Conditioning Inspection on Unknown Bridge Foundations

Helsin WANG¹, Chih-Hsin HU², Chung-Yue WANG³

¹ Institute of Bridge Engineering, China Engineering Consultants, Inc.; Taipei, Taiwan; Phone: +886-2-8732-5567 ext.1218, Fax: +886-2-2736-5222; e-mail: herschel39@gmail.com
² HCK Geophysical Company; Taipei, Taiwan; e-mail: sunhu88@ms29.hinet.net
³ Department of Civil Engineering, National Central University; Taoyuan, Taiwan; e-mail: cywang@ce.ncu.edu.tw

Abstract
Non-destructive testing (NDT) inspection has been verified to efficiently know the current conditioning of bridge foundations. In this paper, NDT techniques were required to inspect the unknown foundations on a damaged heritage railroad bridge for further rehabilitation in Taiwan. Three proposed NDT methods, electrical resistivity tomography, ultra-seismic method, and parallel seismic method, were conducted to identify the bridge foundation depths. Post proof excavation and boring exploration were provided to verify the reliability of these inspection results. The electrical resistivity tomography inspection reasonably identifies the upper portion of soil layers and depth of granite lining layer of the foundations. Being compared with site subsurface results, the ultra-seismic and parallel seismic methods present a precise ability to determine the bridge foundation depths.

Keywords: Unknown foundation, electrical resistivity tomography, ultra-seismic, parallel seismic, proof excavation, borehole exploration

1. Introduction

The as-built condition of foundations is a crucial key to evaluate bridge stability for bridge engineers. For example, materials deterioration, scour variation, or structural cracking could undermine the foundation capacity of a bridge. Furthermore, lacking foundation dimension could impede of rating the flood or earthquake resistance on old bridges.

For more than forty years, non-destructive testing (NDT) or instrumentation inspection has been developed to rapidly evaluate the condition of bridge foundations [1-4]. Currently, both surface reflection technique, including impulse response and ultra-seismic (US) methods, and direct transmission technique, such as sonic logging and parallel seismic (PS) methods, are commonly used to assess the integrity of concrete piles, drilled shafts, and caissons in field [1, 5-6]. Some geophysical methods, like electrical resistivity tomography (ERT) etc., were introduced to subsurface and substructure investigation in past few years (e.g., [2, 4, 7]). In general, the ERT images provide outstanding identification on the interface between foundation and soil/rock and their foundation type. The ultra-seismic and parallel seismic methods have more precise ability to determine foundation depths.

Since bridge conditions may vary from dry riverbed, floodplain, to flowing water, the type of NDT inspection is associated with site situation. Field construction record or post-excavation results is strongly suggested to verify the reliability of NDT inspection results [8]. Meanwhile, in practical a more reasonable NDT inspection principle is suggested by comparing multi-type inspection results if direct information is unavailable [2, 3]. Wang et al. [3] suggest that an effective instrumentation inspection should consist of two inspecting methods at least in order to obtain solid conclusions.

2. Background

A steel truss river-crossing railroad bridge was built in 1913 and assigned as a cultural heritage bridge in southern Taiwan since 1987, as shown in Figure 1. A new prestressed
A concrete railroad bridge was constructed along its upstream side and replaced its transportation function. During 2005 to 2009, this cultural heritage bridge was partially damaged by three successive typhoons. A 200-m long bridge section from P7 to P12 was completely swept away in the main channel. The maintenance agency decided to rehabilitate the remnant bridge. Unfortunately, its subsurface design information cannot be found in the current bridge archive. Therefore, instrumentation inspection was proposed in order to determine the foundation conditions of piers from P1 to P7.

The target bridge was composed of 24 spans, each 63.5 m in length (1,524 meters in length) and 15.1 m in height. Each superstructure was supported with two exquisite and robust brick-masonry piers. Each exposed oblong-shaped pier was constructed with 3 different geometrical dimensions at least (Figure 1(a)). The most upper portion of a pier was constructed of bricks and partial granite blocks with a dimension of 7.55 m in length, 2.83 m in width, and 3.1 m in height. The middle portion of a pier was constructed with granite blocks but with a larger dimension of 8.7 m in length, 4.03 m in width, and 3.64 m in height. The lowest exposed pier was comprised granite lining with a dimension of 9.5 m in length and 5.2 m in width. The real types and depths of the covered bridge foundations were still left for inspection.

3. Instrumentation inspection

The instrumentation inspection was developed along the target bridge from piers P1 to P7 as shown in Figure 2. Two sections of ERT probe layout were developed along piers P1~P3 and P4~P6 of the target bridge. Two wave-based inspections, US and PS methods, were conducted on pier P4. In addition, boring exploration and site proof excavation were conducted on P4/P6 and P4, respectively, in order to verify the NDT inspection results.
3.1 Electrical Resistivity Tomography

ERT is to develop an artificial potential field by probing a pair of current electrodes around a target zone (Figure 3). One pair of electrodes are used to measure the ground potential difference. The underground apparent electric resistivity is functions of potential intensity, potential difference, and relative positions. Traditionally, the measured resistivity image with a display mode of visible-light spectrum, corresponding resistivity values from over 1,000 to less than 1 Ω-m, illustrates the resistivity intensity distributions in space. Since in field mineral composition, grain size, mineral formation, water content, and ion concentration can affect detected apparent electric resistivity, higher conductivity values on resistivity images could be identified as the locations of steel-content structures, anomalies, or pollutants.

Figure 4 presents the ERT inspection results alongside the target bridge from P1 to P6. The lengths of two ERT layout sections are 180 and 165 meters for sections of P1~P3 and P4~P6, respectively. Electrode spacing is selected as 3 meters in order to detect the depths of foundations and soil layers up to 25 meters. The resistivity values of granite lining piers usually range more than 5,000 Ω-m and display as gray contour [7]. Based on the limited ERT images, the bottom of the 3rd granite lining is identified at 5 meters, at least, below the ground surface. Due to concrete blocks arming around pier P6, its measured resistivity image is interfered with concrete blocks and corresponding bottom depth is relatively uncertain. Three-layer resistivity intensity distribution indicates the subsurface profile from the ground surface as three soil layers, 2~3 m sand layer, 3~9 m sand/gravel layer, and 9~15 m clay layer, corresponding resistivity values of 10-100, 100-1,000, and <30 Ω-m, respectively.

Figure 4. Electrical resistivity tomography outcomes along the target bridge: P1~P3 (upper) and P4~P6 (lower)
3.2 Parallel Seismic Method

The parallel seismic method is conducted by using a hammer to generate artificial elastic waves onto a foundation. The transmitting waves are measured at different depths in an adjacent borehole. Sensor spacing is selected as 0.5 meters from the ground surface downward to a depth of 37 meters. Each measured signal is plotted in a sequence of its corresponding depth from top to tip. Wave diffraction echoes represent the consequence from source effect when waves meet an obstacle. Waveform changes, such as direct waves, shear waves, and surface waves, indicate the interface of different media when waves travel through. Wave sequence discontinuity is supposed to be found at the interface of different materials.

Figure 5 shows the measured horizontal and vertical waveforms from the parallel seismic method around P4. The waveform discontinuity is marked at elevation positions of 13.8, 1.8, -1.2, and -15.2 meters, i.e. at depths of 5, 17, 20, and 34 meters, respectively, with an identical measurement error value of ±0.5 meters. The interface at 5 meters deep indicates the bottom of the 3rd granite lining, consistent with the finding in the ERT image (Figure 4). The rest predicted interfaces are suggested to be identified by using other geophysical inspecting methods or the direct findings from proof excavation or site borehole [3, 4, 8].

![Figure 5. Parallel seismic testing results on pier P4](image)

3.3 Ultra-Seismic Method

The ultra-seismic method is performed on one side of a partially exposed foundation
component by aligning several receivers in an equidistant linear fashion. A heavy hammer then is used to strike the component surface, thereby generating small artificial seismic waves. As the shock waves are transmitted through the foundation components, reflection waves are generated at the interface of the component material and the stratum (sand/soil/grave/rock and so forth). Due to variations in acoustic impedance, the direct and reflection seismic waves can be recorded directly by multiple-channel seismograms and used to correlate the travel time of artificial seismic waves in the target foundation. Contrasting this data with waveform imaging can yield a more accurate estimate of the interfaces of foundation components and its reflection depths.

Figure 6 indicates the ultra-seismic inspection results at P4. The vertical or horizontal waveform sequence or imaging from multiple sensors is displayed in a sequence of its corresponding depth horizontally. The direct arrival waves and reflection waves can identify trigger time T1 and terminal time T2, respectively. For example, the trigger time, T1, and terminal time, T2, are -0.33 msec and 11.27 msec, respectively, for vertical waveform sequence (Figure 6(a)). The wave velocity is around 1,205 m/sec. The distance is 6.9 meters away from sensor No.8. The computed foundation depth is around 4.9±0.25 meters from the ground surface, consistent with the findings in the ERT image (Figure 4) and parallel seismic method (Figure 5). For the horizontal waveform imaging, the trigger time, T1, and terminal time, T2, are 0.61 msec and 18.33 msec, respectively, (Figure 6(b)). The wave velocity is around 1,960 m/sec. The foundation depth is around 17.36±0.25 meters from the ground surface, which can be identified as the 2nd interface at the depth of 17±0.5 meters found in the parallel seismic method (Figure 5). This implies that there is a 12-m-deep 4th-layer pier lining existing right below the granite block lining, the 3rd-layer pier lining. This finding is used to be verified by other geophysical inspecting methods or the direct evidence from proof excavation or site borehole [3, 4, 8].
4. Inspection Verification

Proof excavation was chosen to confirm the subsurface situation on P4. An open excavation with 1:1 slope lowered the excavation level down to 4 m from the ground surface. The temporal steel sheeting walls was set right beside P4 and penetrated downward into 13 m deep as shown in Figure 7. Another two steel struts were installed to provide the horizontal support against lateral earth pressure behind the sheeting walls.

The excavation outcomes display that there is an interface existing between the 3rd and 4th lining layers, granite blocks and bricks, respectively, at 5 m deep from the ground surface. This positively confirms the bottom prediction of the granite lining layer (the 3rd lining layer) from the ERT, parallel seismic, and ultra-seismic techniques. However, since porous bricks and compaction soils probably lead to a low electric conductivity difference at the zone of the 4th lining layer, the ERT method cannot effectively distinguish brick caisson from surrounding soils.

Site borehole survey was developed adjacent to piers P4 and P6 with depths of 40 m and 20 m, respectively. The overall space distribution of 4 soil layers is shown in Figure 8 and Table 1. The geologic characteristics and their classification based on the Unified Soil Classification System (in parentheses) along the bridge site from the ground surface consisted of 9 m of gravel with fine sand (GP), 12 m of silty clay (CL), and 14 m of sand/ gravel (SM~SP) overlying 6 m of silty clay (CL). The interfaces of soil layers 2/3 and 3/4 located at 21 and 35 meters deep, respectively, from the ground surface match with those, 20 and 34 meters, found in the parallel seismic method.

![Figure 7. Site proof excavation on pier P4](image)

![Figure 8. Subsurface profile along the target bridge](image)
Table 1. Overall subsurface classification along the target bridge

<table>
<thead>
<tr>
<th>Layer</th>
<th>Soil classification</th>
<th>Elevation (m)</th>
<th>Depth (m)</th>
<th>Penetration resistant value, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gravel with fine sand (GP)</td>
<td>19~10</td>
<td>9</td>
<td>42~66</td>
</tr>
<tr>
<td>2</td>
<td>Silty clay (CL)</td>
<td>10~2</td>
<td>12</td>
<td>4~7</td>
</tr>
<tr>
<td>3</td>
<td>Sand/ gravel (SM~SP)</td>
<td>-2~16</td>
<td>14</td>
<td>59~82</td>
</tr>
<tr>
<td>4</td>
<td>Silty clay (CL)</td>
<td>-16~22</td>
<td>6</td>
<td>25~49</td>
</tr>
</tbody>
</table>

The comprehensive results from these investigation methods are graphically summarized in Figure 9 at pier P4. This pier penetrates into the ground up to 17 meters. The 4-layer lining pier consists of 3 layers of granite blocks with varying heights of 3.1~3.6 meters overlying on 13-m long brick lining. The ERT, parallel seismic, and ultra-seismic techniques have good inspection ability to identify the interface of lining layers 3 and 4 of the pier. The parallel seismic and ultra-seismic methods provide mutual identification on the interface of lining layer 4 of P4 and its surrounding clay. In addition, the interface of soil layers 2/3 can be effectively detected by using the ERT and parallel seismic methods. The interface of soil layers 3/4 can be effectively detected by using the parallel seismic method.

Figure 9. Subsurface profile at position of pier P4

5. Conclusions

In order to preserve a cultural heritage railroad bridge, NDT techniques were required to
inspect its unknown foundation depth. Three proposed NDT methods, electrical resistivity tomography, ultra-seismic, and parallel seismic methods, were conducted to identify the conditions of the bridge foundations. Accordingly, proof excavation and boring exploration were provided to verify the reliability of these instrumentation inspection results. The following conclusions can be drawn:

1. The electrical resistivity tomography inspection provides resistivity distribution over a wider area of formation characteristics and preliminarily identifies the interface between granite lining and surrounding soils. Unfortunately, the electrical resistivity tomography method cannot effectively identify bricks and surrounding soils both with similar electric conductivity values.
2. The overall lining layers consist of 3 layers of granite block lining overlying one brick-lining layer. The embedded conditions (i.e. the lowest two lining layers) of the bridge foundations are discovered as two types of lining, granite blocks and traditional bricks, by using the ultra-seismic and parallel seismic methods.
3. The ultra-seismic and parallel seismic methods present a precise ability to determine the interfaces of two lining layers and surround soils. This also indicates that a solid conclusion could be determined if two inspecting methods at least reach the identical answers.

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