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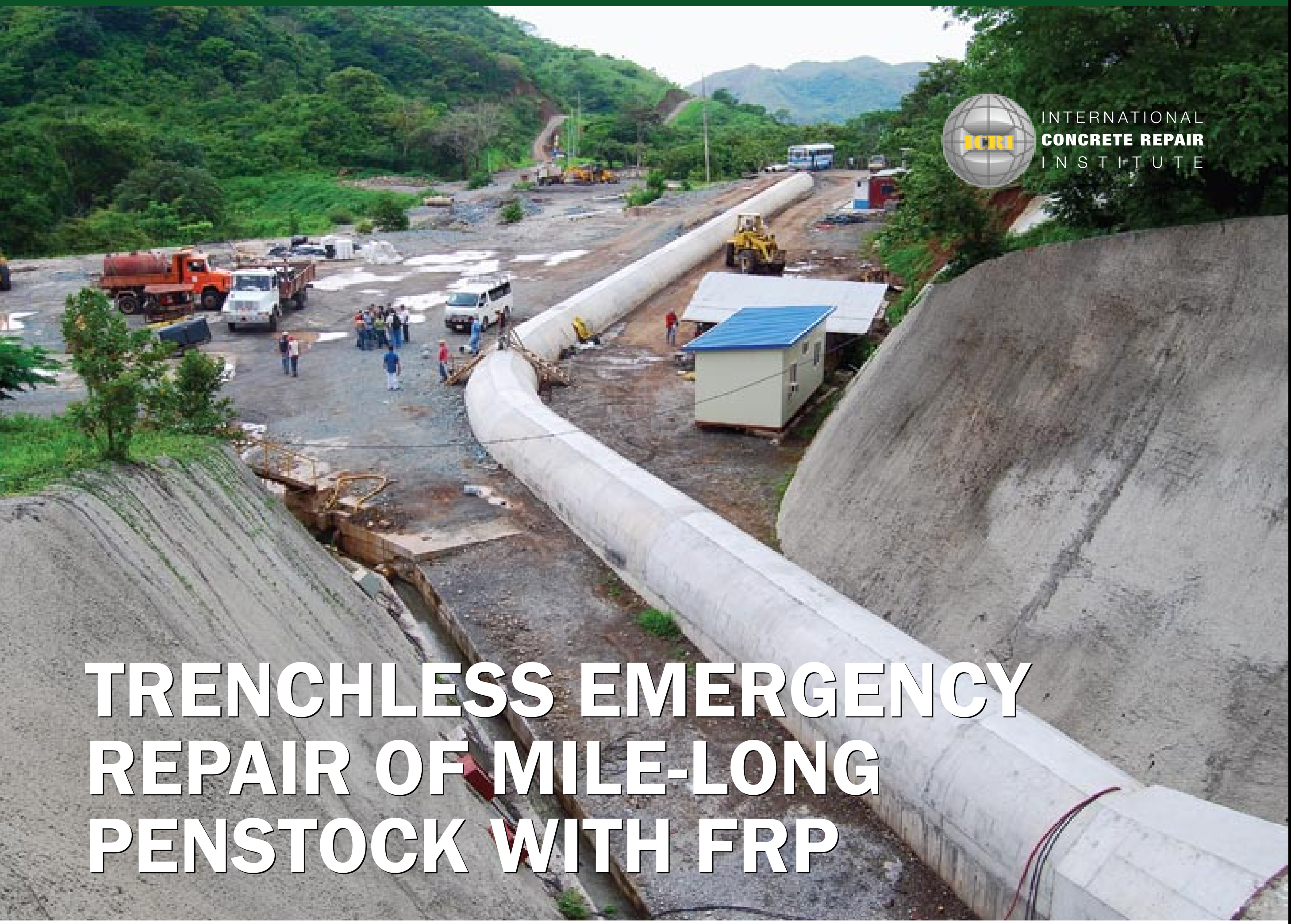

INTERNATIONAL CONCRETE REPAIR INSTITUTE

TRENCHLESS EMERGENCY REPAIR OF MILE-LONG PENSTOCK WITH FRP

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The use of fiber-reinforced polymer (FRP) structural linings to strengthen and/or rehabilitate existing pipelines is increasingly gaining widespread acceptance among power plant and utility facility managers. The versatility of the linings to conform to a wide range of diameters and lengths, their high strength properties, light weight, impermeability, thinness, and fast rate of application/installation are some of the reasons why many managers prefer FRP linings to other retrofit alternatives (*Concrete Repair Bulletin* 2008).

FRP linings typically consist of fabrics made with high-strength fibers that are soaked in an adhesive resin and are applied like wallpaper to the interior or exterior of the pipe surface. The high-strength fibers are typically composed of bundles of very thin strands of glass, carbon, or aramid. Once the resin cures, the fabric turns into a very thin (typically about 0.05 in. [1.3 mm] thick) composite laminate. The density and orientation of the high-strength fibers, as well as the fiber type, are parameters that the engineer can vary to create customized FRP linings that meet specific project criteria.

When applied to the inner surface of a pipeline, the FRP lining becomes a trenchless structural rehabilitation alternative, where all labor, equipment, and materials are introduced into the pipeline through service access points, thus avoiding the need for excavation. Because many major pipelines lie under freeways and urban or industrial developments, excavation is not possible without major disruptions to traffic, production, or other normal operations. The economic impact of the disruptions, coupled with the significant investment required to replace deteriorated pipelines, increase the appeal of this trenchless retrofit option.

Although the use of FRP linings has focused on the rehabilitation of deteriorated pipelines that have been in service for decades, they can also be used to correct design and/or construction errors of new pipelines. Such was the case of the low-pressure penstock at the El Encanto Hydroelectric Power Plant located 75 miles (120.7 km) northwest of San José, Costa Rica. This project included the installation of about 150,000 ft^2 (13,935 m^2) of FRP lining, and is the largest reported FRP pipeline retrofit project completed to date in a single phase. The design problems, and the FRP lining solution implemented to address them, are discussed herein.

PENSTOCK PROBLEMS

The low-pressure penstock at the El Encanto power plant (Fig. 1, cover image) conveys river water from an upstream dam to the turbine complex downstream. The pipeline is built of cast-in-place reinforced concrete with an inner diameter of 84 inch (2.1 m) and a total length of 5742 ft (1750 m). The water flows by gravity, but because of the elevation difference between the dam and turbine complex, as well as the continuous changes in the vertical and horizontal alignment of the pipeline required to conform to the mountainous topography, the water flow is pressurized.

Although the structural design had properly addressed the strength requirements of the pipeline and accounted for the design pressure and hydrodynamic loads, the pipeline's serviceability requirements were overlooked. The pipeline exhibited significant longitudinal and transverse cracking during a pressurized test and, as a result, as much as 20% of the flow was lost due to leaks.

The pipeline was drained and all visible cracks were sealed using typical repair materials. When the pipeline was pressurized for a second time, the repaired cracks leaked again. The leaking at the repaired cracks was most likely due to the increase in the crack width due to the deformations of the pipeline caused by the increase in internal pressure. Given the relative rigidity of most crack sealing materials, full deformation compatibility between the repair material and the surrounding concrete could not be achieved, degrading the integrity of the seal and allowing leaks to reoccur. Figure 2 illustrates typical leaks occurring along the length of the pipeline during tests conducted at maximum operational pressure.

Fig. 2: Leaking after conventional crack sealing

Moreover, the cracks generated multiple paths for humidity intrusion that reached the steel reinforcement of the pipeline, allowing for corrosion problems that, if not properly addressed, could compromise the structural integrity of the pipeline in the future. Complicating the problem even further was the combination of mountainous topography and the constant tropical rains. Because most of the pipeline is buried underground, water draining down the mountains keeps the surrounding soil constantly saturated, which generates seepage pressures. In fact, with the pipeline empty, seepage water was observed draining through some of the longitudinal cracks (Fig. 3).

Fig. 3: Water seeping into pipeline

It was at this point that an engineering consultation and a site visit were quickly arranged. One of the authors inspected the cracks, reviewed structural plans and available local engineering reports pertinent to the leak issues, and identified the main causes of the problem.

To arrive at an optimal engineering solution, all of the aforementioned problems needed to be properly and simultaneously addressed. An additional consideration was the urgency of minimizing the time required to implement the repair, because—obviously—the power plant could not produce electricity while the pipeline was shut down.

SOLUTION TO THE PROBLEM

The application of FRP linings requires a certain amount of preliminary work to the pipe surface to maximize contact and bond strength between the substrate and the FRP. Therefore, pressure washing and/or sandblasting, as well as some patching and/or grinding, must take place in the areas targeted for lining with FRP. In the case of the El Encanto pipeline, the amount of surface prep work was atypically large because the cast-in-place construction process caused significantly more surface irregularities than those associated with the more traditional precast pipes, such as prestressed concrete cylinder pipe (PCCP). Evidence of cast-in-place procedures such as construction joints and formwork fins was visible in the pipeline. The pipeline was pressure washed with 7000 psi (48.3 MPa) machines to remove any scour, sediment, curing compounds, and any other substance that could hinder the bond between the FRP and the pipe surface. Figure 4 shows grinding of protrusions on the interior surface of the pipeline.

An FRP lining consisting of one layer of bidirectional glass fabric was designed to provide a humidity barrier, to offer an effective crack control mechanism, and to supply additional hoop strength to account for future losses of hoop steel due to corrosion. Because in all likelihood the corrosion process at the reinforcing steel had already started due to the two-way humidity paths generated by the existing cracks, the additional hoop strength provided by the FRP effectively increased the useful life of the pipeline. It should be noted that the humidity barrier is effective against water leaking into and out of the pipe, due to seepage or internal pressure effects, respectively; however, the corrosion of the steel

Fig. 4: Preparation work prior to installation of FRP lining

reinforcement will not be slowed significantly as a result of the humidity barrier because seepage water will continue to provide the means for this process to continue. While nonstructural linings can also provide two-way humidity barriers, nonstructural linings cannot account for the loss of structural integrity caused by the ongoing corrosion due to the presence of seepage water.

Moreover, the adhered FRP laminate was designed to achieve full deformation compatibility with the pipe as the pipe expands due to pressurization, and the bidirectional orientation of the high-strength glass fibers in the fabric guarantees that existing and/or future cracks are intercepted in orthogonal directions, providing superior crack control. Nonstructural linings, on the other hand, cannot serve as an effective crack control mechanism.

Finally, an epoxy top coat was applied as a cover for all of the installed FRP. This coat provides resistance to the abrasion caused by sediment carried by the river water, and additional leak proofing by covering any pin holes remaining in the FRP lining. The coating has a gray concrete color, which facilitates quality control by providing visual means of verifying that the entire light green-colored FRP lining is fully covered, and that any uncoated spots can be easily detected.

The time urgency associated with the power plantís imminent start of operations cannot be overstated, which required placing the entire design and manufacturing process on a very short schedule. Epoxy and fabric manufacturing plants were placed on accelerated production runs and part of the production was shipped by air cargo transport.

A technical team comprising two structural engineers and three field supervisors traveled to Costa Rica to oversee the project and train the local installation crews. A technical team fluent in Spanish was required for the job to run smoothly.

INSTALLATION PROCEDURE

The 5742 ft (1750 m) long penstock had four lateral access points at the locations of relief valves, with spacing ranging from 1000 to 1500 ft (305 to 457 m). These 24 x 24 in. (810 x 610 mm) access points were used by the crew to supply FRP materials, tools, and equipment to four installation stations inside the pipeline. (Fig. 5)

The installation direction was opposite to the flow direction to prevent the tendency of the joints in the FRP lining from being lifted by the water flow. Each installation station consisted of a five-man crew inside the pipe applying the FRP lining to the pipeline's interior walls, and another five-man crew performing support activities such as transporting the rolls of lining material from the access point to the installation point, and cutting and preparing the FRP rolls.

An epoxy paste was applied to the top half of the pipeline; the main purpose of the paste is to prevent peeling due to self weight of the saturated FRP fabric and to seal the surface to prevent excessive absorption by the dry concrete surface of the epoxy resin from the saturated FRP fabric. Figure 6 shows the installation of the first roll of FRP lining material at one of the installation stations. The access point is clearly visible on the lower left portion of the figure. No epoxy paste was used in the lower half of the pipe. Because gravity forces in this area tend to hold the FRP fabric in place, only a seal coat of epoxy resin was used to prevent excessive absorption by the dry concrete surface of epoxy resin from the saturated fabric. The edges of the 50 in. (1270 mm) wide bands of fabric were adequately overlapped in the hoop and longitudinal directions to

Fig. 5: Typical 2 ft. x 2 ft. access point

Fig. 6: Installation of FRP sheets on the interior surface of the pipeline

Fig. 7: Construction joint of FRP lining

Fig. 8: Completed segment of pipeline prior to testing

achieve full continuity of the FRP. The edges of the overlaps were feathered with epoxy paste and/or epoxy resin to secure the overlaps in the lining in place.

Specially designed construction joints were prepared at the starting point of each installation run, which also became the end points of the installation front that started at a downstream access point. The joint was later sealed with an epoxy paste (Fig. 7). Nowhere in the 5742 ft (1750 m) length of the pipeline were FRP lining edges left exposed to peeling from water flow, maximizing the water tightness of the installation.

The average rate of production of each of the four installation stations was 2500 ft^2 (232 m^2) of FRP lining installed in an average eight-hour work day. The operation continued seven days a week, allowing the complete installation of approximately 150,000 ft^2 (13,935 m^2) of the FRP lining system in 15 calendar days. This also included the application of the epoxy top coat, which, as stated previously, was used to provide abrasion protection for the FRP, as well as to seal any remaining pores in the installed FRP laminate. The application took place before the lining was fully cured (the surface was still tacky on contact) to ensure maximum bond.

The FRP lining installation was completed on July 8, 2009, and pressurized test runs were successfully completed on July 15. Figure 8 shows a completed lining installation prior to testing.

More than 1 mile (1.6 km) of a 84 inch (2.1 m) diameter pipeline was successfully retrofitted to its original condition in three weeks (one week of preparation work and two weeks of FRP lining installation). The FRP lining is expected to require no maintenance and to have a useful life that will at least match the pipelineís operational lifetime.

PROJECT SUCCESS

The FRP retrofit of the cast-in-place concrete penstock at the El Encanto Hydro-Electric Power Plant in Costa Rica is the largest reported FRP pipeline retrofit job completed in a single phase to date in the world.

The unique features of this project, such as the extent of the prep work required to smooth out the irregularities caused by the cast-in-place procedure; the significant complexities introduced to the engineering design caused by the length of the penstock; the transitions to steep slopes and the changes in the vertical and horizontal alignment of the pipeline due to the mountainous topography; the training of local installation crews with no previous experience with FRP; the urgent need to minimize downtime of the power plant forcing quick design, materials supply, and mobilization of the technical team; and the fact that the project was completed ahead of schedule, made the successful completion of this project an outstanding achievement in civil engineering.

The fact that over one mile (1.6 km) of a large diameter pipeline can be retrofitted to its original condition with minimum downtime and no excavation was required, especially under the unique challenges mentioned previously, is a testament to the versatility and effectiveness of this FRP technology and the experience and technical capabilities of the project team.

REFERENCES

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This project received a 2010 ICRI Project Award of Merit and a 2009 Honorable Mention for the Trenchless Technology Project of the Year Awards.