A Novel Holistic Approach to Rehabilitation of Underground Structures

V. Gall ▪ Gall Zeidler Consultants
T. Martin ▪ Gall Zeidler Consultants
L. Boyd ▪ Gall Zeidler Consultants

ABSTRACT

Water infiltration into subgrade infrastructure can cause major impacts on their performance. In addition to damaging the structure, water intrusion leads to deterioration of installations including electrical and mechanical components and in patron discomfort. To remedy these impacts, leak remediation is often carried out to halt water infiltration. Remediation methods include coatings, drainage, injection/stitch grouting, curtain (backside) grouting, and/or internal umbrella systems. Selection of the rehabilitation method depends on the structure's use, owners' priorities, its installations, structural conditions, surrounding ground, and hydrogeologic conditions. Since many factors influence the rehabilitation method chosen, a novel holistic approach is undertaken to understand leakage causes and consequences to develop the most appropriate, efficient, and reliable solution to extend the structure's life. A reconnaissance phase combines geologic, hydrogeologic, and as-built information with detailed digital scans and visual observations to develop a database of existing conditions. This database, called a tunnelband, is used to develop the rehabilitation solution and made part of the contract documents, allowing for an informed bid by specialty contractors. Tunnelband and the preferred rehabilitation system are portrayed in contract documents, which are procured in various contract types depending on the owner's preference and project characteristics. The pool of contractors are required to submit their understanding of this holistic approach by developing and supplying the owner with a detailed workplan. The completed rehabilitation is portrayed in detailed as-built drawings which also provide the owner with an operation and maintenance manual outlining for periodic observation of the structure and checking of its performance. Ultimately, this information is implemented into a "BIM Digital Twin" that is used by the operations and maintenance staff for long-term observations. This proposed novel framework for leak rehabilitation is currently being used successfully in a number of projects throughout the United States.

INTRODUCTION TO LEAKAGE REMEDIATION

One of the most significant long-term hazards inherent to subgrade infrastructure is water infiltration through and into the structure (Bergeson & Ernst, 2015). If left untreated, water intrusion can create a negative user experience, cause deterioration of critical components within the structure, and can compromise the integrity of the structure itself.

There are a number of different factors that influence water intrusion. Most subgrade infrastructure is wholly or in part below the water table, and over time, exposure to groundwater can lead to the development of pathways for water to flow into the structure in particular in older structures and/or structures where the waterproofing installed as part of the initial construction has become ineffective. This effect can be exacerbated by porous and permeable geology that allows for higher groundwater

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flow. In concrete-lined structures, a common location for water intrusion to occur is at construction joints; water can also enter through circumferential cracks that developed within the concrete slabs. Masonry-lined tunnels can also exhibit efflorescence and leakage through either cracks in the tunnel structure or in between the masonry units. In metal-lined tunnels, water intrusion may present as corrosion and dampness at joints, and can often be identified as rust or leakage within each segment in more severe cases (McKibbins, Elmer, & Roberts, 2009).

Water infiltration can affect structures of any age, but older infrastructure commonly experiences the most severe effects due to degradation of the lining and waterproofing. Newer structures may also exhibit water intrusion if the waterproofing was not successfully chosen, designed or installed. Given water infiltration can affect subsurface infrastructure regardless of age, type of construction, lining, and ground conditions, a number of remediation methods are employed worldwide to halt water intrusion regardless of the structure or leakage characteristics. Additionally, numerous repair materials exist on the marketplace, with varying characteristics. Several companies have even successfully developed their own proprietary materials for waterproofing, to include in particular grout mixtures.

With so many factors affecting the success of the remediation, it is critical to select a remediation strategy that is appropriate for the structure experiencing water intrusion. The authors propose a novel holistic approach to water intrusion that takes into account not only the existing leaking structure conditions, but fully understands the structural, waterproofing, geology, and hydrogeology of the structure. Any as-built records, from previous rehabilitation efforts and original construction, are also reviewed with the goal of a complete understanding of the water intrusion of the structure. Fully understanding these factors allows for a thorough evaluation of repair methods, and for the most appropriate repair method for both the structure and the owner's operational needs to be chosen.

REMEDIATION METHODS

Water infiltration is a ubiquitous feature of numerous subsurface structures, and displays many forms depending on varying structural and hydrogeological characteristics. To address water intrusion in these wide range of conditions, a number of repair methods and repair materials have been developed. These include both positive-side (i.e., outside the tunnel structure) and negative-side (i.e., inside the tunnel) methods, and employ different strategies to control, divert, or stop water intrusion.

Several of the predominant methods used in contemporary subgrade water intrusion remediation are presented below. Each of these methods presents a viable strategy for halting water intrusion, and some methods may be used simultaneously.

Crack Injection

Crack injection, also known as "stitch grouting," is a negative-side remediation method that halts water intrusion through a crack or joint, mostly within concrete structures. Holes are drilled at an angle in an alternating pattern on either side of the joint or crack, and intersect the plane of the deficiency near its midpoint within the slab. Packers are installed, and the crack is flushed with water and then injected with grout such as epoxy, polyurethane, and acrylic resin (Figure 1).

This technique for repairing cracks in concrete can be successful, but there are several limitations of this method. Crack injection is used primarily to repair leaks at discrete cracks and joints, and is not a system-wide water infiltration solution. Additionally,

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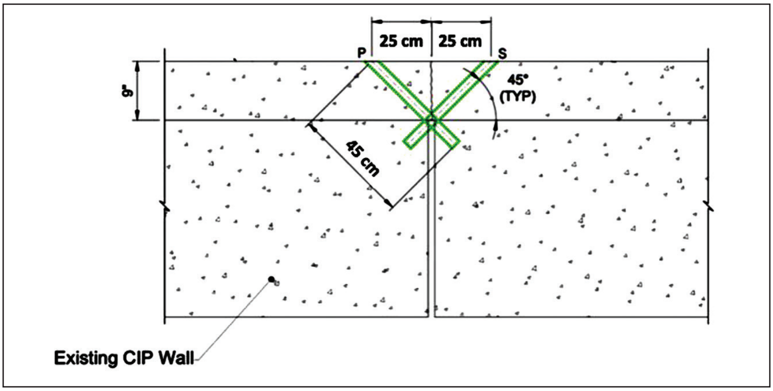

Figure 1. Typical configuration of crack injection holes intersecting a joint

halting water at one crack typically causes the water to migrate to another location nearby where water can find a pathway into the structure. This commonly leads to "chasing" leaks throughout a structure to fully halt water intrusion, and multiple treatments are often required.

Coatings

Coatings such as crystalline waterproofing are another method for halting leaks through negative-side repair. These coatings can be applied to individual cracks or applied broadly (typically in conjunction with discrete crack repair) to help limit the chasing of leaks. This coating applies a material that reacts with water, which causes a catalytic reaction that produces a non-soluble crystalline. Through the process of diffusion, the crystalline waterproofing chemicals spread throughout the pores and any hairline cracks within in the concrete, allowing this reaction to take place anywhere the crystalline waterproofing material is exposed to water. These insoluble crystals continue to grow until water infiltration is halted.

Figure 2 shows crystalline waterproofing as installed along a crack in concrete. Following application of the repair material along the identified crack, a coating was then applied to the entire structure, which helps to limit new leaks from appearing elsewhere.

While, like crack injection, this method is useful for repairing leaks along discrete cracks, and has the added benefit of the ability to cover a broader area, this is not a system-wide water infiltration solution. Additionally, unlike crack injection, which can be used on cracks with considerable width, the use of coatings such as crystalline waterproofing are generally only recommended for hairline cracks.

Figure 2. Crystalline waterproofing applied along a crack

Curtain Grouting

Curtain grouting is a positive-side remediation method which involves treating the outside of the structure's lining and to some extent the surrounding ground to fill any

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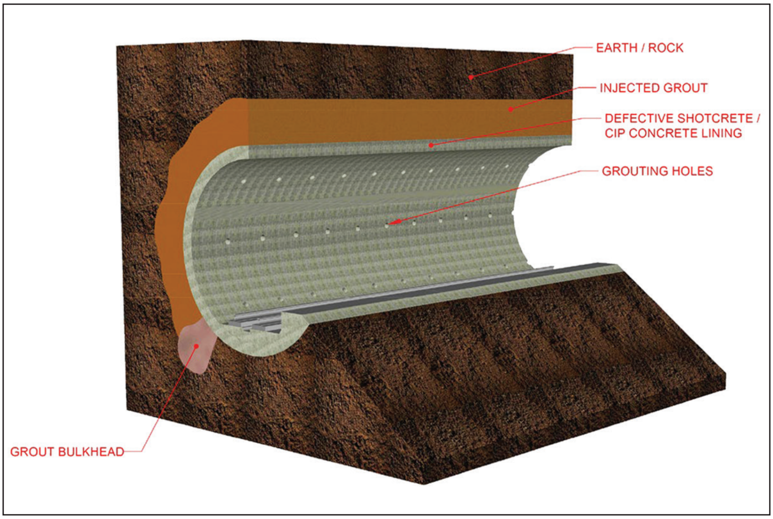

Figure 3. Diagram showing grout injected behind the lining and in the substrate.

voids and eliminate the source of water infiltration before it reaches the structure. In this approach, holes are drilled through the lining in a systematic pattern to penetrate the entire thickness of the lining, whether that is steel, cast iron, concrete, shotcrete, brick or another lining type. For steel and cast iron linings existing grout ports may be used for grout injections. These holes reach, at a minimum, the exterior of the structure, and can be drilled into the surrounding substrate as well (Figure 3).

Curtain grouting is a versatile option that can be used in all structure types and practically all ground conditions.

Lining Replacement and Umbrella Systems

An umbrella system is the most consists of installing a secondary lining following the installation of a waterproofing membrane against the existing liner.

This is typically the most expensive and involved remediation option, and requires the tunnel or structure to be out of service for extended periods of time. Given that, this is an option that should only be considered in cases where the existing lining is unsalvageable and water intrusion is widespread, severe, and systemic. However, installation of waterproofing and drainage systems limits future remediation needs and ensures the longevity of the structure following installation.

Drainage and Dewatering

Most subsurface structures are constructed with internal drainage systems that divert groundwater through or around the structure. Over time, these drainage systems can become clogged and inoperable, which can lead to additional water intrusion from the water that cannot be adequately diverted. In some scenarios, repairing the drainage system greatly decreases the amount of water intrusion observed.

Dewatering is another method to control the water. Diversions can be constructed that move water through the structure with minimal impact on the structure and its components.

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PROPOSED HOLISTIC APPROACH

Application of the most appropriate water infiltration mitigation strategy is critical to ensure a successful project. With widely varying characteristics that affect water intrusion, and many available remediation strategies available, it is important to carefully craft a leak remediation program that considers these characteristics as well as an understanding of the goals of leak remediation for a particular site. This proposed holistic approach is based on the authors' understanding that there is no universally-appliable leak remediation program, but rather the most appropriate leak remediation strategy for a particular project is derived from a holistic understanding of the structure, the causes of leak remediation, and the owner's goals for the structure.

Basis of Design

The foundation of the recommended design and project specifications is based on past experience and a thorough review of national and international standards. For example, reference to curtain grouting is made to STUVA (2014). These standards and peer-reviewed papers aid in the development of details included in the project specifications in a grouting program and assist in the understanding of acceptable installation of remediation strategies.

Inspection and Desktop Study

The most important aspect of leak remediation is gathering all necessary information to make educated recommendations about a project site. Early on in the process, all available data are identified and reviewed to fully understand the structure's layout, the history of its construction, and any factors that could influence the chosen remediation strategy. Some of the most important information to gather at this step is the geology encountered during investigation, the quantity and locations of groundwater inflows, and data from the as-built records to better understand how the structure was built and how the waterproofing, if performed, was applied.

A comprehensive walkthrough and itemization of leaks is performed following this stage, and digital scans are typically performed at this point in the investigation. The digital and visual data are then combined with as-built structural, geological, and hydrological information into a comprehensive database of existing conditions. This database, called a Tunnelband, is used to develop the rehabilitation solution and made part of the procurement documents, allowing for an informed bid by specialty contractors.

During this phase of the work, it is also essential to capture the owner's goals of the project, and understand the purposes of leak remediation. Depending on the structure's uses, the owner's future plans for the structure, and also varying goals in public areas (e.g., station platforms) and private (e.g., ancillary back of house rooms) areas, the recommended remediation strategy may change. For example, an owner of a subsurface mass transit station may want to ensure that no leakage occurs in all areas of the station where the public can access, but may find small amounts of residual leakage acceptable in back rooms, storage facilities, and throughout adjacent tunnels. Understanding the owner's goals, and working with them at every step in the process will aid in ensuring that the leak remediation strategy is consistent with their expectations and will help facilitating a successful project.

Remediation Selection

Following the gathering of all relevant information, a design phase is undertaken where all of these data are taken together to recommend a comprehensive remediation

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strategy for the structure. When taking the gathered information into account, there are still several other factors to consider when recommending a path forward.

Structure Types

While there are some remediation methods that are independent of structure and lining type, many are not. Curtain grouting is a viable option anywhere that a systematic grid for grouting can be developed, but crack injection is generally only appropriate for concrete-lined structures, or in some masonry-lined structures. Replacement of the lining can only be accomplished where sufficient clearance can be maintained after the new lining is installed. Additionally, most coatings can work on all lining types, however special care must be taken when performing this repair method on shotcrete-lined tunnels; due to the rough surface that is generally present, it may need to be smoothened by cementitious coatings prior to application.

Ground Conditions

Most remediation options are suitable for a wide range of ground conditions, however curtain grouting is much less dependent on the substrate than some of the other remediation methods. Dewatering, for example, is suitable in cases where the substrate is rock; however, this is much more difficult in soft ground.

Impact on Operations During Construction

For an existing structure, the leak remediation program will impact the typical operations of the structure to a certain extent. If performed within a transit network, it is likely that the work can only be performed during scheduled outages, which may be limited to a few hours at a time at nights and certain times over the weekend. In a road tunnel, an adjacent tunnel may be briefly used for bi-directional traffic, but this is also typically limited to short periods of time. Work must not only be completed during these windows, but at the end of each window, the structure must be clear of any tools and work debris, and be fully operational. For these reasons, lining replacement or installation of an umbrella system can generally not be performed without a prolonged shutdown of the structure, which is not generally possible in many situations. Even the utilization of modern lining overcutting machines behind a protective shield that allow for traffic operation have their limitations and will cause limited shut down periods.

Procurement

During the design phase, preparing for the procurement and execution phases is essential. Given that any of the more involved remediation methods involve a high level of specialization, a specialized contractor is necessary to assure the success of the remediation project. It is recommended that a prequalification process be undertaken to allow for qualified bidders to be selected prior to the distribution of the Contract Documents.

When prequalifying is not possible, i.e., due to an owner's legal obligations early notice of procurement is crucial for obtaining multiple competitive bids. The nature of these projects typically requires specialty contractors to form partnerships with larger, general contractors. These pursuit partnerships take some time to form, and the earlier notice given to potential bidders, the better.

During Construction

During construction, it is critical to ensure the presence of a qualified Engineer of Record representing the design intent as well as perform a thorough qualified

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inspection to verify the remediation was performed in accordance with the Drawing and Specifications (Gall, 2000). The presence of an Engineer of Record on site aids in capturing data regarding the work being performed, and a thorough inspection can demonstrate the work has been acceptably performed, can be used to direct the Contractor to revisit certain areas, and can be used by the owner as part of a repository of data for the work that was performed.

Leakage Criteria

The definition of acceptable leakage criteria post-construction should be established early in the project life with the owner. Leakage criteria can be uniform throughout the whole structure or varied based on location; an owner may want certain areas to be completely dry. The leakage criteria should be clearly defined in the specifications and drawings. Although a completely dry structure is sometimes preferred, a common baseline for acceptable leakage criteria to be included in the specifications is accepting localized damp spots due to capillary action, but prohibiting dripping or flowing leaks. Another utilized metric is accepting leaks that, when blotting paper is applied, the amount of leakage must be less than a certain diameter on the blotting paper.

Maintenance after Construction

After construction is completed, the completed rehabilitation is outlined in detailed as-built drawings which also provide the owner with an operation and maintenance manual outlining for periodic observation of the structure and checking of its performance. Ultimately, this information is implemented into a "BIM Digital Twin" that is used by the operations and maintenance staff for long-term observations. While this is important information to have in all cases, this is particularly important when crack repair, dewatering, or drainage is performed. As mentioned previously, crack repair can lead to water finding new pathways through the structure, and continued maintenance should inspect the structure periodically to identify if new leaks are appearing. Additionally, maintenance needs to be performed on a regular basis for drainage lines to keep them in good working order and unclogged.

CASE HISTORY—WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY

In 2018, GZ as part of a General Engineering Team under Gannett Fleming, was tasked by Washington Metropolitan Area Transit Authority (WMATA) in the Washington D.C. Metropolitan Area, USA, with performing water intrusion assessments on tunnels in multiple areas of their system. This followed a well-received pilot grouting program which addressed water intrusion in two miles of underground tunnels in Maryland. The goal of the assessments was to optimize future leak remediation work and involved performing inspections, executing a desktop study of all available documents, and preparing a report summarizing the findings. Both visual and digital inspections were carried out, with digital scanning performed, including highly-detailed photogrammetry of the lining. Over 21 miles of tunnels, shafts, and adits were assessed. and recommendations were made to WMATA for locations to prioritize. Several separate leak remediation designs were then developed, and these are in various stages of implementation.

Implementation of the Proposed Holistic Approach

Prior to gathering information or providing recommendations, GZ met with WMATA to understand their goals of the leak remediation program. Given the size of the WMATA network and the spatial variability of magnitude of water intrusion experienced along the lines, along with the infrastructure present at different locations along the system,

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WMATA prioritized certain locations and conditions along the network. Priority was assigned to areas experiencing dripping or flowing leaks and areas where internal infrastructure could eventually be compromised by continued water infiltration. This led to the goal of optimizing the remediation strategy in terms of cost (in both time and money) of remediating the infiltration and the benefits of the leak remediation program.

Once the goals and priorities were well understood and following the gathering of this information, a tunnelband was developed for all of the structures, displaying the geology, hydrogeology, inspection findings, photographs, and construction documents. This wealth of data allowed each section of tunnel to be compared to each other section of tunnel, which were used to both evaluate known problem areas and also identify additional areas that may experience negative impacts from water infiltration in the future. The tunnelband data were then used in conjunction with WMATA's goals and priorities to consider possible remediation methods; after this exercise, unique recommendations were made depending on the structure type, owner priorities, leakage regiment, and access considerations (Figure 4).

Innovative Inspection Techniques

Given the long distance of the tunnels which were evaluated, conventional inspection techniques would have led to a considerable effort, both in manpower and track time. An estimate predicted over 90 shifts of night inspection would be required, at a minimum. As an alternative, high-resolution scanning was adopted. A hi-rail vehicle was outfitted with equipment to allow for multiple miles of scanning to be completed each night. This shortened the track time required to under three weeks. These scans were then reviewed during normal office hours. This innovation greatly reduced operational impacts on WMATA and field staff required, without sacrificing the accuracy of the inspection.

BENEFITS OF THE PROPOSED HOLISTIC APPROACH

Typically, a one-size-fits-all leak mitigation solution would be applied that may treat each leak agnostic of leakage characteristics, ground conditions, owner priorities, and the structure of the tunnel. This repair strategy would grout each leak independently without context of the structure's overall leak regiment. Compared to recommendations resulting from the proposed holistic approach, this approach requires greater material and labor costs, may lengthen the duration of the remediation program significantly, and does not significantly improve the results.

In addition to avoiding diminishing returns, this holistic approach can also proactively identify areas that should be addressed sooner to avoid potential negative effects in the future. An understanding of the spatial characteristics of ground conditions can aid in identifying where leakage may be seasonal, or areas where a prolonged multi-year drought can decrease flow from leaks during the duration of the drought. Utilizing a targeted, tailored holistic approach allows for funds, time, and labor to be optimized to meet the Owner goals. Additionally, understanding the structure as a whole, to include geology, hydrogeology, inspection findings, photographs, and construction documents, allows for an optimized and durable remediation solution in line with Owner priorities.

CONCLUSIONS

Water intrusion into existing underground structures leads to premature deterioration and increased maintenance costs. Often water intrusion is treated with one size fit all remedies, and little care is paid to the cause or characteristics of the water

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Figure 4. (top) Hi-rail vehicle used in scanning; (bottom) Scan from a WMATA tunnel

infiltration. Commonly, the symptom is treated, rather than the cause of the leakage itself. This can lead to an unsatisfactory remediation effort and requires additional time and money spent to repair the structure to the satisfaction of the owner. Utilizing a holistic approach to tunnel remediation allows the most appropriate methods for the rehabilitation to be implemented, taking all the structural, operational, and stakeholder considerations into account.

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