inspecting defects or anomalies in construction materials, especially concretes in civil infrastructures [1-3]. These inspection techniques, consisting of ultrasonic, impact echo, radiography, ground penetrating radar, magnetic induction, or photoelastic methods, can be applied to identify structural dimension, crack depths, inner voids, interface positions of concretes, residual stresses, sizes and positions of reinforced bars, delamination, and debonding between reinforcing and concrete in concrete or reinforced concrete structures [1].

However, the methods using ultrasonic, radiographic, or impact echo method cannot accurately identify the inner defects of huge concrete structures, such as dams, pylons, bridges, tunnels, road pavements, and nuclear power plants. Instead, the elastic wave tomography, a geophysical technique, can effectively generate a cross-sectional profiling image on an object. With properly-set parameters and geometries of the elastic wave tomography, the inner anomalies or engineering properties of concrete can be reliably detected.

2. Inspection technique

The elastic wave (seismic) tomography is based on ray tracing and wave diffraction or scattering. The target region bordered by impact sources and receivers is divided into several rectangular cells (or pixels) (figure 1(a)), dependent upon resolution. Using the information of wave field, i.e., travelling time or amplitude, the velocity values of each cell can be quantitatively solved. The composed velocity profiling images are utilized to evaluate the engineering properties of concrete components or a whole structure.

Initially, assuming the constant wave velocity in each cell, the relationship between the energy and object response can be expressed as:
\[ t_i = \sum_{j} l_{ij} S_j, \quad i=1, \ldots, I; \quad j=1, \ldots, J \]  

where \( t_i \) is the travelling time of the \( i^{th} \) path, \( l_{ij} \) is the \( i^{th} \) path distance for wave propagating through the \( j^{th} \) cell, \( S_j \) is the slowness (the reciprocal of velocity) in the \( j^{th} \) cell, \( I \) is the total path number, and \( J \) is the total cell number. Through the forward modeling process, the travelling time of the wave transmitted through the model can be calculated; however, the time estimated by the velocity model is different from the actual velocity results. By repeatedly modifying slowness \( S_j \), an optimal cross-sectional velocity image represents the inner structure distribution of the object where the elastic waves travel between the sources and the receivers (figure 1(b)).

Leslie and Cheeseman (1949) [4] suggested a classification for evaluating concrete quality based on P wave velocity in table 1. Either poor concrete or anomalies or both usually lead to relatively low wave velocity values. In general, concrete with a higher P wave velocity value represents better quality for engineering usage.

| Classification     | P wave velocity (m/s) |
|--------------------|-----------------------|
| Excellent (E)      | More than 4,500       |
| Good (G)           | 3,600–4,500           |
| Questionable (Q)   | 3,000–3,600           |
| Poor (P)           | 2,100–3,000           |
| Very Poor (VP)     | Below 2,100           |

3. Dam condition and inspection
The concrete gravity dam located in central Taiwan was constructed for providing local drinking water in 1977. The M=7.3 Chi-Chi Earthquake triggered the nearby fault extended to the right bank of the river, lifted the ground surface up to 2.2 m, completely crashed 3 spillways, and structurally damaged the remaining facilities in 1999. An emergency rehabilitation plan was finished for repairing the damaged components in late 2000 [5]. Currently, the improved dam was consisted 2 scouring sluiceways, 15 spillways, and one fish way (figure 2). Since 2000, several piezometers, water level gauges, water
level wells, inclinometers, seismographs, and settlement points have been installed to monitor the dam conditions, including pore water pressure, water level, seepage condition, displacement, and surface conditions as well [5-9].

The proposed elastic wave tomography inspection items covered all key concrete components, 17 dam pillars, 2 scouring sluiceways, and 15 spillways, where various surface cracking, spalling, or seepage were reported in annual inspection [6-9]. The sensor array installed in linear fashion with a spacing of 1 m on the downstream side of the dam pillars measured the transient elastic waves generated on the upstream side of the pillars with an impact spacing of 1 m (figures 3(a) and 3(b)). Due to full level water on the dam watershed, the investigators stayed and struck on the spillway concrete every 0.5 m and the elastic waves were measured on the upstream side of the dam by using underwater sensor array with an installation spacing of 1 m (figures 4(a) and 4(b)).
4. Inspection results and analysis

An overall comparison of inspection results in 2010 and 2017 on the 17 dam pillars are demonstrated in figure 5. The velocity images in all dam pillars indicates different degrees of deterioration in concretes, especially the filled materials and cracking positions. Most of concrete conditions are classified as level questionable (Q) or good (G). In 2017, the lowest velocity zones measured in 2010 expanded inwards the inner portion of dam pillars in PP0, PP2, SP1, SP2, and SP6–SP10. In addition, the lowest velocity zones (lower bound 3,000 m/s of questionable level Q) were significantly identified on Pillars SP7, SP10, and SP11, but the velocity reduction percentage in 2017 is less than 6%.

Figure 5. Comparison of inspection results measured in 2010 and 2017 on dam pillars.

Figure 6 shows the most severe damage case found in dam pillar SP11 (sensor position marked with a triangle; wave source position marked with ×). In 2010, two lowest velocity zones were located at the top and middle positions of the pillar (figure 6(b)). Their concrete quality approached the lower bound 3,000 m/s of questionable level Q (labelled Q-). This could be caused by the 921 earthquake and long-term loading interaction with the gate supporter and overpass viaduct (figure 6(a)). In 2017, the overall concrete quality decreased but the total velocity reduction was less than 6%. The lowest velocity zones
significantly expanded outward (figures 6(c) and 6(d)). By the way, a new lowest velocity zone was found on the pillar top located right beneath a machine position on the downstream side.

Figure 7 indicates an overall comparison of inspection results in 2010 and 2017 on the 15 spillways and 2 scouring sluiceways. The velocity variation information reveals that all components had different degree of deterioration in concretes. Most of concrete conditions are classified as level questionable (Q) or good (G). In 2017, the low velocity zones measured in 2010, especially SP1~SP12, spatially expanded and the total velocity reduction value was less than 12%.

The most severe spillway SP10 shows in figure 8. In 2010, two lowest velocity zones were located at the upper and toe positions on the downstream side of the spillway (figure 8(b)). The concrete quality was identified as the lower bound 3,000 m/s of questionable level Q (labelled Q-). In 2017, the total concrete quality degraded and the lowest velocity zones spatially expanded outward (Figures 8(c) and 8(d)). Most of the wave velocity reduction was less than 6~10%. The ground penetrating radar results also verified that some anomalies, most likely cracking, exist on the upper portion and toe position of the spillway, as shown in figure 9.

Figure 6. (a) Image; (b) velocity image in 2010; (c) velocity image in 2017; (d) reduction image.
Figure 7. Comparison of inspection results in 2010 and 2017 on spillways and scouring sluiceways.

Figure 8. (a) Image; (b) velocity image in 2010; (c) velocity image in 2017; (d) reduction image.
Figure 9. Ground penetrating radar results on spillway SP10: (a) left and (b) right survey lines.

Figure 10. Survey lines of 3-D wave tomography on spillway SP10 in: (a) 2010 and (b) 2017.
Similar to the conventional elastic wave tomography inspection, three survey lines were set along spillway SP10 for the three-dimensional (3-D) inspection (figures 10). Figures 11(a) and 11(b) indicate the 3-D elastic wave tomography inspection results on spillway SP10 in 2010 and 2017, respectively. In general, the overall wave velocities decreased, but the corresponding concrete quality was still remained as level good (G) or questionable (Q); some portion approaching the lower bound of questionable level (i.e., 3,000–3,200 m/s; Q-). The surface low-velocity zone expanded deeper up to 2–3 m. Several limited low wave velocity belts spatially spread and these linking belts formed a relatively low wave velocity zone.

5. Conclusions

The elastic wave tomography inspection was applied to trace the condition changes on a repaired concrete dam in central Taiwan. The conventional and three-dimensional inspection results indicate that concrete components had various degree of deterioration, especially the filled materials and cracking positions, and this situation was verified with the ground penetrating radar investigation. Most of concrete conditions are still classified as level questionable or good. The pervious detrimental zones are spatially extended at two inspections in 2010 and 2017. The concrete quality on the lowest wave velocity
zones is identified as level Q- (i.e., the lower bound 3,000 m/s of questionable level Q). The condition monitoring on cracking, spalling, and leakage is suggested to focus on these detrimental hot spots.

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