Velocity tomography-based condition inspection on concrete pylons of a pedestrian suspension bridge

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Abstract. The velocity tomography inspection, including modified cross-hole sonic logging and ultrasonic velocity tomography methods, was introduced to detect the reinforced concrete pylons of a pedestrian suspension bridge in northern Taiwan. At the first stage, the modified cross-hole sonic logging method was employed to rapidly identify the positions of gross anomalies on the shafts and horizontal beams of the bridge pylons. The possible anomaly sections, usually with a relatively low velocity, were chosen for the ultrasonic velocity tomography testing in order to finely determine the velocity spatial distribution image and localize the anomaly positions. The on-site inspection results indicate that the lower horizontal beams and connection zones with concrete shafts on the pylon were significantly attributed to a questionable level (i.e., velocity of 3,000~3,600 m/s). These structural detrimental positions have been provided for the bridge agency for the further improvement plan on the bridge pylons.

1. Introduction
The construction history of pedestrian suspension bridges in Taiwan can be traced back to the late 1890s. At that time, the pedestrian suspension bridges were constructed in the mountain areas for traffic purpose. However, the main transportation infrastructures in Taiwan greatly promoted the traffic convenience since the 1980s construction booming period, and these old pedestrian suspension bridges were gradually abandoned or demolished instead. Recently, the new native affairs and tourism policies give a new life for the pedestrian suspension bridges as either landmarks or tourist spots or both. The new construction booming of pedestrian suspension bridges comes back again [1].

The as-built condition of bridges is crucial for bridge engineers to evaluate their capacity and stability. The Taiwan Bridge Management System (TBMS), the most complete bridge database in Taiwan, archives the fundamental and biennial inspection data for more than 28,000 infrastructures, including all vehicular bridges or viaducts, culverts, and part of pedestrian concrete bridges, in Taiwan. However, the pedestrian suspension bridges are excluded from this TBMS archive. In addition, most of these pedestrian suspension bridge agencies are attributed to tourism or native affairs who have insufficient budget, inadequate manpower, and amateur experience to maintain and repair their bridges [1].

A pedestrian suspension bridge usually consists of two main suspension cables, a numbers of suspender cables, wind resistant cables, main girders, horizontal beams, decks, two pylons (bridge towers), and anchors. Pylons are the key components for supporting the main cables and could directly
affect the performance of a pedestrian suspension bridge [1, 2]. In this paper, a velocity tomography inspection process will be introduced to detect the current conditions of the reinforced concrete (RC) pylons of a pedestrian suspension bridge located in northern Taiwan.

2. Inspection techniques

The Japan Road Association [3] has provided the management guidelines on pedestrian suspension bridges. Based on inspection frequency and target, four inspection levels are legislated as common, routine, in-depth, and repair inspections. Once aberration or anomalies are found during inspection, non-destructive testing can be used for inspecting specific items or components of pedestrian suspension bridges [1]. Using a two-phase velocity tomography inspection, including modified cross-hole sonic logging and ultrasonic velocity tomography methods, can efficiently identify the anomaly positions and give the cross-sectional velocity images on the RC pylons on pedestrian suspension bridges.

2.1. Modified cross-hole sonic logging method

The traditional cross-hole sonic logging method was developed in integrity testing for drilled shafts or concrete piles by the French National Center for Building and Civil Engineering Research (Centre Experimentale de Recherche et d’Études du Bâtiment et Travaux Publics, CEBTP) in the 1960s [4, 5]. Two or more access tubes are installed beside the reinforcing cage before concrete placement. A transmitter and a receiver are synchronously lowered down in an adjacent pair of tubes. The ultrasonic pulse signals through the concrete between the tubes are measured and recorded as the transducers are continuously lift up in the tubes (figure 1(a)). The identified flight arrival time based on complete pulse time histories (waterfall plots; pulse echo) (figure 1(b)) can provide the general ultrasonic pulse velocity or apparent velocity at each measurement depth in concrete piles [4-6].

When treating a traction-free RC pylon as an embedded drilled shaft or concrete pile, a pair of sensors are directly installed on the two sides of the shaft without any access tubes and moved up with a specific spacing (dependent upon the required precision) throughout the whole pylon shaft. Similar ultrasonic pulse velocity profiles are the gross uniformity at each measurement positions on the pylon.

![Figure 1. Cross-hole sonic logging method: (a) set-up schematic; (b) pulse time history.](image)

| 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           |
Ultrasonic pulse velocity is a function of concrete modulus, density, Poisson’s ratio, and anomalies, such as voids, honeycombs, cracking, delamination, and aging in concrete, or debonding between reinforcing and concrete. Either poor concrete or anomalies or both usually lead to relatively low ultrasonic pulse velocity values. Leslie and Cheeseman (1949) [7] suggested a five-level classification for evaluating concrete quality based on P wave velocity listed in table 1. In general, concrete with a higher P wave velocity is attributed as better quality.

2.2. Ultrasonic velocity tomography method

The principle of ultrasonic velocity tomography is based on the travelling time and amplitude changes of seismic waves which pass through the regular formations or geological structures. Using these measured messages can re-construct the stratigraphic section information [4]. Herein briefly assuming an anomaly existing a rectangular body, seismic (impact) waves are generated at different positions, and the seismic signals are received by multiple receivers arranged around this target surface, as shown in figure 2(a). De-coding all the transmitting waves in each propagation path can identify the velocity changes as the shock wave passes the anomaly. Iterative computation on these wave signals can re-construct the velocity cross-sectional profile, and the spatial distribution image (tomography) can indicate the possible size and shape of the embedded anomaly (usually with low velocity values) in the target body (figure 2(b)).

3. Bridge condition and pylon inspection

The 76.7-m span river-crossing pedestrian suspension bridge located at a county scenery area in northeastern Taiwan was constructed in 2002. The bridge agency noticed the safety issue on frequent concrete spalling on the RC pylon surfaces and launched the visual inspection on the whole bridge conditions and NDT survey on the pylons. In response to the inspection findings, the bridge agency proceeded a contingent rehabilitation plan and installed a dynamic monitoring system.

Each pylon consists of two vertical concrete rectangular shafts and two horizontal concrete beams, as shown in figure 3(a). The dimensions (height × width × thickness) of each concrete shaft and beam are 870 cm×80 cm×100 cm and 80 cm×210 cm×100 cm, respectively, and their relative positions are indicated in figure 3(b). The modified cross-hole sonic logging testing was conducted along the shaft sides and horizontal beams labelled as dashed lines in figure 3(b) with a spacing of 10 cm. The on-site survey images were shown in figure 4. After reviewing the results, the second-phase ultrasonic velocity tomography method was used to inspect the possible anomaly zones (with low velocity or significant velocity changes) in detail (a spacing of 5 cm) and identify the cross-sectional distribution of anomalies.
4. Inspection results and discussion

The key inspection results are presented herein to effectively localized the detrimental zones on RC pylons by using the velocity tomography inspection. The inspection findings of the modified cross-hole sonic logging testing on one pylon, composed of shafts A and B, are demonstrated in figures 5, figure 6, and figure 7. Figure 5 and figure 6 show the survey line positions, pulse time histories, and apparent velocity profiles along shafts A and B, respectively. All apparent velocities can be attributed to a good (G) condition, i.e., 3,600–4,500 m/s, in concrete (table 1). Relatively lower apparent velocity values and significant velocity changes are found nearby the lower horizontal beam. The connections (marked with shadow zones, at positions of 360~440 cm) at the lower horizontal beam have a significant apparent velocity nadir below 3,600 m/s (the boundary between good and questionable levels in concrete quality). However, the connections (marked with shadow zones, at positions of 760~840 cm) at the upper horizontal beam have a relatively higher apparent velocity value.

The ultrasonic velocity tomography method was used at two positions of 260 and 340 cm at shaft A. A significant difference in their apparent velocity, i.e., 4,000 m/s versus 3,600 m/s, can be found at these two positions. Figure 7 indicates the survey line positions and velocity distribution images at these two
inspection positions. The general velocity distribution at the position of 340 cm (figure 7(b)) has a low velocity trend when setting velocity 3,600 m/s as the classification criterion in concrete quality. The velocity distribution at the position of 260 cm (figure 7(d)) has limited and scattering low velocity spots only. This indicates that the concrete quality adjacent the connection belongs to a questionable level at shafts. Relevant repair work should highlight on these spots in future.

Figure 5. Modified cross-hole sonic logging testing on shaft A: (a) survey line position; (b) pulse time history; (c) apparent velocity profile.

Figure 6. Modified cross-hole sonic logging testing on shaft B: (a) survey line position; (b) pulse time history; (c) apparent velocity profile.
These testing results indicate that concrete placement could be the most key factor affecting the concrete quality. When constructing the lower part of the pylon (below a position of 440 cm), a common concrete placement problem, such as less workability or vibration/tamping, could occur at the connection between the shafts and lower horizontal beam. This led to relatively poor concrete quality and low apparent velocity values at the connection zone. Maybe the previous experience, the constructors improved the placement operation and the concrete quality became better during the construction period at the upper portion of the pylon.

**Figure 7.** Ultra-sonic velocity tomography testing at cross sections of 340 cm and 260 cm at shaft A: (a), (c) survey line positions; (b), (d) velocity distribution images.
Figure 8. Modified cross-hole sonic logging testing on lower and upper horizontal beams: (a), (d), (g) pylon schematics; (b), (e), (h) pulse time histories; (c), (f), (i) apparent velocity profiles.
Figure 8 shows the inspection results on two horizontal concrete beams by using the modified cross-hole sonic logging testing. Two survey lines were chosen at the upper and lower portions of the lower horizontal beam and one survey line was set the lower portion on the upper beam. On the lower horizontal beam, the apparent velocity values vary from 3,400–4,000 m/s (figure 8(c) and figure 8(f)) and the concrete quality scatters two sides of the boundary between good (G) and questionable (Q) levels. In addition, relatively lower apparent velocity below 3,600 m/s is found at the two connection zones and the concrete quality can be attributed to a questionable (Q) condition in concrete. On the upper horizontal beam, the apparent velocity values range from 3,800 to 4,200 m/s, classified as a good (G) condition (figure 8(i)). Less various range and relatively consistent spatial scattering indicate a better uniformity on the upper horizontal beam. In future, the lower horizontal concrete beam should be the repair target.

5. Conclusions
The two-phase velocity tomography inspection, including modified cross-hole sonic logging and ultrasonic velocity tomography methods, was introduced to inspect the current conditions on the RC pylons of a pedestrian suspension bridge in Taiwan. Using the modified cross-hole sonic logging method can rapidly identify the positions of gross possible anomalies in the pylons. The velocity distribution images at the anomaly zones finely localize the real spatial positions by using the ultrasonic velocity tomography method. The connection zones at the lower horizontal beam and shafts are identified as a questionable (Q) level, with a velocity of 3,000–3,600 m/s, in concrete quality. Various concrete quality is also detected on the lower horizontal beam. These relatively low velocity zones or portions are suggested to be listed as the future repair targets.

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