DESIGN OF A SMART SUBSTRUCTURAL HEALTH MONITORING SYSTEM FOR THE NEW I-10 TWIN SPAN BRIDGE OVER LAKE PONTCHARTRAIN

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ABSTRACT

A new Interstate 10 Twin Span Bridge over Lake Pontchartrain is being constructed to replace the existing bridge that was heavily damaged by Hurricane Katrina in 2005. The new bridge consists of two 3-lane spans with 30 feet elevation above the surface of the Lake makes it less vulnerable to high storm surge. The bridge is supported by groups of battered pile foundations. In order to verify the analysis method used in the design and to address some concerns raised during the design phase, LA DOTD decided to install a health monitoring system on a selected M19 eastbound bridge pier of the main span. The pier consists of 24 square PPC battered piles (batter slope 1:6). The system includes both sub-structure and super-structure instrumentations for use in short-term monitoring during a static lateral load testing, and for long-term monitoring during selected events such as wave, wind and vessel impact. The sub-structure instrumentation includes strain gauges and MEMS In-Place Inclinometers (IPI) cast inside the foundation piles, triaxial accelerometers to measure lateral movements of pile cap, water pressure cells to measure wave forces, tiltmeters, and corrosion meters in the pile cap. The superstructure instrumentation includes strain gauges and corrosion meters inside the columns; strain gauges in the bent cap, steel girders, concrete girders, and one diaphragm; and installing a weigh in motion (WIM) system in the concrete bridge deck. A unique lateral load test was designed and conducted at M19 pier to assess the validity of the analysis method used to design the pile foundations. The test was conducted by pulling the M19 east and west bounds toward each other using two high strength steel strands that were run through the pile caps. A total of 1870 kips lateral load was applied in increments using two hydraulic jacks. This paper will present the design and development of the sub-structure instrumentation plan of I-10 Twin Span Bridge and its use during the lateral load test.

KEYWORDS

Sub-structure health monitoring system, lateral load test, pile foundation, pile instrumentation, FB-MultiPier, smart bridge.

INTRODUCTION

For years, the traditional monitoring of bridges and other civil engineering structures, to ensure their safety, was based mainly on visual inspections by expert engineers for critical bridge members that are usually carried out every two years. Due to existing large numbers of bridges nationwide, it becomes impossible to evaluate health conditions of all existing bridges from traditional inspection. The need to diagnose the status of aging structures that continue to deteriorate and to optimize the cost of bridge maintenance motivated the importance for developing structural health monitoring (SHM) systems to evaluate the performance of civil engineering structures. This has been realized at the national level since the 1990s, especially after the advancement in sensors and computer technology, which makes it feasible and affordable to install advanced sensors for newly built bridges. Since then, several research projects were funded by the National Science Foundation (NSF), Federal Highway Administration (FHWA), and state Departments of Transportation (DOTs) (TRB 2007; University of Michigan Transportation Research Institute 2009). However, the need for sub-structure and super-structure health monitoring of bridges has gained great momentum since the tragic collapse of I-35 Minnesota Bridge over Mississippi river in August 2007.

With the development in advanced sensor and computer technology, more newly built bridges are instrumented. In 2005, large numbers of various types of sensors were installed at different locations of the arch section for the
new Svinesund Bridge joining Sweden and Norway to monitor the health status of the bridge during the first five years of its service life (Ülker-Kaustell 2006). A sub-structure health monitoring system was also installed at the new I-35 Minnesota Bridge that was built to replace the collapsed bridge to provide live monitoring of the sub-structure loads during construction and long-term health monitoring of the bridge (Geotechnical & Structural Engineering Research 2009).

Pile foundations are usually used to carry axial loads of bridges deep to the hard bearing soil layer. However, in some cases, such as earthquakes, high winds, wave action, and ship impacts, the resistance of piles to lateral loadings is critical. The problem of a laterally loaded single pile and pile group has been under investigation and researched for more than three decades (Ashour et al. 2002). The p-y method (Matlock 1970; Reese and Welch 1975; API 1993; Reese 1997; etc.) is considered the most commonly method used for the analysis of laterally loaded piles. Several research studies have been conducted to back-calculate the p-y curves for different soil types and piles/pile groups from full-scale lateral load tests of single or group of piles. The measured deflections along the pile can be fitted into curves using the assumed function. Then by using integration and/or differentiation techniques, p-y curves at different depths can be determined.

This paper will present the design and development of the sub-structure instrumentation plan for short-term and long-term monitoring of the M19 eastbound pier of the new I10 Twin Span Bridge over Lake Pontchartrain. The instrumentation system was used to monitor the M19 pier during the lateral load test that was conducted to validate the analysis method used to design the pile foundations.

DESCRIPTION OF I-10 TWIN SPAN AND M19 PIER

The existing interstate I-10 Twin Span Bridge that crosses Lake Pontchartrain between New Orleans and Slidell sustained serious damage from the storm surge associated with Hurricane Katrina that hit the area August 29, 2005. The new 5.4-mile (8.7 km) long bridge is located 300 ft (91.44 m) east of the current bridge. It was built entirely with high-performance concrete for a 100-year designed life. The new bridge has an elevation of 30 ft. (9.14 m) which is 21 ft. (6.4 m) higher than the old bridge, and an 80-ft. (24.38 m) high-rise section near the Slidell side to allow for marine traffic. The bridge consists of two parallel spans; each span has three 12-ft. (3.66 m) travel lanes and two 12-ft. (3.66 m) shoulders [60 ft. (18.29 m) wide total].

Figure 1 presents a photo of the M19 eastbound and westbound piers site. In order to validate the analysis method used in the design of pile foundation and for long-term monitoring of I-10 Twin Span Bridge, the LADOTD decided to install a structural health monitoring system at the M19 eastbound pier. The M19 pier is the second pier south of the marine traffic underpass. It supports 200-ft. (60.96 m) long steel girders in the north side and 135-ft. (41.15 m) long concrete girders in the south side. The foundations of M19 piers consist of 24 precast prestressed concrete (PPC) 110-ft (33.53 m) long battered piles (batter angle of 1:6) with an outer dimension of 36 in. (0.91 m) and a circular void of 22.5 in. (0.57 m). The average embedded length of the piles is 87 ft. (26.5 m). The size of M19 pile cap (or footing) is 44 ft. long × 42.5 ft. wide × 7 ft. deep (13.4 × 13.0 × 2.1 m). The water depth is 12 ft. below footing surface.

Figure 1. M19 East and West Bound Piers Site
Laboratory and in-situ testing programs were performed to characterize the subsurface soil conditions at the M19 pier as well as along the whole I-10 Twin Span bridge location. One soil boring was performed close to the M19 pier down to 200 ft. (60.96 m). A total of 48 Shelby tube samples were extracted for laboratory testing. Standard Penetration Tests (SPT) were also conducted in sandy layers. The laboratory testing program included moisture content, soil unit weight, Atterberg limits, and unconsolidated undrained (UU) triaxial tests.

Five in-situ cone penetration tests (CPT) were performed at M19 pier down to 160 ft. (48.77 m) each, one CPT at the mid of the M19W pier, and four CPTs at distances 5-10 ft. (1.52-3.05 m) out from the four corners of pile cap. The main purpose of performing the CPT tests along the Twin Span bridge site was to locate the depth of the bearing sand layer to support the piles. The depth of bearing sand layer at M19 pier site was found to be at depths ranging from 100 ft. (30.48 m) to 110 ft. (33.53 m) below the water surface. However, the PPC piles at the M19 pier were tip on stiff silty clay layer at an average depth of 87 ft. (26.52 m) below the water surface.

The laboratory and in-situ testings at the M19 pier site revealed the subsurface soil stratigraphy for the site to consist of medium to stiff gray and tan silty clay to clay soil with silt and sand pockets and seams down to 110 ft (33.53 m) depth (undrained shear strength ranging from 0.28 to 2.02 tsf (26.8 ~ 193.4 kN/m²)) with a layer of medium dense light gray sand between 35 ft. (10.67 m) to 47 ft. (14.33 m) (SPT-N values ranging from 16 to 22). Medium dense to very dense sand with interlayers of silty sand, clayey sand, and silty clay soil was found between 110 ft. (33.53 m) and 160 ft. (48.77 m) (SPT-N values ranging from 3 for loose clayey sand to 86 for very dense sand). The soil stratification from the soil boring, profile of undrained shear strength, and profiles of tip resistance (q_c) and sleeve friction (f_s) obtained from CPT tests are depicted in Figure 2. The figure also presented the CPT soil classification based on the probabilistic region estimation method developed by Zhang and Tumay (1999).

Figure 2. Profile of Soil classification, soil properties, and classification
DEVELOPMENT OF INSTRUMENTATION MONITORING PLAN

A structure health monitoring system was designed and installed at the M19 eastbound pier of the new I-10 Twin Span Bridge over Lake Pontchartrain. This includes instrumenting both the sub-structure and the super-structure of the M19 eastbound pier.

The sub-structure monitoring system includes instrumenting selected piles with inclinometers and strain gages, instrumenting the pile-cap with accelerometers, tiltmeters, water pressure cells, and corrosion meters, as described next. A plan view of the M19 footing with a layout of sub-structure instrumentation is presented in Figure 3.

**Instrumentation Plan of Piles**

Eight selected piles (piles 4, 5, 6, 7, 8, 9, 10, and 12 in Figure 3) were instrumented with MEMS In-Place Inclinometers (IPI). The IPI consists of a string of tilt sensors connected together and placed permanently in the structure through a PVC casing tube. It can measure the position change (inclination) in each string in a direction perpendicular to the axis of the string. For each pile, a 100-ft. (30.48 m) 3.34-in. (8.48 cm) diameter PVC casing tube was installed during the pile casting phase (Figure 4a). The initial deformation profiles of casings for the selected piles were measured, prior to installing the IPI sensors, using a traditional vertical inclinometer probe, after casting of pile cab. Then six IPI sensors were calibrated and properly installed inside the casing the each pile. The IPI were placed at every 5 ft. (1.52 m) beginning at 5 ft. (1.52 m) until 65 ft. (19.8 m) from the bottom level of the pile cap with lowest one tied to an anchor point at the bottom of PVC casing at 85 ft. (25.9 m) from the bottom of the pile cap. The measurements from the six IPIs will provide a profile with depth of the lateral deformation of the pile.

Twelve selected piles (piles 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12) were instrumented with resistance type sister bar strain gauges to measure the strain distribution at the two different locations caused by the applied lateral load. Each pile was instrumented with two pairs of resistance strain gauges at -16 ft. (4.88 m) and -21 ft. (6.40 m) from the pile top, taking into consideration the possibility of cutoff after pile driving. The strain gauges were installed during the pile casting phase (Figure 4b). Measurements from strain gauges can be used to calculate the axial load and bending moment transferred to the instrumented pile. The piles’ strain changes were monitored during casting, strand cutting, and storage. Moreover, pile 1 was instrumented with battery powered data logger to monitor the strain change during delivery. The recorded strain change during storage and delivery of pile 1 is illustrated in Figure 5. It can be seen that the pile experienced appreciable strain change only when the pile was moved for storage (August) and when the pile was moved to barge for delivery (end of October).
Instrumentation Plan of Pile Cap

Instrumentation of pile cap started immediately after placing the footings’ rebar mesh reinforcements. Two triaxial accelerometers were calibrated and installed on top of the pile cap (footing) at two corners across from each other (NE and SW corners). Accelerometers will be used to measure any applied dynamic load during the long-term monitoring of M19 pier and to set up a trigger criterion system to start collecting and saving data from other instruments in any event for future analysis. Four uniaxial MEMS tiltmeters were calibrated and installed.
on a 45° diagonal at mid-width of each side of the pile cap to measure the rotation of the pile cap during long-term monitoring. Eight water pressure transducers were calibrated and installed mounted flush with the pile cap facings (two per facing) to measure the water wave force impact during selected events. In addition, eight ECI corrosion meters were installed in the pile cap, two corrosion meters at each corner at top and bottom of the pile cap, to measure any corrosion that might occur during long-term monitoring. Corrosion meters are usually attached to support rebars with tie wraps at corrosion prone areas.

The super-structure monitoring system includes instrumenting the columns, bent cap, steel girders, concrete girders, and one diaphragm with strain gauges and corrosion meters. An OSMOS weigh in motion (WIM) system was also installed at the concrete bridge deck of the M19 pier.

The instrumented system was used to monitor the piles-cap-column system of the M19 eastbound pier during short-term static lateral load testing and will be used for long-term health monitoring during selected events, such as cyclical wave, wind, and vessel impact. The permanent data logging system will be programmed to “trigger” when the loading event of interest is detected and configured to capture live load responses due to selected events and data stored for later review.

**DESIGN OF LATERAL LOAD TEST**

Initial preparation for the lateral load test started during the pile cap casting phase by installing two 4-in. (10.16 cm) diameter PVC pipes in both M19 eastbound and westbound piers for use later to run steel strand tendons through during the lateral load test. Two dead-end anchorages were installed at the M19 eastbound pier footing; each includes a trumplate and bursting steel spiral. A 1-in. (2.54 cm) thick plate was installed over each of the 3-in. (7.62 cm) thick blockout on the live-end at the M19 westbound pier footing. The plates were fixed to the footing by steel anchors and epoxy.

A unique lateral load test was designed to assess the validity of the analysis method used to design the bridge pile foundations using the FB-MultiPier program (FB-MultiPier user’s manual, 2005). The test was conducted by pulling M19 eastbound and westbound piers toward each other using high strength steel tendons that were run through pile caps via the pre-installed 4 in diameter PVC pipes.

Preparation of the site for lateral load test started a week before the designated test day. This includes preparing the sub-structure monitoring system and setup of lateral load test. The sub-structure instrumentation was tested, piles strain gauges and MEMS IPI instrumentation were connected to data loggers that were placed inside the protection wall, and the data acquisition monitoring system was temporarily assembled and connected via internet phone to the data acquisition server. Initial readings of all instruments were recorded a day before the test. Survey station prisms were installed at M19 eastbound and westbound, M17 eastbound, and M20 eastbound to monitor the movements of footings and in bent caps of the M19 piers using automated laser survey system. Figure 1, presented earlier, shows the load test site at the M19 pier.

Setup of lateral load test started two days before the test. Two floating barges were deployed to the site. One barge was placed between the two pile caps to allow access and to provide support to steel strand tendons to eliminate slack and keep them out of water. Another barge was placed next to M19 westbound to carry jacking/hydraulic equipments and allow access to the live-end. The steel strands were run through the pre-installed 4-in. (10.16 cm) PVC pipe from the dead-end at M19 eastbound toward the live-end at M19 westbound. Strands were anchored at the live-end, then each strand was pre-loaded to 2 kips (8.9 kN). Setup preparation for the load test was then completed one day before load test by connecting hydraulic pumps, hoses, gauges, and manifolds to the two 600-ton jacks. The jacks’ gauges were also connected to the data acquisition system for measurements of the applied load. Figure 6 illustrates the jacking system at the live-end of the M19 westbound pier.

The designed sequence of lateral load test includes preloading each tendon to 300 kips (1334.6 kN), increasing the load incrementally to 600 kips (2669 kN)/tendon, unloading to 300 kips (1334.6 kN), reloading incrementally to 1000 kips (4448.2 kN)/tendon, unloading again to 300 kips (1334.6 kN)/tendon, and finally cutting the strands. The estimated total time of testing was 6 hours. During the testing, horizontal movements of footings and bent caps of the two M19 piers were monitored using the automated laser survey system with station prisms. This was in addition to monitoring strains and deformations measurements within the foundation piles after each load increment. Two criteria were setup to stop the test at any time before reaching the intended max-applied load of 2000 kips (8896.4 kN): (1) if the maximum lateral displacement of M19 westbound bent cap reaches 3/4 in. (1.91 cm), based on lateral design load; and (2) if the maximum tension strain change at the top two strain gages in pile 8 reaches 160 microstrains. This criterion will limit the maximum positive moment at pile head to 1500 kips-ft (2034 kN-m) and maximum negative moment to 750 kips-ft (1017 kN-m). None of these criteria occurred during the lateral load test; however, the test was unloaded earlier at a maximum applied load of 1870 kips (8318.17 kN) when the stroke in one 600-ton jack reached its maximum.

Figure 7 presents the later deflection profiles for selected piles 8 and 11 (as an example) measured at different load increments. The figure indicates that most of the lateral deformation occurred within the upper 50 ft. (15.2
the lateral load test. A maximum lateral load of 1870 kips (8318.17 kN) was applied, and the corresponding
conducted at the M19 eastbound pier to evaluate the analysis method used in the design of pile foundations. The
maximum lateral deformation of the M19 eastbound pier as measured using laser survey was 0.66 in. (1.68 cm).
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corrosion meters. The system was used for short-term monitoring the bridge during the lateral load test, and will
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eastbound pier of the new I-10 Twin Span Bridge over Lake Pontchartrain. The system includes instrumenting
eight selected piles with In-Place Inclinometers and twelve selected pies with resistance type strain gages, and
instrumenting the pile-cap with two accelerometers, four tiltmeters, eight water pressure cells, and sixteen
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steel tendons using two 600-ton jacks. The sub-structure system was used to monitor M19 eastbound pier during
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SUMMARY AND CONCLUSIONS

This paper presented the design and development of the sub-structural health monitoring system at the M19
eastbound pier of the new I-10 Twin Span Bridge over Lake Pontchartrain. The system includes instrumenting
eight selected piles with In-Place Inclinometers and twelve selected pies with resistance type strain gages, and
instrumenting the pile-cap with two accelerometers, four tiltmeters, eight water pressure cells, and sixteen
corrosion meters. The system was used for short-term monitoring the bridge during the lateral load test, and will
be used for long-term monitoring the structural health of the bridge. A unique lateral load test was designed and
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the lateral load test. A maximum lateral load of 1870 kips (8318.17 kN) was applied, and the corresponding
maximum lateral deformation of the M19 eastbound pier as measured using laser survey was 0.66 in. (1.68 cm).
The installation of the super-structure monitoring system was recently completed, which included instrumenting the two columns, bent cap, steel girders, concrete girders, and one diaphragm at the M19 eastbound pier with strain gauges and corrosion meters, as well as installing an OSMOS WIM system at the concrete bridge deck of the M19 pier to capture traffic loads for the three lanes. The health monitoring system will be used for long-term monitoring of the M19 eastbound pier under dynamic loads caused by selected events (winds, waves, and vessel collisions).

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