

Western Dam Engineering Technical Note

A SEMI-ANNUAL PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the **Western Dam Engineering Technical Note**, We present articles on **unmanned drones, overtopping protection methods for embankment dams, cellular grouting for conduit sliplining, and conduit repair with mechanical seals.** This semi-annual newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to the design, inspection, safety and construction of small to medium sized dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

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Employing Unmanned Aircraft Systems in Dam Inspections

Tim Saffold

Introduction

Unmanned aircraft systems (UAS) commonly called “drones,” offer innovative solutions for obtaining data needed to meet dam inspection requirements. Simply stated, UAS combine an air vehicle, sensor, controller, and software interface to create a programmable data collection tool—and the data it produces can be processed and manipulated to suit many purposes.

Where data has been captured traditionally through direct inspection by individuals or by manned aviation, UAS now provide a capability to gather accurate and meaningful data more safely, quickly, and cost-effectively. The ultimate goal is then to translate those data through processing and analysis into what is often referred to as *Decision Quality Information (DQI)*—information that supports decisions or courses of action that produce favorable outcomes in a timely manner. All this has direct safety implications that can benefit those who inspect dams, analyze the data, or act on the information the data supports.

Extracting the maximum benefit from using UAS in dam inspections warrants a few key considerations. Applying these considerations will support positive results; ignoring them could increase risk, jeopardize obtaining quality data, or negate the benefits of UAS altogether.

The intent of this article is not to create a prescriptive formula for UAS planning and use, but rather to increase awareness of how the technology can best be employed as a dam inspection resource. This article is not intended to be comprehensive as there is more to UAS selection and employment than can be presented in this article.

It's all about the data

Know what you want to learn. This is critical because if one fails to define data quality objectives (DQOs) precisely, the risk of increasing costs and producing undesirable outcomes goes up considerably. Here's why: The desired data output determines what type of

sensor should be integrated onto the UAS—the wrong sensor produces wrong or bad data. Moreover, the type of sensor will determine the type of UAS required to carry it—the wrong UAS could mean less flight time or worse, a crash. The type of UAS selected must be able to safely operate in the desired environment as a stable data collection platform. The raw data may require processing to a data quality standard so that the processed data will be DQI. A breakdown in correctly addressing any of the considerations above could result in failure to produce DQI. Resources will have been expended with little or no value gained.



Figure 1. Employing UAS to Inspect a Concrete Dam

Asking precise questions about the data output when considering using UAS will help to achieve desirable outcomes. For example, if the desired outcome is to identify cracks in a dam structure using UAS, then a series of questions should follow: 1) is there a specific crack size and location that should be imaged or is the desire to image all cracks? 2) What resolution and accuracy are desired? 3) Does the data need to be viewed real time or is it sufficient to download and view post-flight? 4) Are there any secondary and tertiary effects created by the crack that need to be examined? 5) What is the operating environment like around the dam to be imaged? 6) How should the data be organized and managed for optimum benefit?

Asking these questions in the context of dam inspection standards will help refine sensor requirements and strengthen operational planning and use. When these questions have been answered, the type of sensor needed to collect the desired imagery

can be determined. Sometimes, more than one type will be required.

Sensors

Sensors are the different types of data collectors that can be integrated onto the UAS platform. These include the appropriate software interfaces to enable sensor control.

As advances in sensor technology continue to deliver lighter weight, reliable, and capable sensors, the types listed below have been integrated more readily onto UAS platforms. They are listed in order of most common and least expensive to less common and most expensive.

- HD optical for both still and video imagery
- Thermal or infrared (IR) for both still and video
- Light detection and ranging (LIDAR)
- Multispectral
- Hyperspectral

Optical sensors are the most common type found on UAS and offer the UAS operator a variety of data quality options. Regardless of sensor type, data quality often can be enhanced with operational methods that maximize sensor strengths and minimize limitations. The following optical image, captured by an optical sensor at standoff range of approximately 75 feet, illustrates an element of power transmission infrastructure. The data quality objectives were to determine if cotter pins were in place and assess the condition of insulators while remaining a safe distance from the powerline.



Figure 2. Example optical image of a transmission line captured by a zoomed sensor.

Thermal or infrared sensors are useful for detecting temperature variations that could identify and document various conditions in and around dams. For example, a temperature variation could indicate a seep in structural areas of the dam or in the environment immediately surrounding the dam. Thermal imaging has been employed to investigate fugitive emissions from power generating infrastructure into rivers or lakes. This technology can also be useful in identifying wildlife activity in and around dams. Other applications certainly exist, based on any requirement to make determinations using temperature differentials. The images below illustrate thermal detection of gas leaks and liquid spills in pipeline infrastructure. While not specific to dams, the images still highlight the applicability of thermal imaging.



Recently, technical advances in the miniaturization of LIDAR sensors have increased their availability on UAS platforms. LIDAR is a surveying method that creates dense point clouds of an object or area that can be used in 2D and 3D modeling as well as mapping. While more expensive than photogrammetry, LIDAR is a proven capability that has delivered highly accurate data products consistently over time.

Improved photogrammetric techniques are generating products that now approach the accuracy of LIDAR. Typically less expensive than LIDAR, photogrammetric products can be produced from data collected by the more commonly available optical sensors. Through precise software controls, UAS can collect hundreds of images of an area that can then be processed into highly accurate images or 2D and 3D models. This technique is extensively used in UAS technology and is a cost-effective solution for many data requirements.

Multispectral and hyperspectral sensors are available for some UAS platforms but are not commonly employed on a routine basis like optical, thermal, and LIDAR sensors. While higher in complexity and cost, the data from these sensors can further determine and document structural integrity issues, vegetation

encroachment, species identification, and surface or subsurface changes that may be indicative of a developing adverse condition.

Air Vehicle (AV)

The AV is what most people focus on when considering UAS, but it is only the most visible component of the unmanned aircraft system package, as described in the introduction. For dam inspections, careful attention has to be paid to the type of AV selected primarily due to the operating environments around dams. This operating environment can be complex for the following reasons:

- Wind and airflow phenomena around the dam
- Size of the dam infrastructure
- Orientation of the dam infrastructure
- Obstacles—powerlines, towers, buildings
- Electromagnetic interference (EMI)
- Limited emergency recovery options
- Operator positioning to maintain Federal Aviation Administration (FAA) required line-of-sight

A detailed discussion of these is beyond the scope of this article, but each is addressed briefly below.

Wind and airflow:

Wind and airflow phenomena around dams can produce undesirable effects for the unsuspecting operator. Changes in velocity and direction can affect flight characteristics and result in unrecoverable situations. Velocity and direction can be inconsistent at different locations around the dam. Typically, the larger the dam, the more challenging wind phenomena can be. The effects of wind and airflow are multiplied at high elevations where the air density is reduced. Employing a multi-rotor with sufficient power such as an Octo-copter is recommended.

Size of the dam and infrastructure:

In addition to wind and airflow, size presents challenges, especially if imaging the entire structure. Flight management becomes critical as batteries typically last no more than 25 to 30 minutes, with a reserve time calculated to allow a margin of error for recovery. Dam size also affects where the pilot can fly from to maintain control and line-of-sight with the AV.

Orientation of the dam:

Orientation affects lighting as well as wind and airflow, forcing the operator to consider multiple options for control of the AV to obtain optimum imagery. The orientation of the dam or of the area in question may necessitate employing a gimballed sensor to obtain different look angles. This may affect consideration of the type of AV for repositioning and recovery.

Electromagnetic Interference

UAS can be susceptible to Electromagnetic Interference, or EMI, some more so than others, and dams, particularly hydro-electric dams, present many opportunities to experience the negative effects of this. EMI can affect both the AV and the sensor control, prevent the UAS from powering up normally, cause erratic flight characteristics, and in rare cases disable the UAS completely. The photograph below is a dam environment in the southeast that warrants an EMI evaluation prior to any UAS flight operation. What's shown is the proximity of the switching station to the dam face to be inspected by the UAS and some cabling that extends from the switching station to the generator room. What is not shown are the powerlines, antennae, and other power components that directly contribute to EMI. If operating in an EMI environment, it may be cost-effective to use a UAS with "return to start" programming, in case control is lost.



Figure 3. Dam and switchyard where EMI could interfere with UAS operation.

Obstacles – powerlines, towers, buildings:

The AV may have to fly around these obstacles to avoid impact and to preserve sensor look angle. Again,

a multi-rotor with gimbaled camera capable of maneuvering to precise locations is recommended.

Limited emergency recovery options:

Dams often present limited emergency recovery options of the UAS equipment due to water, obstacles, or other critical infrastructure, such as a switching station associated with the dam. The photograph below illustrates this point and suggests giving careful consideration to using a UAS that can effectively communicate any problems to the pilot. This capability would facilitate expeditious and safe recovery and varies between systems.



Figure 4. Access and obstacles such as those shown here need to be considered for safety equipment recovery.

Operator positioning to maintain line of sight:

The FAA requires pilots to maintain sight of the AV at all times during flight. Besides the federal regulation, this is good operating practice.

To provide maximum flexibility for this in dam inspections, careful consideration has to be given to the AV's size, power, signal reliability, and general operating parameters.

Types of Air Vehicles:

When selecting the appropriate AV, all of the above factors need to be analyzed along with careful consideration to size, power, stability, loiter time, and maneuverability needs. AVs can be grouped by their size (very small, small, medium, or large); flight range (very close range, close range, short range, mid-range,

and endurance); or the generic methods of flight. For the purposes of this article, UAS vehicles for dam safety applications are often grouped by their flight methods and fall into four general types: Multi-Rotor, Fixed-Wing, Single-Rotor, and Fixed-Wing Hybrid. The most maneuverable systems are vertical takeoff and landing (VTOL) vehicles, which come in a variety of sizes and configurations comprising the Multi-Rotor, Single-Rotor, and Fixed-Wing Hybrid vehicles. Small multi-rotor UAS vehicles (e.g., quadcopters) are often appropriate for smaller earthen dams. Larger and more powerful VTOL UAS vehicles, including single-rotor vehicles, should be considered for larger dam sites. Fixed-wing vehicles are usually best-suited for aerial surveys of larger areas (e.g. up to about 5,000 acres or so at which point manned systems may become more efficient). Fixed-wing UAS are not well suited for detailed inspections due to their lack of VTOL and hover capability. Fixed-wing hybrids are not commonly used in current dam safety applications due to their expense, flight difficulty, and limited availability.

Operations and Mission Planning

After the data objectives have been determined, the appropriate sensor has been identified and agreed upon, and the appropriate AV has been selected—an AV that can carry the sensor and safely fly in the environment where the dam is located—it is time to focus on the tasks of planning and effective deployment. Data, sensor, and AV directly impact what can be done by either limiting or expanding a UAS' range of usefulness. To achieve optimum results from the UAS, pre-planning should never be shortchanged.

What if there is an emergency situation requiring rapid deployment and use? Then spend time thinking it through in advance and make certain the pilot and UAS are prepared to safely fly to acquire the best data possible. The bottom-line is plan and then refine the plan; think through the alternatives and ensure all safety requirements are properly addressed. Include any regulatory requirements such as FAA and state and local privacy regulations or ordinances in planning and then adhere to them during operations.

When operating a UAS, avoid the unplanned “pick-up-game.” That is, be disciplined in the operational methodology, so as not to introduce additional and unnecessary risk, regardless of urgency (or perceived urgency). Innovative thinking and flexibility ensure each launch is well thought out with the objective of safe flight to acquire the best data possible, while mitigating the risks that could abruptly end the flight on terms unfavorable to the operator and those who need the data.

Potential Applications

Considering the types of data, DQI, and timeliness of data capture described previously, UAS technology has numerous potential applications to dam practices. A few that readily come to mind include:

- Inspections of difficult access sites
- Emergency response—damage assessment
- Flood plain mapping
- Pre and post flood documentation
- 3D modeling of dam infrastructure
- Pinpoint inspection and documentation
- Structural assessments
- Environmental effects in and around structure
- Upstream/Downstream conditions
- Pre-construction survey and mapping
- Construction management/monitoring
- Security
- Wildlife monitoring and assessment
- Vegetation species assessment around dam
- Volumetrics of surface level sediment deposits
- Right-of-way survey and assessments

There are other applications that once tested and verified could be beneficial as either a one-time or repeatable employment of UAS capability. Effective application of the technology relies on the data quality and the data quality will depend on the numerous factors outlined in this article.

Other Considerations

Despite the name UAS, these systems are not without the need for “manned” operation. They require a pilot and in some cases a sensor operator and visual observer to complete a project safely. Automation is making operations simpler but not necessarily easier.

Automated data processing tied to different software applications is reducing costs while creating better, more accurate data products. However, there are still times when processing has to be improved with professional intervention and data manipulation. The key point is that employing UAS in dam inspections should never be considered an automated, push-of-a-button exercise.

UAS offer numerous innovative solutions for collecting data important to dam inspections. However, UAS may not always be the best solution. On dams where the risks to UAS operations would be considered high or even moderate, careful consideration has to be given to traditional inspection methods. In some cases, it might be prudent to combine UAS with traditional methods to create the greatest efficiencies and obtain the optimum data mix.

Another consideration is what to do with the data and how to keep it secure. Data management and data storage were not addressed earlier in this article, but both are important. Large amounts of data will be collected when employing UAS. A data management, storage, and security plan should be established prior to data collection. This plan should be tied to the operational methodology so that when the UAS team collects the required imagery/data, it is accomplished in accordance with the prescribed data management plan. This will save many hours of labor post flight and post data processing that will reduce the overall costs of employing these systems.

Yet another consideration is that UAS do not fly everywhere within the dam infrastructure. Enclosed areas such as tunnel spillways present problems with command and control of the AV as well as camera manipulation to obtain the best imagery possible. Lighting can present unique challenges as well. Any effort to fly within enclosed features of major dam structures should be carefully assessed and planned.

Finally, careful consideration has to be made regarding whether to purchase, lease, or employ a professional contractor to obtain these services. UAS employment is no pickup game and should never be treated as such. A hobbyist approach is very risky to UAS operation and will more than likely fail to deliver the professional results essential to dam safety applications.

Effective, professional employment is wrapped neatly in several factors that include:

- Proper UAS—Sensor—Air Vehicle—Data Processing (properly selecting among the many choices)
- Certified Operators are required —FAA Part 107 minimum
- Trained Operators—Experience counts
- Operations Methodology—No pickup game
- Safety Program—Essential to risk mitigation
- Aviation Liability Insurance
- Proper Personal Protective Equipment (PPE)
- Aviation Mindset—Always consider UAS employment a “Flight Operation”

Failure to apply these factors in the decision to self-perform or hire-out a specialty contractor could result in the UAS becoming a shelf ornament or a heap of twisted junk, or even worse, a high speed projectile with up to 8 propellers turning at high speed going to unintended places with unintended consequences.

Summary

UAS technology presents exciting and innovative methods to improve dam inspection safety. The proliferation of commercial grade UAS systems along with rapid advances in sensor technology are making data collection with these systems safer, more efficient, and more cost-effective. However, there are many considerations relevant to employing these systems and the advantages versus the risks and potential disadvantages should be weighed carefully.

For many who seek UAS solutions, the options appear endless; but in reality, when it comes to the criticality of dam inspections, the options narrow quickly. It’s all about the data and acquiring that data safely and efficiently. Processes and methods should be repeatable and standards of performance should be exacting. Much of the commercial UAS industry appears to be moving in that direction, which should be great news for dam inspectors.

No doubt much additional work will be done to make UAS dam inspections more of a routine task, but at this time, most would consider dam inspections with UAS far from routine. The considerations highlighted in this article readily point to that. But this author predicts

that the pace of progress will result in UAS being employed many times over for dam inspections across the United States. Safely inspecting this vital part of our nation’s critical infrastructure absolutely demands it.



Effective exploitation of UAS capabilities requires consideration of:

- Data objectives (e.g., resolution, still or video, real-time or post-flight download, etc.) to appropriately select the type of sensor
- Operating environment to appropriately select the Air Vehicle
- Access, line-of-sight and required vantage points, and emergency vehicle recovery options.
- Data management plan
- Expertise needed to achieve desired results safely and efficiently.

Overtopping Protection of Embankment Dams

Elliott Drumright, PhD, PE

Introduction

It is common for the inflow design flood (IDF) to increase during the life of a dam, due to changes in downstream hazards or hydrologic methods. Traditional approaches to modifying such dams include raising the crest or rebuilding/modifying the spillway to accommodate the increased flow. However, in cases where the economics of raising the crest or modifying the existing spillway are not feasible, designing armoring to allow the dam to be safely overtopped may be an acceptable solution. This article presents several potential overtopping protection methods to be considered relative to the site-specific needs. The information presented in this article is drawn heavily from the [FEMA Technical Manual: Overtopping Protection for Dams](#)[1], and the reader is encouraged to review that free publication for additional detailed information.

The decision to implement overtopping protection for an embankment dam must strongly consider the potential risk of failure of the protection system, which could quickly lead to a full breach of the dam. Even a small defect or design flaw could lead to catastrophic failure once the embankment is exposed to the overtopping flow.[1] For this reason the use of armoring protection to allow the IDF to overtop an embankment dam is preferably limited to low hazard structures (those with limited downstream consequences in a dam breach scenario). An evaluation of the type of risk and hazard classification of the dam should be incorporated into the decision-making process. There is precedent for using armored overflow spillways on embankment dams of all hazard classes, with both success stories and failures. Designing overtopping protection for intended overflow of large, high hazard embankment dams requires special consideration and design provisions and the expertise to apply them correctly to the site. Use of overtopping spillways will also likely invoke additional review by the corresponding regulator, and they should be contacted as early as possible when overtopping spillways are proposed.

Overtopping Protection Methods

Cast-In-Place Concrete Systems

Roller-compacted concrete (RCC) and conventional reinforced concrete exemplify cast-in-place concrete systems for overtopping protection. Although more expensive than the other methods presented, they are more robust and versatile in terms of applicable flow depth and velocity that can be accommodated. Like other forms of embankment overtopping protection there are critical elements in the design of such systems to ensure adequate performance.

Roller-Compacted Concrete:

Used since the 1970s, RCC is a mixture of gravel, sand, cement and water, mixed to a zero-slump consistency, placed in horizontal lifts spread by earthmoving equipment and compacted with a roller, similar to a pavement (Figure 1). RCC is most cost effective if the aggregate material (gravel and sand) sources are available nearby and the material can be processed on site. Therefore, cost-effectiveness of RCC diminishes on small-volume projects. Used as overtopping protection, RCC can be placed over the entire downstream face of a dam, or over a portion of the downstream face, to act similarly to an auxiliary spillway. Design history and experience with RCC is extensive, and RCC can accommodate a wide range of flow velocities and depths. The higher weight of RCC as compared to earth materials also acts as a global stabilizing force on the downstream face of the dam. As RCC is a rigid material it can span (and obscure) defects and voids that might develop below it. RCC can provide a roof which can facilitate development of internal erosion failure modes. RCC is also susceptible to hydrostatic and hydraulic uplift forces. For these reasons detailed design of underdrainage between the embankment and RCC must be considered. RCC is susceptible to weathering and often begins to degrade and crumble at the surface over time, promoting the need for a relatively thick section (e.g., several feet). Placed typically in a series of cascading steps rather than a sloping, smooth surface, the energy dissipation versus step height must also be considered to avoid cavitation and damage to the RCC in higher flow

situations. Larger projects may warrant large-scale physical modeling.



Figure 1. Roller-Compacted Concrete [1].

Conventional Reinforced Concrete Slab (CRCS).

Overtopping spillways typically includes a reinforced concrete slab, side training walls and a well-designed underlying drainage layer, constructed on a portion of the downstream face of the dam to convey high velocity flows. Adequate design of underdrain system and joint treatment are required to prevent stagnation pressures and uplift of the slabs. Accurate flow depths are needed to design side wall heights to prevent unintended overtopping. Disadvantages of reinforced concrete overtopping protection is their cost (being among the most expensive of the methods presented here), their susceptibility to settlement, development of adverse joint offsets and the ability to form a roof and mask underlying defects such as voids formed by internal erosion processes. Their primary benefit is that, if designed and constructed correctly, it can withstand very high flow velocities.

Precast Concrete Systems

Articulated concrete blocks (ACBs) and tapered wedge blocks are the two primary types of precast concrete overtopping systems.

Articulating Concrete Blocks (ACBs).

Concrete blocks placed over earth materials designed to provide a hard surface to resist the erosive forces of moving water (Figure 2). These blocks can be interlocking or interconnected with cables or anchors

and placed as larger mats, and can be used in conjunction with other methods of overtopping protection. As with RCC and CRCS, ACB liners are designed with a bedding and drainage layer to assist in relieving uplift pressures and to reduce subgrade erosion when water is flowing. The underdrain and foundation system also need to be designed to prevent migration of materials through block openings. Geotextiles have sometimes been used to provide a “permeable” separator; however, these can clog overtime and eventually be a detriment to the performance of ACB liners. In some cases, the open-faced blocks are filled with soil and vegetated for aesthetics, which also provides resistance at low flow velocities. ACB systems can accommodate small deformations caused by subgrade settlement or creep, but performance testing has shown these systems can fail if the blocks lose sustained contact with the subgrade. The National Concrete Masonry Association [4] and various ASTM Standards provide design guidance for ACBs. The recent ASDSO Journal of Dam Safety publication also included a valuable article on the design and performance of ACBs as overtopping protection. [3]



Figure 2. ACBs (foreground) and riprap (background) lining a spillway chute at a dam in Colorado.

Tapered Wedge Blocks.

Tapered wedge blocks are precast concrete block units that are tapered and laid shingle-fashion from the toe of the slope to the crest, with adjacent runs staggered to offset the joints. The exposed height of the blocks

must be designed with respect to energy dissipation and the potential for cavitation.

Rock Systems

Three basic types of rock systems are commonly used to provide overtopping protection: gabions, riprap and flow-through rockfill/reinforced rockfill.

Gabions:

Gabions are rectangular-shaped baskets or mattresses of heavy wire mesh that are filled with rock and assembled in a stair-stepped fashion for slope or channel protection. The baskets can be laced together to enhance global and sliding stability (Figure 3). Gabions are moderately flexible and can conform to modest ground movement, can be constructed easily, can be filled with clean stone and designed to drain freely, and can dissipate energy from flowing water. Disadvantages are mostly long-term and include the infilling of the rock fill with silt over time reducing the permeability, and corrosion and breaking of the wire mesh over time, allowing the rock fill to fall out of the baskets. Corrosion potential can be reduced by ordering galvanized or coated wire for the baskets.



Figure 3. Gabion Installation on a Slope [1].

Riprap:

Riprap used as slope protection, includes a layer of high quality rock placed on a well-designed bedding layer, placed against the downstream face of the dam (Figure 4). Overtopping flow is conveyed within and over the riprap, reducing flow velocity on the surface of the erodible dam shell, thus reducing rill erosion (or wave-induced erosion if used on the upstream slope of

the embankment). Riprap as overtopping protection is typically limited to use on small dams with relatively low unit discharge quantities. Riprap is typically not used for overtopping protection on large dams (high slopes with resulting high velocities during overtopping), due to the large size required to resist the design flows and the risk of inadequate performance.

Significant research is available on the hydraulic capacity of riprap, and the slope / flowrate combinations that contribute to instability of a riprap installation. However, there remains much uncertainty in the design and analysis of riprap for overtopping protection, and conservative approaches are recommended. Flow hydraulics on steep embankment slopes cannot be analyzed with standard flow equations. Uniform flow and tractive shear equations do not apply to shallow flow over large rough elements, highly aerated flow, or to chute and pool flow, all of which can occur during overtopping. Riprap design criteria for overtopping protection of embankment dams should prevent bedding layer and stone movement to ensure the riprap layer does not fail. Empirically-derived design criteria offer the best approach for design. FEMA [1] provides recommended design guidance for design of riprap overtopping protection including rock size for a given slope and unit discharge and design considerations for riprap bedding.



Figure 4. Riprap Installation [1].

Flow-Through Rockfill and Reinforced Rockfill:

Although applicable for overtopping protection, these techniques are used principally in the design of new dams and are not discussed further here. Further design details are included in FEMA [1].

Geomembranes, Geocells, and Fabric-Formed Concrete

Geomembranes, geocells and fabric-formed concrete are hybrid methods of overtopping protection that utilize various types of geosynthetics. These are less frequently used in dam construction and are often limited to low discharge flows.

Geomembranes:

Geomembranes are a subset of geosynthetics and consist of any number of different polymers produced in thin sheet form, overlapped and seamed at the joints. They are commonly installed on a prepared subgrade and must be covered with soil for protection against puncture and degradation from ultraviolet light exposure. The upstream and downstream ends of the membrane must be anchored into the subgrade, usually in a trench backfilled with compacted earth materials.

Geocells:

Geocells are made from polyethylene strips that are interconnected to form a honeycombed structure. When laid on the subgrade they are then filled with earth materials or concrete. Seeding can be added to encourage vegetation between the cells.

Fabric-Formed Articulating Block Mats:

Fabric-formed articulating block mats are cable-reinforced cellular bags that are placed on the subgrade and then filled with grout, forming a mattress of pillow-shaped, rectangular blocks, interconnected by the cables (Figure 5).



Figure 5. Fabric-Formed Articulating Block Mats (Courtesy of Synthetex).

Vegetation and Reinforced Turf

Vegetation and reinforced turf are two more natural looking methods that may provide adequate overtopping protection for low-velocity flow, typically limited to low hazard structures.

Vegetation:

Robust vegetative cover on the downstream face of an embankment provides some protection from rill development due to precipitation, through reinforcement of the soil surface from the roots. In this situation a level and uniform dam crest and downstream slope is critical to promote laminar flow and reduce dangerous concentrations of flow that can occur at isolated low areas on a dam crest or around obstructions (e.g. boulders or tress) on the downstream slope. Vegetation also reduces the velocity of moving water by providing resistance to flow. It is most effective on small dams with modest downstream slopes, and in climates where enough precipitation falls to maintain a thorough vegetative cover.

Reinforced Turf:

Vegetative cover can be enhanced through the use of reinforcement. Fabrics, meshes or mats protect the soil surface while the vegetation establishes, and allows the roots to penetrate and bind around the mesh, creating a system of soil, roots and geotextile.

Newer examples include Hydroturf™, a synthetic turf attached to a high-friction geomembrane with an integral drainage layer that is then covered with a high strength sand/cement infill (Figure 6). The high-

friction geomembrane lessens the chance of sliding on sloping surfaces.

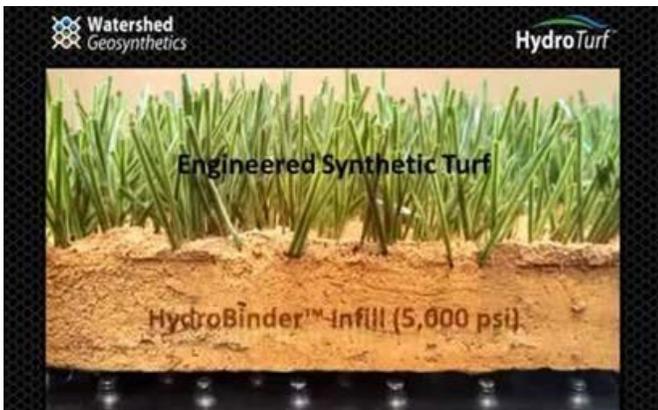


Figure 6. Cross-Section of Hydroturf™ (Courtesy of Nilex Products)

Design Considerations

General design considerations for overtopping protection of dams includes: hydraulic analysis; stream power/erodibility; joint detailing; filtration; uplift and underdrainage; anchorage detailing; seepage cutoff; and material durability. The robustness of the system should also be considered. Damage, deterioration, poor quality materials and poor construction can significantly affect the long-term performance of the system.

A summary of design geometry and hydraulic limits for various overtopping systems is included in Table 1. The FEMA technical manual provides references and summarizes pertinent design considerations for the various methods. Most of the overtopping methods in Table 1 are for dams of low to modest height. Although RCC and CRCS are suggested as appropriate for dams approaching 200 feet in height, the authors suggest that for large, high hazard dams, with significant downstream consequences in a breach scenario, overtopping should only be considered when other alternatives are found to be infeasible and if all failure modes for the spillway can be adequately addressed.

Table 1. Summary of Design Limits for Overtopping Protection Systems [1]

Protection system	Chapter	Dam height (feet)	Unit discharge (ft ³ /s/ft)	Overflow depth (feet)	Flow velocity (ft/s)	Shear stress (lb/ft ²)
RCC	2	100-200	316-340	20	20-30+	
CRCS	3	150-200	240-280	20	80+	
Cable-tied ACBs	4	40	30	4.2	26	19+
Wedge blocks	4	50-60	42	5.5	45	
Gabions	5	25	30-40	4.5	24-30	35
Grass	6	25-50	6-24	1-4	9	13.5
Reinforced grass	6	40-50	32	5	20	
Synthetic turf	6	40-50	30	5	29	9+
Reinforced rockfill	7	140	153	10-14		
Rockfill	7	50	10-24	2-4		
Riprap	8	50	10-24	2-4		
Geo liners	9	25	2	1	26	
Geocells	9	25			29	16
Fabric-formed concrete	9	25				60

Notes:

- Typical embankment slopes assumed (1.5:1 to 3:1)
- See reference chapter for more information.
- Natural grass systems assume good cover and are time dependent (i.e., for short durations).
- Rockfill and riprap systems are size and gradation dependent (i.e., larger rock of uniform size performs best)

Case History

Grace Lake Dam and Leo Dam, El Paso County, Colorado

Grace Lake Dam and Leo Dam are two of three low-head dams located on Beaver Creek, a tributary to Monument Creek. Grace Lake Dam has a jurisdictional height of 12 feet and a length of 310 feet. Leo Lake Dam has a height of 15.3 feet and a length of 240 feet.

As part of a comprehensive rehabilitation effort, mats of articulated concrete blocks (ACBs) were placed over the embankment upstream slope, crest, and downstream slope at each dam. On the downstream side of each dam, the ACB mats were placed over geogrid, 1 foot of gravel bedding, a geotextile, and 1½ feet of drain sand overlying embankment fill.

The ACBs were installed as panels (mats) consisting of Armorflex Class 50T (tapered) blocks. The seams between mats and structures had revetment cables attached to reinforcement embedded in structures where possible, and then the seams were filled with backfill concrete. The mat openings were then backfilled with soil and seeded. The projects are shown in Figures 7 and 8.



Figure 7. Downstream Face of Grace Lake Dam after Installation of ACB Overtopping Protection.



Figure 8. Placement of ACB Mats on the Crest and Downstream Slope of Leo Dam (looking northeast).

Useful References

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Cellular Grout Use in Conduit Sliplining

Nathan Walker, PE

Cellular grout has a long history of use in a variety of applications. It is a lightweight material composed of a uniform void cell structure prepared with a foaming agent. Cellular grout may contain common concrete admixtures, sand or coarse aggregates, or supplementary cementitious materials (pozzolans) such as fly ash or slag. Dam safety officials and regulators have seen an increased number of requests when sliplining conduits to utilize cellular grout for filling the annulus, which is the void space located between the two conduits. This article summarizes the current industry-specific considerations, the potential advantages and disadvantages, and case study comparing the use of cellular grout to traditional Portland cement grout. The March 2013 issue of Western Dam Engineering Technical Notes reviewed conduit rehabilitation including sliplining and annulus grouting: [Low-Level Conduits – Rehab or Replace?](#) [1]

Cellular Grout Background

The chief characteristic of cellular grout is the incorporation of a foaming agent, which creates a cellular matrix of small air bubbles as compared to the use of aggregate and sand in traditional cement grouts. The presence of air bubbles reduces the unit weight and increases grout mobility but also lowers the grout strength. The air bubbles in the cellular matrix survive the grout hydration period until the grout hardens, resulting in a homogeneous matrix of air voids. Similar to other grout materials, the period of time the grout remains fluid is key to proper use and cellular grouts can provide unique benefits for applications involving large volumes or long pumping distances.

Cellular grout has been successfully used for annular space grouting of various types of high density polyethylene (HDPE), fiberglass, concrete, steel, corrugated metal and ductile iron conduits ranging in size and length. Cellular grout typically involves proprietary equipment developed by specialized contractors who are trained and experienced in its use. Various agencies have developed specifications for cellular grout use. The U.S. Army Corp of Engineers'

(USACE) *Grouting Technology Engineering Manual* provides technical criteria and guidance for annular space grouting of conduits. The USACE considers any application where low to moderate strength can be tolerated and lightweight grout is desirable as a candidate for cellular grout. [2]

Cellular Grout Mix Design

Cellular grout can be designed as either pervious or impervious with typical wet cast densities ranging from 20 pounds per cubic foot (PCF) up to 70 PCF and ranging in 28-day compressive strength from 50 pounds per square inch (psi) up to 1100 psi. Strength is directly correlated to density and desired strength is achieved through varying the ratio of cement slurry to foaming agent. If higher strengths are required, sanded mixes can be used; however sanded cellular grout is not as fluid and can require additional placement steps.

Impervious cellular grout with a permeability range of 10^{-5} to 10^{-6} cm/s has been successfully used in dam outlet conduit sliplining where control of water flow is desired. Pervious cellular grout is typically used to avoid disruption of water flow and is beyond the focus of this article.

The frequency of large diameter conduit rehabilitation has increased and sliplining has emerged as a preferred method of rehabilitation. In these cases large volumes of grout materials with suitable characteristics are needed. Large grout volume mix design often seeks to reduce material cost and heat of hydration through the use of pozzolans such as fly ash or slag, or other means. Testing has shown the addition of pozzolans reduces early-age compressive strength and elastic modulus, and affects the setting time of grout. These factors should be taken into consideration during selection of the mix design based on the application requirements.[3] If slower set time and reduced early-age compressive strength are not critical, use of pozzolans can be beneficial, as they tend to reduce shrinkage and improve pumpability.

Cellular Grout Specification

Specifications for traditional grouting of a conduit sliplining annulus typically include considerations for

minimum contractor qualifications, mix design, low shrinkage or net positive expansion, set time, fluidity, trial testing, placement procedures, quality control, and contingency plan requirements. These same considerations should be developed for the use of cellular grout along with the following additional requirements:

- 1) Minimum specific gravity of 1.1. to ensure displacement of any water;
- 2) Minimum grout strength suitable for intended application; and
- 3) Testing to verify compressive strengths.

Natural Resources Conservation Service (NRCS) Specification 85₍₄₎ is a sample performance specification for conduit sliplining involving the use of cellular grout.

Cellular Grout Placement

Some cellular grout applications have utilized gravity placement; however, pumping is the recommended placement method for annulus grouting during conduit sliplining since this method better ensures uniform grouting and complete filling of the annulus.



Figure 1. Annular Space Slipline Grouting with Cellular Grout

Cellular grout is relatively fluidized and self-leveling and can be readily pumped long distances at low pressure and flows well through tight spaces and small openings. This characteristic allows for grouting of conduits without the need for frequent injection points associated with traditional cement grout. The homogenous structure of cellular grout reduces

potential segregation during pumping compared to traditional cement grout and reduces the buoyancy of carrier pipes during annular space slipline grouting. As a result, there is an increased likelihood that annular spaces can be completely filled while reducing the chances of premature grout setting. Also, avoiding higher injection pressures can minimize the possibility of conduit damage.

Cellular Grout Advantages

There are a few unique advantages to using cellular grout for conduit sliplining compared to typical cement grouts. These can be summarized as (1) low injection pressures, (2) reduced unit weight and related pipe buoyancy, (3) economical use of cementitious materials, (4) decreased heat of hydration and associated decreases in temperature of grout and adjacent piping, and (5) increased pumping distances.

Reduced Unit Weight and Buoyancy

Typical traditional cement grouts are relatively dense, with unit weights of approximately 100 to 120 lb/ft³. This results in significant buoyancy during grouting. Buoyancy and uplift of the carrier pipe during annulus grouting requires special provisions to avoid pipe movement and the structural damage that can result. This may include grouting in lifts, attaching centralizers or braces, or filling the carrier pipe with water to prevent movement during grouting.

Cellular grout density is typically less than half that of traditional neat cement grout. The lower density grout significantly reduces buoyancy forces on the carrier pipe and minimizes associated deflection during annulus grouting which may eliminate the need for mitigation in some applications.

With higher fluidity and self-leveling characteristics, cellular grout readily flows into irregular cavities, does not require consolidation, requires less pressure for injection, and can be pumped longer distances without concern for segregation of the mix. As a result, improved filling of annulus voids and reduced risk of collapsing the carrier pipe or damaging the existing pipe can be expected during slipline-grouting of large volumes over long distances.

Low Injection Pressures

Cellular grout injection pressures can typically be achieved below 10 lb/in² even for long pumping distances involving small annular spaces. Cellular grout pumping distances have exceeded 20,000 feet including the Arrowhead Tunnels Project in Southern California.[5] Reduced pumping pressure also reduces the risk of hydrofracturing the soil around the existing pipe, which is often in a deteriorated state prior to and during grouting.

Low Heat of Hydration

On large-diameter applications the heat of hydration of conventional Portland cement grout can be detrimental to both the host and carrier pipe materials. Cellular grout has a reduced volume of cementitious materials and therefore generates less heat during hydration. Depending on the size of the annular space being filled and the materials being utilized, this may provide a significant benefit to the project.

Economical Use of Cementitious Materials

Cellular grout can be economical for annular space grouting during conduit sliplining due to a reduction in the quantity of raw materials used such as the cement and sand required for the grout production, recognizing that a majority of the mix volume is composed of air.

Placement costs of cellular grout can also be reduced due to ease of pumping long distances and minimizing the number of grout injection points.

In addition, low-weight cellular grout mixes used for annulus grouting typically have expansion ratios greater than 5, which reduces the amount of grout mix required. This can minimize the overall footprint of the grouting operation and associated construction traffic, which may improve other jobsite logistics.

Cellular Grout Disadvantages

Despite the advantages, cellular grout use in conduit sliplining does have some distinct disadvantages that can be summarized as (1) specialized design and construction, and (2) application limitations.

Specialized Design and Construction

Traditional cement grouts are common and can be supplied from local ready mix suppliers or batch mixed on site. However, specialized equipment and experienced, licensed contractors are required for use of cellular grout. As a result, cement grout is generally used on smaller projects due to the cost of mobilizing a specialty contractor.

If the use of cellular grout is warranted for a particular conduit sliplining application, special design considerations must be evaluated. Best practice in these applications mandates use of a qualified engineer experienced in the design, specification, and use of cellular grouts. The engineer should work closely with the dam safety regulator to clearly identify the design, testing, and placement requirements that should be addressed in a performance specification for the work.

Application Limitations

According to the Federal Emergency Management Agency (FEMA), cellular grout should not be used in embankment conduit applications for significant or high hazard dams due to the grout's porous nature and lack of strength for structural encasement.[6] This highlights the need for proper impervious cellular grout mix design, specification, and performance testing including suitable strength, density, and similar considerations summarized in this article and detailed in the referenced USACE engineering manual and sample NRCS specification.

Large diameter conduits may require multiple lifts, since bubble collapse can occur under hydrostatic head greater than about 4 feet of grout. Collapse of bubbles will effectively provide a grout consistency similar to traditional cement grouts, which will negate the advantages of using cellular grout. This could also result in variable conditions around the pipe, with collapse of bubbles on the bottom and potential voids along the crown.

FEMA also recommends cellular grouts should not be used where exposed to flowing water or the environment since cellular grout is typically less durable.[6] Although not typically exposed to these

conditions in conduit sliplining applications, these limitations should be considered for each application.

In general, if there is not a distinct advantage for a particular conduit sliplining application to use cellular grout, such as large volumes or long pumping distances, the use of conventional cement grout should remain the preferred approach.

Cellular Grout Case Study

The Montana Dam Safety Program is familiar with a couple of recent successful conduit sliplining projects involving cellular grout including the Estler Lake Dam Rehabilitation completed in 2015.



Figure 2. Conduit Sliplining with Relatively Large Annular Space Prior to Cellular Grout Placement at Estler Lake Dam

The 80-linear-foot, 24-inch by 36-inch concrete arch, outlet conduit constructed in 1903 had exceeded its useful life. This conduit was sliplined with a much smaller 18-inch-diameter HDPE conduit, leaving a large annular space to be grouted. Due to site access challenges (including location of the construction staging area being located over 1 mile downstream of the project site), and given the large volume of grout required to fill the annular space, cellular grout was

utilized for the annulus grouting. The cellular grout provided a solution that was much lighter than cement grout, required significantly less raw material to be supplied to the site and produced a highly flowable mix, capable of filling the large annulus.[7]



Figure 3. Cellular Grout Placement at Estler Lake Dam

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Mechanical Seals for Conduit Repair

Henrik Forsling, PE and Carolyn Bocovich, PhD

Introduction

Outlet conduits provide essential control of the reservoir levels in dams. In embankment dams, leaks due to cracking or joint offsets in the outlet conduit may cause excessive seepage into (infiltration) or out of the conduit (exfiltration), which could lead to internal erosion (i.e., piping of embankment materials), which in turn could threaten the structural integrity of the dam. If an outlet conduit needs rehabilitation due to circumferential cracking, localized longitudinal cracking, localized deterioration, joint offset or joint separation, mechanical seals can provide a simple, relatively low cost rehabilitation option as compared to more comprehensive replacement or rehabilitation options. Mechanical seals have been used for more than 30 years to repair pipe joints, strengthen weak joints, bridge localized cracks or deteriorated sections, seal off abandoned laterals, and seal the ends of a cured-in-place pipe (CIPP) liner.

Mechanical seals comprise a sleeve that is adhered to the interior of the host pipe by a mechanical interlock, sometimes in combination with a chemical adhesive. Depending on the mechanical seal system, the sleeve is typically of rubber, PVC, or stainless steel over a polyurethane gasket.

Figure 1 shows a rubber sleeve with ribbing along the edges to improve contact with the conduit wall. In this application, the seal is held in place with retaining compression bands, which are locked into place by a hydraulic expander.

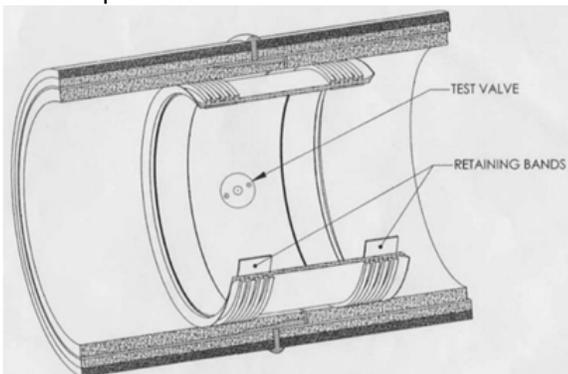


Figure 1. Sketch of a Rubber Sleeve (courtesy of HydraTech)

This particular sleeve includes a test valve in the seal to allow testing for leaks after installation.

Figure 2 shows a stainless steel grouting sleeve with an absorbent gasket. The gasket is placed in the annular space between the sleeve and host pipe, and is filled with an absorbent polyurethane grout that when in contact with moisture, will expand to fill the annulus. The sleeve is locked in place by inflating a plug that expands against the sleeve and engages a mechanical lock.



Figure 2. Stainless Steel Sleeve with Gasket (photo courtesy of Link-Pipe®)

Advantages and Disadvantages

Mechanical seals can provide advantages compared to other conduit rehabilitation options, depending on material, size, shape, and condition of the conduit.

Advantages

Mechanical seals are relatively low cost and can be installed in the dry or in the wet (i.e., with divers), as shown on Figure 3. They can be designed to provide a seal for up to about 300 lb/in² in a pressurized pipe or 100 feet of external head pressure.

More importantly, the installation does not require excavation to expose the conduit exterior, and the relatively simple and rapid installation limits the duration the conduit needs to be taken out of service.

Cost of the seals and installation is very dependent on size and shape of the conduit, location of the conduit, and extent of repair.

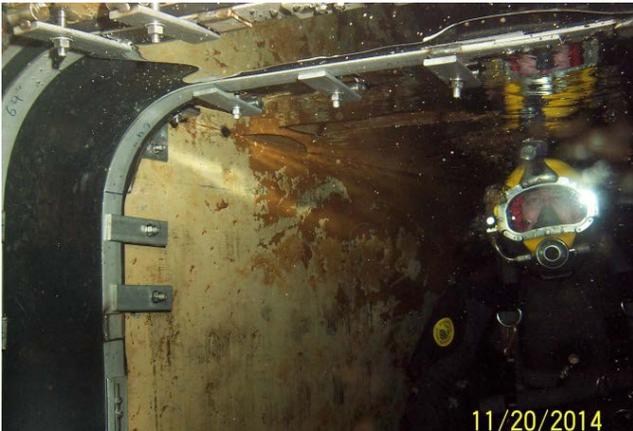


Figure 3. Example of a Mechanical Rubber Seal Installed in the Wet in a Rectangular Conduit (photo courtesy of HydraTech)

Mechanical seals are typically installed in circular conduits (Figure 4); however, these seals can be customized for irregular conduit shapes such as oval, horseshoe, rectangular, and square shapes (Figures 5 and 6).



Figure 4. Example of a Circular Mechanical Rubber Seal in a Concrete Conduit (photo courtesy of HydraTech)

Mechanical seals can be installed in circular conduits greater than 4 inches in diameter depending on the seal design/manufacture, and in host pipes of steel, cast or ductile iron, concrete, masonry, PVC or HDPE. The flexibility of rubber mechanical seals also allows for installation over offset joints, where installation of a conventional liner may be prohibitive, and over joints where some movement is expected due to settlement or vibration. The relatively low profile of the seal typically provides negligible loss of flow capacity through the conduit and reduces the risk of cavitation.

Seal options are available for corrosive environments or to meet potable water requirements, e.g., NSF 61.



Figure 5. Example of a Mechanical PVC Seal in a Horseshoe-Shaped Masonry Conduit (photo courtesy of Link-Pipe®)



Figure 6. Example of a Non-Circular Mechanical Rubber Seal (photo courtesy of HydraTech).

Disadvantages

Most mechanical seal designs require manned entry for installation. This limits their use to conduits greater than approximately 20 inches in diameter and requires training for confined space entry. One example is that irregular conduit shapes or offset joints need a rubber seal that requires manned entry of the conduit for installation. Also, mechanical seals for irregularly shaped conduits require custom fabrication of the retaining bands, which will increase the lead-time and may be prohibitive if urgent repairs are required.

Some manufactures require installation certification for product warranties. Although certification can be earned, most manufactures offer installation services or recommend certified consultants to install their seals.

If the overall condition of the outlet conduit is poor, long sections of the conduit or numerous joints need repair, or if the host pipe has sustained thickness loss where its capacity to resist external pressure has been significantly compromised, other rehabilitation methods may be better suited and more economical. In such instances, as outlined by FEMA [1], typical rehabilitation methods that do not require excavation of the conduit include lining the existing pipe with a smaller diameter pipe, slip-lining, CIPP lining, or spray-in-place pipe (SIPP) lining. Note that SIPP may not be suitable in applications where the liner needs to be a fully structural liner, as defined by AWWA M28 [2].

Previous Western Dam Tech Note articles have discussed considerations for more comprehensive outlet pipe replacement or rehabilitation with HDPE slip-lining or CIPP liners: [Low-Level Conduits – Rehab or Replace?](#) [2] and [You Down with CIPP? – Yeah! You Know Me!](#) [3].

Case Studies

A mechanical seal was used to reinforce a repair patch in the 30-inch-diameter pre-stressed steel cylinder outlet pipe at Pike Creek Dam in Lewistown, MT. A routine inspection found an approximately 10-inch-diameter hole in the pipe wall (Figure 7). The hole extended through the concrete liner and steel cylinder, and every other pre-stressed wire was corroded completely through.



Figure 7. Hole through Pipe Wall (photo courtesy of NRCS).

Due to the corroded metal, it was concluded that a concrete patch could not be adequately bonded to the substrate area, and a mechanical seal was installed over the patch repair to provide protection and reinforcement.



Figure 8. Patch repair of pipe wall damage prior to mechanical seal installation (photo courtesy of NRCS).

A 14-inch-wide mechanical rubber seal and five retaining bands were used to reinforce the patch, as shown on Figures 9 and 10.



Figure 9. Retaining Compression Bands Locked into Place by a Hydraulic Expander (photo courtesy of NRCS).



Figure 10. Mechanical Seal and Completely Installed (photo courtesy of NRCS)

At Stillwater Dam in Larkspur, CO, the 30-inch-diameter reinforced concrete pipe (RCP) outlet conduit had a circumferential crack that varied in width from approximately 3/8-inch at the invert to less than 1/16-inch at the top or crown of the pipe. Water flow was observed through the crack and some fine- and coarse-grained soil deposition was observed within the crack and in the invert of the pipe.

The repair, which was installed in 2006 and is still performing well, consisted of injecting the crack and

void outside of the pipe with a hydrophobic polyurethane grout. Thereafter, the crack was bridged by an 18-inch-long stainless steel sleeve with an absorbent gasket saturated with polyurethane grout in the annulus between the sleeve and host pipe (similar to the sleeve shown on Figure 2).

A schematic of the relatively simple and inexpensive repair is shown on Figure 11. The cost of this project was approximately \$12,500 including all engineering construction oversight and construction. Although not “cheap” the cost was considerably less than other methods considered.

Conclusions

Mechanical seals can be a good alternative to more extensive (and expensive) pipe rehabilitation options for conduits with localized areas needing repair. These internal seals offer a simple, low cost rehabilitation option that does not require excavation, and the rapid installation does not require the conduit to be taken out of service for an extended period of time.

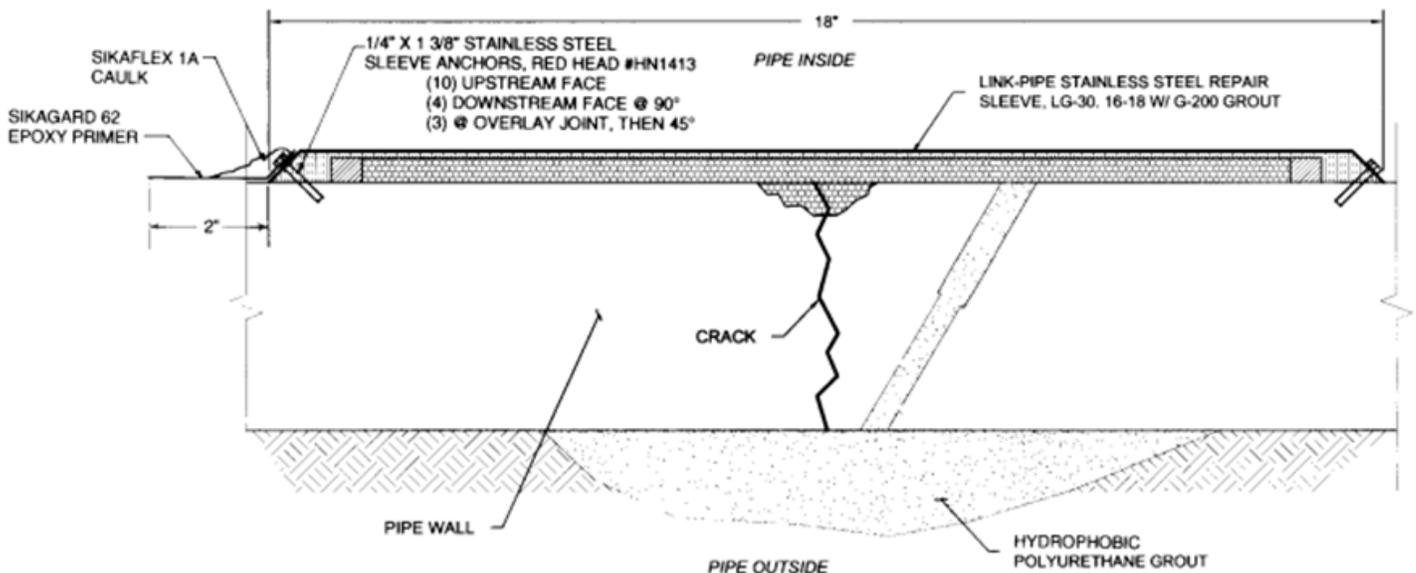


Figure 11. Repair of Cracked 30-Inch-Diameter RCP Outlet.

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