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To cite this article: H Wang et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 615 012039

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IOP Conf. Series: Materials Science and Engineering 615 (2019) 012039 doi:10.1088/1757-899X/615/1/012039

Overwater depth inspection on a submerged pile bent

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Abstract. In this paper, a foundation inspection strategy was developed to determine the condition on a fully-submerged pile bent foundation supporting an overwater vehicular bridge in Taiwan. The electrical resistivity tomography inspection displayed the overall conditions of the salt-content canal. Using the reciprocal principle-based ultra-seismic inspection could finely determine the foundation depth. The time lapse analysis and traditional frequency analysis provided varying degrees of reliability on the pile length estimate, positively reconfirmed with the design charts. The entire investigation demonstrates the conclusiveness in determining the foundation depths when two testing methods are corroborated with appropriate analysis modes.

1. Introduction

Bridge safety is highly associated with management and maintenance. For the need of bridge agencies, the web-based Taiwan Bridge Management System (TBMS), the most complete bridge database in Taiwan, was funded by the Ministry of Transportation and Communications (MOTC) in 2001. Currently, the TBMS archives the fundamental and inspection data for more than 28,000 infrastructures, including vehicular bridges or viaducts, culverts, and common pedestrian bridges, with a span greater than 6 m in Taiwan.

Accordingly, bridge agencies are mandated to record the location, geometrical dimension, construction materials, and structure type of all components in bridges in this inventory. Biennial bridge inspection is required to not only assure the safety and performance level but also effectively find the aberration and damage in bridges for future maintenance and repair.

However, under limited budget, inadequate manpower, and amateur experience situations, the local governments that manage more than 17,000 bridges usually have uncertainty issues related to information preservation, design specifications, and construction quality. As a result, the substructure information is usually left as blank or marked as "Unknown" in the TBMS. Facing growing extreme climate hazards, the most severe challenge for bridge agencies is to evaluate their flood or earthquake resistance in disaster-prone areas without relevant information, especially substructure information. In addition, the budget allocation for bridge improvements is highly associated with knowing current conditions for government decision makers. All of these challenges demonstrate that the effective development of appropriate inspection techniques on unknown bridge foundations is a very important task for geotechnical and bridge engineers.



7th International Conference on Euro Asia Civil Engineering ForumIOP PublishingIOP Conf. Series: Materials Science and Engineering 615 (2019) 012039doi:10.1088/1757-899X/615/1/012039

2. Foundation inspection

Several non-destructive testing (NDT) techniques have been reviewed on the Foundation Characterization Program (FCP) funded by the Federal Highway Administration (FHWA) [1]. However, obtaining complete substructure information is still a time- and cost-consuming work by using several inspection methods for each bridge agency. The Geo-Institute Deep Foundation Committee of ASCE suggests that an appropriate and practical rule is to run a secondary type of test and both inspection methods also reach the same outcomes for deep foundations [2]. Recently, an efficient and economical non-destructive inspection strategy was developed to acquire bridge substructure information in Taiwan [3]. Such a two-phase inspection strategy consists of (1) Overall subsurface spatial distribution at a bridge site outlined with electrical resistivity tomography [4]; and (2) Pier foundation depth finely determined by ultra-seismic inspection [5]. Using these two testing modes can effectively achieve the identification feasibility on unknown foundation depths.

3. Bridge condition

This study inspected a twin-lane vehicular reinforced concrete bridge located in northeastern Taiwan (figure 1). The designated 2-span bridge was part of the access network for local residents and agricultural products transportation. The superstructure consisted of eight 51-m-long I-type girders and was supported by pile bents, which were located within a 45-m-wide tidal reach drainage canal.



Figure 1. Bridge panorama images: (a) downstream side; (b) upstream side.



Figure 2. Substructure profile of the submerged pier.

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Pile bents (i.e., partially embedded concrete piles) were used for crossing over the drainage canal full of soft clay and silty sand in order to accelerate the bridge construction speed. The pile bents were composed of two cast-in-place piles (drilled shafts) with a diameter of 1.5 m and a length of 31.8 m, as shown in figure 2. The exposure height beyond the riverbed was designated as 1.8 m below the pier cap bottom at its design phase. However, the estuary of the drainage canal merely has a distance of 2 km to the bridge site. The varying tidal level significantly traced back to the upstream, caused the riverbed variation, and also led to the water table approaching the pier cap bottom (i.e., complete submergence on the pile bents) at its highest tidal level.

4. Testing results and analysis

An electrical resistivity tomography technique with SYSCAL Pro, Switch Pro, termination strip, and electrode probes were utilized to display the electronic potential field on the target bridge. The survey line of an overwater electrical resistivity tomography inspection was settled parallel to the direction of flow and kept a distance of 0.5 m away from the pile bents (as shown in figure 3). One survey cable section with electrodes was hanged downward from the bridge deck, dragged to the downstream side with a fishing raft, and fixed the cable end on bamboo staffs. Similarly, another survey cable section with electrodes was dragged to the upstream side and fixed on another end with bamboo staffs as well. Being tied with empty plastic bottles, all electrodes were kept floating nearby the water surface of the drainage canal. The total survey length was 150 meters long and set with an electrode spacing of 3 meters.



Figure 3. Overwater electrical resistivity tomography inspection on (a) downstream side; (b) upstream side of a submerged bridge pier.

Another bridge, named as Bridge A, was 40 meters away from the upstream side. The locations of pile bents were marked in the resistivity image, as shown in figure 4. Using a pole-diploe inspection mode, two pretty low resistivity contours, shown as grey and light blue scales, were marked as dashed rectangles, underlying right below two bridge piers. These represented the locations with a relatively high content of reinforced bars existing in the pile bents. Theoretically, the bottom of the dashed rectangles was identified as the foundation bottom. The pile bent depth on the target bridge was identified as 10 meters, much shorter than its designated length, 31.8 m. This could be affected by flowing saline water. Repeated scour and deposits weakened the interface among saline water, soft soils, and piles bents in this tidal reach canal. The resistivity image obviously indicated a relatively high salinity in river and failed to identify the foundation depth on the target bridge.

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Figure 4. Overwater electrical resistivity image profile across the submerged bridge piers.

The modified ultra-seismic inspection [3] was executed on the pier cap supported by submerged pile bents due to a high tidal level. The transducer packet was fixed at the top position of the pier cap and the measured transient-state seismic waves were recorded with a Geometrics multi-channel Strata View seismography set (figure 5(a)). An investigator repeatedly struck the lateral side of the pier cap with a hand-held hammer in an equidistant fashion (0.2 m) from the cap top down to water surface (figure 5(b)). As the impact waves traveled downwards through the submerged and embedded components, the reflection waves would be created at the interface of the foundation bottom and underlying stratum.



Figure 5. Ultra-seismic inspection: (a) geophone installation; (b) striking on the pier cap side of a submerged bridge pier.

Figure 6 shows the conventional ultra-seismic waveform imaging (time lapse analysis) in the vertical direction. One needs to find all the trigger times (or dominant peak times) from each time history first. Linking all points at the trigger times on the ultra-seismic waveform image forms as the direct wave line (the solid arrow). The apparent wave propagation velocity of direct waves is computed as 3,833 m/sec (bar wave velocity) (slope of solid arrow). Then a draft reflection wave line with a slope value opposite to the direct wave line (the dashed line) can be drawn on the waveform

image. The possible reflection wave lines (dashed lines) are parallelly shifted to cross over the waveform image until passing all impact reflection points. By extending both the direct wave line and possible reflection wave lines, the intersection point corresponds to the reflection source (i.e. the pile bent length).

In this case, the possible pile bent length varies from 25.51 to 34.52 m. However, the precision of such a plot-based analytical approach is always affected by various factors, such as overlapping waveform echoes, identification difficulty in waveform, inconsistent responses from different impacts, and installation condition. Usually, an experienced investigator should provide a reasonable and professional judgement from the measured waveform image.





Figure 7. Vibration spectrum of Impact 1. (note: A cut-off at noise-induced extreme peak)

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In order to improve the precision of using ultra-seismic inspection, the surface response timehistories are transferred into spectra for frequency analysis by using the fast Fourier transfer (FFT). All 10 velocity spectra have similar vibration response distributions. A typical spectrum response in Figure 7 indicates regular-span, Δf , resonance peaks and a single extreme peak at around 360 Hz induced by background noise (labelled with an ellipse). Based on the one-dimensional wave theory, the pile length, *L*, is given by [6, 4]

$$L = C_{bar} / (2\Delta f) \tag{1}$$

where C_{bar} is the bar wave velocity and Δf is the frequency span (i.e., 55.65 Hz). The pile bent length (including pier cap height) is estimated as 34.44 m, around a 2.5% error to the nominal length.

5. Conclusions

An efficient and economical inspection strategy, consisting of (1) electrical resistivity tomography and (2) ultra-seismic inspection, was developed to extract bridge substructure information in Taiwan. This foundation inspection strategy can be introduced to determine the foundation length of a fully-submerged pile bent. The inspection conclusions can be drawn as the following:

- 1. A relatively high salinity in riverbed soft soils and water weakens the overwater electrical resistivity tomography ability and the estimated depth is shorter than the design length.
- 2. The modified ultra-seismic inspection technique provides more flexible installation for evaluating the condition of completely-submerged pile bent foundations.
- 3. The conventional time lapse waveform image analysis has a wider range of length prediction values. The determination of unknown pile bent lengths is still highly dependent upon investigator's experience and judgement.
- 4. Based on the one-dimensional wave theory, the frequency analysis provides a relatively reliable length estimate by using the average frequency span between two adjacent resonant frequencies.
- 5. The entire set of investigations presented demonstrates the conclusiveness in determining the foundation depths when the results from testing methods are corroborated with appropriate analysis modes.

Acknowledgements

The authors would appreciate the support granted by the CECI in Taiwan through CECI Research Project No.05929 "A Verification Study on Bridge Pile Bent Foundations with Non-Destructive Depth Inspection Technique."

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