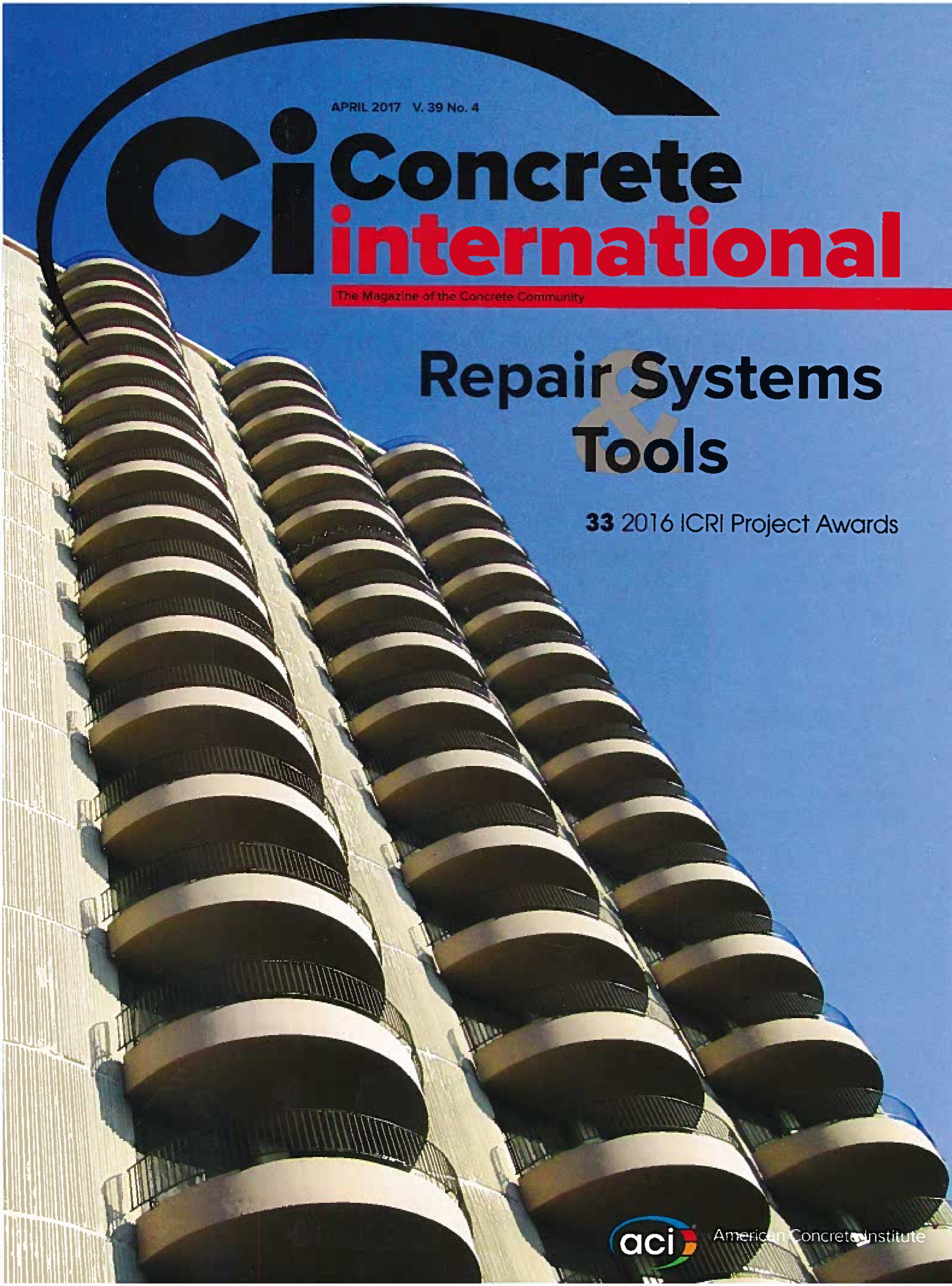
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Repair of ASR-Damaged Piles

Challenges included limited working space and a crocodile-infested river

by Mo Ehsani, Stephen Day, and Tony White

About 4.5 miles (7.2 km) north of Cairns, Queensland, Australia, the southbound carriageway of the Captain Cook Highway passes over the tidal estuary of the Barron River. Constructed in 1977, the bridge over the estuary is 579 ft (176 m) long and 34 ft (10 m) wide, with seven spans of 77 ft (23 m). The superstructure consists of prestressed concrete (PC) beams and reinforced concrete (RC) deck, while the substructure consists of piled abutments and blade piers rising from pile caps, each supported on 10 closely spaced PC piles.

The octagonal piles have minimum diameters of just under 21 in. (533 mm), and the clear spacing is as low as 12 in. (305 mm). The upper 4 ft (1.2 m) of the piles are within the tidal range. However, the piles are generally underwater, and it is rare for more than 20 in. (508 mm) of a pile to be exposed (Fig. 1).

In 2000, severe cracking was noted in 13 of the 40 piles in the four piers located in the main river channel. Analyses showed that the cracking was caused by alkali-silica reaction (ASR). To protect the piles from premature failure due to corrosion and to inhibit the further development of ASR cracking, the Queensland Department of Transport and Main Roads (DTMR) determined that encasing the piles was the preferred long-term treatment. A 15-year journey ensued as the DTMR searched for an economical, durable solution that could be safely executed.

Repair System Requirements

DTMR established two main criteria for an acceptable repair system. Based on the work of various researchers, including Carse,[1] it was known that the rate of ASR is reduced with increasing confinement. Therefore, the first criterion was to ensure that the pile encasement system could provide a minimum confining pressure of 300 psi (2.1 MPa). It was also well documented that ASR required water, and corrosion required an electrolyte and oxygen. Thus, the second criterion was to ensure that the encasement system would block the ingress of chlorides, moisture, and oxygen in the concrete.

Initial considerations

The DTMR's initial assessment showed that a traditional RC jacket could be designed to meet the design criteria. However, further investigation identified serious challenges, including:

- The close spacing of the piles would make it nearly impossible to install individual jackets with the needed confinement; and
- Work would have to be executed within the murky, crocodile-infested waters of the estuary.

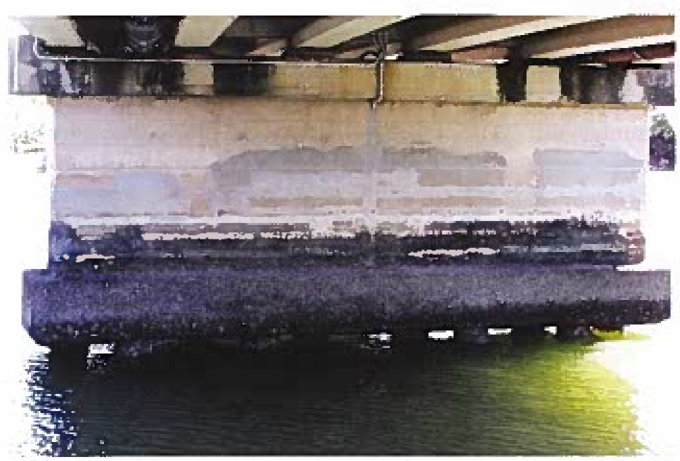

Fig. 1: View of a typical blade pier rising from a pile cap supported on 10 closely spaced PC piles

Fig. 2: The 2003 prototype FRP jacket used finger joints bent inward to be embedded in the grout, subsequently placed in the annulus formed between the pile and the jacket

The former challenge precluded the use of individual RC encasements, and the latter challenge created obvious safety concerns. Both increased the complexity and cost of the traditional approach, so the DTMR investigated additional approaches that would better fit its limited budget.

While DTMR had prior experience using fiber-reinforced polymer (FRP) jackets in above-water pile remediation works, they were also aware that FRP jackets are typically supplied in half shells that are bolted or adhesively bonded together in the field. The vertical joint is the weak link in this system, not only limiting the development of high confining pressure but also allowing ingress of moisture and oxygen. Therefore, traditional FRP jackets were deemed unsuitable for this project.

Initial FRP prototypes (2003)

A review of other types of FRP jackets failed to identify a commercially available jacket that met the desired technical requirements and could be easily and confidently installed underwater. That prompted the DTMR to become an active partner with the University of Southern Queensland (USQ) and the NSW Roads and Traffic Authority (RTA) in a joint project to develop an FRP jacket system for concrete piles suffering ASR cracking.

A prototype FRP jacket was subsequently designed and tested. At the time, epoxies promoted as capable of underwater curing were not considered to be sufficiently advanced to meet the project objectives, so a mechanical jointing system was sought. A prototype was designed with a finger joint system. The "fingers" were turned in so that they could be anchored in the hardened grout that would be subsequently placed in the annulus between the pile and jacket (Fig. 2). In trials, however, the prototype was unable to withstand the hydraulic pressure of the fresh grout—the project was terminated.

Market explorations (2006)

In late 2006, the DTMR called for proposals for the jacketing of the piles—innovative jacketing solutions were encouraged. Four proposals were received, and all were based on RC encasement. Two of the submitting companies were contracted to develop and provide an indicative price for their solutions.

Although initial estimates indicated that one option would offer significant cost savings, the final estimate showed that the specific challenges of the site resulted in costs that exceeded the available funding. At this stage, it was decided to postpone the jacketing project pending further development of FRP solutions.

Reinitiated investigations (2014)

In 2014, all piles were cleaned and inspected by divers. The underwater inspection indicated that the number of cracked piles had increased from 14 in 2004 to 22 in 2014.

At about the same time, the recently developed PileMedic® system[2] was identified as a remediation system that would meet the technical and practical needs of the DTMR project. The system also promised to do so at an economical cost (around 40% of the previously tendered prices for a traditional RC encasement). A project proposal was prepared and subsequently ratified by DTMR's Structures Branch as a trial installation. Funding was secured and construction documents were prepared to enable the works to proceed. DTMR's in-house construction branch (Roadtek) was engaged to undertake the works, subcontracting with QuakeWrap (Australia) to provide training and technical advice to the local commercial divers that would complete the underwater works.

The Adopted Solution

The PileMedic system had its beginnings almost 25 years ago when FRP products were being studied for strengthening of bridge piers to resist seismic loads.[3] The early generation of FRP was applied using a technique known as wet layup. In that system, fabrics of carbon or glass are saturated with epoxy and directly wrapped around and bonded to the column. While that system does provide structural enhancement, it has a few limitations. The column must be repaired and patched to provide a smooth surface prior to wrapping. Furthermore, because wet layup systems require immediate bonding to the surface of the column, they are difficult to implement when a column is submerged in water.

PileMedic laminates comprise sheets of carbon or glass fabric up to 60 in. (1524 mm) wide that are saturated with resin and passed through a roller press that applies uniform heat and pressure. The laminates are very thin, with thicknesses ranging from 0.01 to 0.026 in. (0.25 to 0.66 mm), so they can be easily wrapped around columns having diameters of 8 in. (203 mm) or more. Also, the number and pattern of the layers of fabrics can be adjusted to produce custom mechanical properties.

The first application of PileMedic for repair of submerged piles was carried out in Miami, FL.[4] Since then, many transportation agencies have conducted successful evaluations of the product for structural enhancement projects. Studies have included a Caltrans project for strengthening concrete columns damaged in earthquakes,[5] a Texas Department of Transportation study for strengthening and protecting corroded steel H-piling,[6] and a Nebraska Department of Roads study for strengthening deteriorated timber piles.[7]

Design of the pile jacket

For confinement of a column or pile, the jacket is designed using a hoop stress analysis (Fig. 3). For example, a PileMedic PLC150.10 laminate has a breaking strength T of 4050 lb/in. (709 kN/m) of width. If two layers of the laminate are used to create a jacket with $d = 25$ in. (635 mm) around a pile and the grout infill in the annular space, the laminate can provide a confining pressure p given by

$$p = 4T/d = 4 \times 4050/25 \quad 648 \text{ psi (4.5 MPa)}$$

This confining pressure increases the compressive strength of the original pile and the newly placed grout. The pressure can be changed by using different types of laminates that have different tensile strengths, and by changing the number of layers that are wrapped around the pile. Safety factors and durability considerations must also be included by applying reduction factors to the breaking strength values. Guidelines

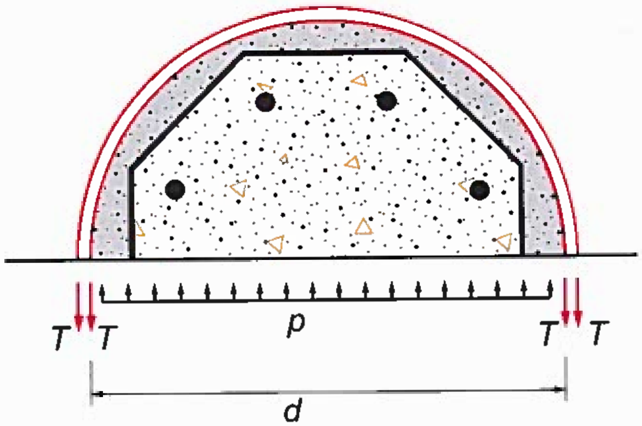

Fig. 3: Free body diagram for calculation of confining pressure provided by two layers of the laminate system

Fig. 4: Coated laminate being passed to the diving crew for installation

such as those published by ACI Committee 440[8] provide detailed information for such factors.

PileMedic laminates are supplied in rolls that are 4 ft wide and 250 ft (76 m) long. The rolls can be easily cut to any length in the field, allowing a single roll of laminate to be used for repair of piles of virtually all shapes and sizes. Standard details call for the laminate to be wrapped twice around the pile (that is, 720 degrees), with an additional 8 in. lap beyond the starting point.

If the design also calls for an increase in the bending capacity of the column, laminates can be constructed with biaxial fabrics that provide longitudinal (along the height of the pile) as well as hoop stresses. By using an epoxy grout, a jacket will be bonded to the concrete pile and will thus contribute to the bending capacity of the pile or column. The Caltrans test mentioned earlier was one such application.

Field installation

A total of four piers, each having 10 submerged piles, were repaired on this project. The Barron River bridge site is known to be a habitat for crocodiles, bull sharks, and jellyfish, so a steel cage was positioned around each pier to protect the installation crew. A barge was used to provide a working platform and staging area for materials and equipment. The barge also included a small crane for loading of materials such as resin and grout.

The diving crew consisted of four workers—two divers performing the installation, one backup diver, and one supervisor. On the barge, a two-worker crew was given the task of cutting the laminates and mixing and applying the epoxy paste.

The repairs required the creation of a 2 in. (51 mm) annular space around each pile, so the diameter of the jackets had to be 25 in. (635 mm). A 25 in. circle has a circumference of 78.5 in. (1994 mm), so the 4 ft wide laminates were field-cut to lengths of 2 × 78.5 + 8 = 165 in. (4191 mm). To create the required standoff distance between the existing structure and the laminate, spacers (for example, short pieces of polyvinyl chloride pipe) can be attached to the surface of the structure.

The portion of the laminate that is immediately adjacent to the annular space does not need to be coated with adhesive—only the second ply and the 8 in. extension must be coated. In this case, a length of 78.5 + 8 = 86.5 in. (2197 mm) of the laminate was coated with adhesive. The laminate was placed flat on a table; a two-part epoxy resin adhesive (supplied with the system) was applied. The adhesive has a consistency similar to toothpaste and can be applied using a notched trowel to achieve a uniform thickness of 30 to 40 mil (0.8 to 1.0 mm).

Next, the coated laminate was passed over the cage to the diving crew (Fig. 4). The lightweight jackets are relatively easy to handle once they are submerged. The crew wrapped the laminate around the pile and previously installed spacers. The epoxy adhesive serves as a lubricant and allows easy adjustment of the size of the jacket. Ratchet straps can also be temporarily wrapped around the shell to maintain its shape and diameter while the epoxy cures. Because the resin cures underwater, installation can be completed without the need for cofferdams and dewatering.

The first 4 ft wide jacket was installed with the bottom edge about 18 in. (457 mm) below the mud line. The next jacket was applied with a 4 in. lap along the height of the pile (the epoxy adhesive was applied to seal this region). The process continued until a jacket of desired height was created.

Once the jacket was installed, the annular space was filled with a cementitious underwater grout using the tremie placement method. A shear mixer and pump were used for this application. As the grout was placed, its hydrostatic pressure pushed the two layers of the laminate together. This is expected to improve the bond by providing more uniform contact between the layers. Moreover, the heat of hydration generated by the grout can be expected to cause faster curing of the epoxy resin. The ratchet straps were removed the next day, completing the repair.

The field installation had its unique challenges. While the repairs were scheduled for the dry season to avoid flash floods, there was still the need to be prepared for rapid evacuation. The visibility in the murky water was low—often limited to only 1 ft (0.3 m). The large tidal flow, which ranges from 6 to 10 ft (2 to 3 m), also had to be accommodated.

The project was completed in around 5 working weeks (35 days). It generally took 1 day to install the steel protective cage, 4 days to wrap 10 piles and place the grout, and 1 day to demobilize from one pier and move to the next. The crew performed the work exceptionally well, however, adapting to the constant challenges faced working in a trying tropical environment.

Cost savings

In retrospect, the agency's decision to delay the project was fortuitous, as the development of the new laminate technology resulted in significant cost savings. The adopted solution provided savings of 160% compared to the original reinforced concrete encasement option.

Project credits: The Queensland Department of Transport and Main Roads, Owner; Roadtek, General Contractor; and JD Marine, Underwater Contractor.

References

1. Carse, A.H., "Report on the Mechanism Causing Cracking in the Prestressed Piles of the Houghton Highway Bridge," Queensland Department of Transport, 1992.

2. Ehsani, M., "FRP Super Laminates Present Unparalleled Solutions to Old Problems," *Reinforced Plastics*, V. 53, No. 6, Aug.-Sept. 2009, pp. 40-45.

3. Saadatmanesh, H.; Ehsani, M.R.; and Li, M.W., "Seismic Strengthening of Concrete Columns with Fiber Composite Belts," Proceedings of the 1992 Materials Engineering Congress – Materials: Performance and Prevention of Deficiencies and Failures, ASCE, Atlanta, GA, 1992, pp. 677-690.

4. Ehsani, M., and Tipnis, A., "Miami Building First to Benefit from Innovative PileMedic® Jacket," *Concrete Repair Bulletin*, July-Aug. 2011, pp. 16-18. (Video: http://goo.gl/DX9ItL)

5. Yang, Y.; Sneed, L.; Saiidi, M.S.; Belarbi, A.; Ehsani, M.; and He, R., "Emergency Repair of an RC Bridge Column with Fractured Bars using Externally Bonded Prefabricated Thin CFRP Laminates and CFRP Strips," *Composite Structures*, V. 133, Dec. 2015, pp. 727-738. (Video: http://goo.gl/HRHzjr)

6. Dawood, M.; Karagah, H.; and Shi, C., "Repair Systems for Deteriorated Bridge Piles, Technical memorandum #4a," TxDOT Project 0-6731, 2015, 41 pp.

7. Mohammadi, A.; Gull, J.H.; Taghinezhad, R.; and Azizinamini, A., "Assessment and Evaluation of Timber Piles Used in Nebraska for Retrofit and Rating," Draft Final Report, Nebraska Department of Roads, Apr. 2014, 51 pp.

8. ACI Committee 440, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-08)," American Concrete Institute, Farmington Hills, MI, 2008, 76 pp.

Selected for reader interest by the editors.

—PileMedic, **www.pilemedic.com**

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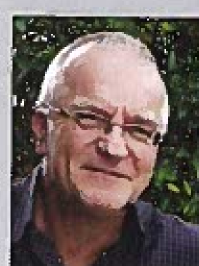

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