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CULVERT REPLACEMENT USING PIPE RAMMING, TUNNELING, OR PIPE JACKING

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ABSTRACT: Culverts are major drainage features under highways. Corrugated metal pipes (CMP) were typically used as the culvert material starting in the 1930s, with widespread usage in the 1950s and 1960s. These culverts have since corroded, sagged, and/or collapsed. With a 50-year life cycle, culvert replacement is now a major issue for most state departments of transportation (DOTs). Originally, the culverts were installed using open trench excavation methods while a highway was under construction. Engineered fill was used to bury the culvert as the highway embankment was constructed. The backfill was typically native materials, compacted in lifts with undocumented quality control. To replace these aging culverts, open trenching of the existing highway is not possible. Culvert replacement with trenchless methods is the only solution.

Engineers face several issues when looking to replace aging culverts, including:

- Providing structural repair to the culvert
- Providing increased hydraulic capacity
- Meeting new structural requirements for load capacity or seismic design
- Allowing passage of new maximum flood events
- Meeting new environmental requests to improved wildlife habitats
- Restoring eroded backfill materials

Culvert rehabilitation methods may include traditional rehabilitation methods like slip lining, fold and form, inversion processes, and other relining systems. However, all of these methods sacrifice internal diameter. Other culvert replacement approaches include either consuming the existing pipe with an entirely new culvert or installing a new culvert parallel to the existing culvert with the old culvert either being rehabilitated or abandoned. This paper will discuss these other culvert replacement approaches and cite the advantages and design issues faced when using pipe ramming, tunneling, or pipe jacking as the construction method.

1. INTRODUCTION

Culvert construction in the United States became increasingly necessary with the freeway construction projects initiated under the Eisenhower administration (1953–1961) and the signing by President Eisenhower in 1956 of the National Defense Interstate Highway Act. Culverts were typically constructed in established drainage swales and

low points within the topography. They serve as conduits for water to drain/pass from one side of the highway to the other. Many of the culverts were designed for a 50-year life cycle, which is now ending.

This paper will focus on the most common type of culverts presently coming to the end of its life cycle: corrugated metal pipe made of galvanized steel or aluminum. A brief discussion of pipe rehabilitation will be provided. Then the paper will discuss the design and construction issues associated with the consumption and parallel replacement approaches when using new trenchless construction methods of pipe ramming, tunneling, and pipe jacking.

2. TYPICAL CULVERT FAILURES AND PROBLEMS

The heavy construction industry was told that corrugated metal sections would be inexpensive and durable materials that could be used to build culverts as part of the highway construction process. The culverts were inexpensive and fast to assemble, but as evidenced by recent findings, they are prone to corrosion, sagging, squatting, and splitting of seams (Finnicum et al., 2008).

Figure 1 shows some examples of typical corrugated metal culvert failures. Corrosion is the loss of material through chemical alteration or erosion of the structural material. Rust is a common form of corrosion. The constant wetting and drying of the culvert invert leads to corrosion of the invert and exposure of the bedding and backfill materials. Continued flows through the culvert will wash away this material, undermining and removing the ground support.



Figure 1. Typical culvert failures: corroded invert (left); squatting and splitting of the seams (right) (Tenbusch, 2009).

Squatting is caused by the culvert deforming, losing roundness, and becoming wider than its diameter. Squatting can be caused by poor side compaction, excessive overburden, or excessive traffic loads. It can lead to collapse of the culvert crown into the free space. Once this happens, nothing is supporting the earth embankment above the culvert. This can lead to the formation of sink holes and actual collapse of the highway surface.

Sagging occurs along the culvert's profile. One portion of the culvert settles more than the others. This settlement can be the result of compaction/placement of the bedding material, loss of backfill material, or just differential settlement of the native material. The result is that the culvert loses its design grade/profile and a low spot(s) is/are formed. Water will collect and pond in the low spot of a sagged culvert, helping accelerate the corrosion process. Sagging is a major problem for culvert replacement as the invert for a portion of the alignment is below the design grade. Additional work is needed to repair the culvert and the surrounding underlying materials and to restore the design grade.

Splitting of the seams is another failure mode. If the culvert is made of various pieces, the joints/seams are the weak points. Seam failure leads to failure and loss of bedding, which leads to the culvert squat or sag (Taher and Moore, 2009). If the metal pieces are joined by bolts, the bolts are prone to corrosion, leading to splitting of the seams and allowing the structural joints to open. Differential loading or settlement can also lead to multiple types of failure.

Culverts are typically confined and supported by compacted native fill. The usual construction method for culverts is the removal of surface deposits to a stable subsurface material and then the addition of bedding, compacted as required. The culvert structure is then built onto the bedding and the native backfill compacted around the structure as required. If a narrow slot was cut into the ground for the culvert, the effective placement of backfill material could be a difficult task. Road bedding, the road surface, and/or top soils are placed on top. In almost all cases, the underlying ground and granular bedding act as a French drain, allowing water to flow around and under the culvert. If the granular bedding material is compacted and stable, the flow of groundwater does not have a negative impact. However, if the existing culvert pipe becomes deteriorated in a way that allows the bedding surrounding it to shift and/or become unconsolidated, the ever-present groundwater begins to cause the fine fraction of the soil to move with the flow of water, accelerating the failure process.

Excessive water flows through the bedding could be caused by blockage of the upstream opening and flows that exceed the design capacity of the culvert. The buildup of the upstream hydrostatic pressure could cause water to flow along the outside of the existing pipe. When this excess water flows through the fill, the flowing water could wash the fine fraction of the soil away, creating differential settlement and leading to culvert failure (sagging or squatting). In addition to increased hydrostatic pressure upstream, inadequate conduit sizing could cause increased velocity in the culvert, which would result in erosion at the outlet. In some cases, the underlying ground would compress or expand, depending on seasonal factors like groundwater and freezing or ground behaviors like swelling clay, all leading to culvert failure.

Since many of the culverts were built as part of the original highway construction, records of the actual fill placed around them are not available. Most highways were built using a balanced cut and fill approach. Therefore, the fills could be either soils or rock from the adjacent hillside, and since the cuts and fills were balanced, all materials were used. Historically, culverts were great locations to get rid of odd-shaped and various sized rock blocks, boulders, and cobbles. These pieces were buried in the fill and around the “permanent” culverts. When it becomes time to replace these culverts, these irregularly shaped rock blocks could present potential construction issues.

The other problem resulting from the corrugated metal pipe and plate section culverts is the rough-rippled invert. The ribbed invert is rough and in hydraulic terms will let soil and sediment collect in the invert. This material creates ponding, forming natural habitats for various types of species. The culvert invert habitat has generated new environmental requirements if the culvert is replaced or renewed.

In addition, these older culverts have become de facto routes for migratory wildlife, which are blocked from surface migration. This use has also created new environmental requirements that did not exist when the culverts were originally designed and constructed and that need to be taken into consideration when a culvert is evaluated for replacement or renewal.

4. CULVERT CONDITION ASSESSMENT

When considering culvert rehabilitation or reconstruction, an investigation needs to be performed to assess the culvert’s condition, flow requirements, design requirements, environment, factors that affect construction, backfill materials outside of the culvert, and other impacts. The design process should consider all of these before plans are developed for replacement or renewal of the culvert.

Culverts need to be replaced for several reasons:

- Bedding or backfill is eroded
- Improper bedding, including compaction or improper compaction of the backfill
- Culvert material is corroded or abraded
- Continuity of the culvert is broken

- Load distribution changes, including road widening and new construction
- Culvert cross-sectional shape has squatted
- Culvert is sagging and ponding of water is occurring

When the culvert was first built, the typical design criteria would have included a 25-year flood event. The Federal Emergency Management Administration (FEMA) now requires new projects under their jurisdiction to be designed for 100-year floods plus 1 foot of water head (Brown et al., 2001). This upgrade is required for all repairs or alterations to the existing structure. The actual flood requirements and what level of repair triggers the new flood design requirements should be verified with the appropriate governing agency. These requirements will establish the cross-sectional area needed for the new culvert and in turn the finished diameter of pipe to be installed by the construction method used.

During the condition assessment, factors that may affect the construction process need to be noted. Key factors include:

- As-built material, including lining and coating
- As-built dimensions
- As-is dimensions including sagging of the design profile
- Previous work to the culvert including rehabilitation and modifications
- Geometry and configuration of the inlet and outlet head walls
- Subsurface and aerial utilities
- Other interrelated improvements
- Methods and means of access to the base of the culvert
- Nearby cathodic protection systems

The problem and issue with the existing culvert needs to be understood so as to select the correct replacement method. For example, determining the culvert's linings and coatings is important because a galvanized steel culvert may need to be mechanically cut. Galvanized material produces toxic gases when cut with a torch. The design should accommodate the needs of the contractor as he or she deals with the existing pipe.

5. REHABILITATION VERSUS REPLACEMENT

Repair of the culvert happens either of two basic ways – rehabilitation of the existing culvert or new construction.

5.1 Rehabilitation

Rehabilitation does not remove the existing culvert material, but instead provides a new inner layer. The American Society of Civil Engineers recently published a manual on trenchless renewal methods for culverts (ASCE, 2009), which outlines some of the in-place options available. The new lining material should be selected based upon safety and life-cycle considerations. Installation of any lining system will decrease the internal diameter, thereby potentially reducing hydraulic capacity. Sometimes, the new smoother finish could maintain or slightly increase the hydraulic capacity. However, a new inner lining is unlikely to meet the 100-year storm plus 1-foot flood requirement.

Rehabilitation does not address or repair the eroded bedding or backfill materials. The loss of this material could be a contributing cause of the culvert's failure.

Another problem with the rehabilitation approach is the construction sequence and timing. If the culvert is a part of a natural flowing stream, damming upstream would be required with bypass pumping. This construction step is difficult to permit from an environmental perspective as marine life in the stream would be altered by the pumping, and the formation of deeper waters would change the ecosystem. In areas with well-defined dry and wet seasons, the culvert rehab work would need to be scheduled for the dry season, which still would not protect against thunderstorms and sudden changes in weather.

In some instances, rehabilitation is just not possible (Syachrani et al., 2009). An existing culvert that is surrounded by unconsolidated or shifting bedding must be replaced. Lining will not affect the dramatic effects of groundwater eroding the soil along the outside of the host pipe. Many of the problems with a culvert, like squatting or sagging, will not be corrected by inserting a new lining. A sagging culvert will still pond water, allowing the deposition of sediment and debris, which results in diminished hydraulic capacity.

5.2 Replacement with New Construction

The alternative to rehabilitation is replacement with new construction. The culverts can be replaced with two different approaches:

- *Consumption.* The existing culvert is completely engulfed by a bigger new culvert and removed in its entirety.
- *Parallel construction.* A new culvert is installed and the existing culvert is then either rehabilitated or abandoned.

5.2.1 Consumption

In the consumption approach, a new culvert is installed completely around the old culvert (Figure 2). The advantage is that the culvert's cross sectional area is increased, increasing the culvert's flow capacity. The entire old culvert is removed, and a portion of the bedding materials can be removed, providing a better soil-structure interaction for the new culvert. The size of the installation must consider how the space inside the pipe will be adjusted to match the grade of the original culvert. Part of the new excavation will not be used, so an additional effective diameter may be needed. To adjust for the old grade, the invert will be filled, typically with concrete. The poured invert can be made flat, notched, or even roughened to allow the accumulation of some flow debris in the invert for environmental reasons. Since the consumption method removes the old culvert, any sagging in the original culvert alignment can be removed by increasing the diameter of the new pipe.

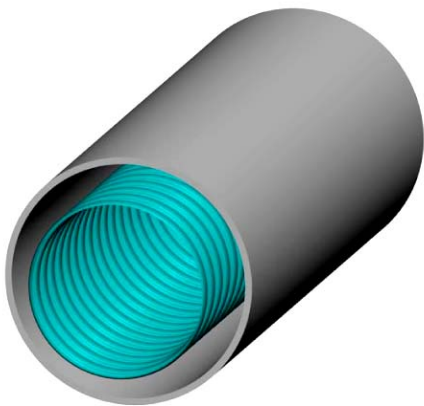


Figure 2. The original culvert is consumed in place by the new culvert.

If the culvert has flowing water, the water can be redirected into a new bypass pipeline and allowed to pass through the existing culvert during construction, if there is room. The consumption method also allows the work to be completed from the downstream end. Depending on the amount of equipment used, the new culvert can be evacuated if a storm hits during construction. After the storm has passed, the construction can resume with minimal effort. In the consumption approach, the work can be completed using pipe ramming, tunneling, or pipe jacking.

The consumption method is useful when the area to the left or right of the existing culvert is not available. Determination of the backfill material used around the original culvert is important to avoid hitting obstructions during construction.

5.2.2 Parallel Construction

The second replacement method is the building of a new barrel parallel to the old culvert (Figure 3). In this approach, a new culvert is installed next to the old culvert. The advantage of this approach is that the culvert's effective cross-sectional area can be increased as needed to meet the flow capacity requirements. The invert of the new barrel can be set to the design profile, so a smaller effective overall diameter is needed with this approach. The old culvert remains in service during construction. Once the second barrel is in place, the old culvert can be replaced by the consumption method, repaired, rehabilitated, or abandoned.

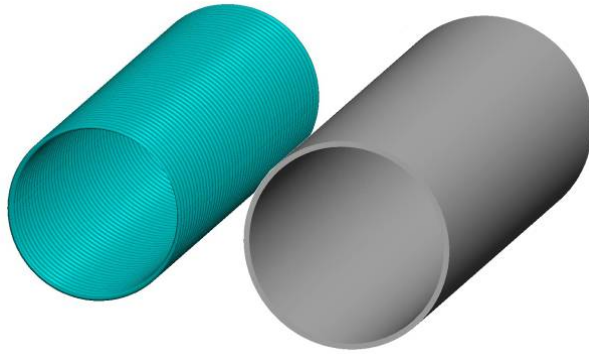


Figure 3. A new culvert is added on either side of the original culvert.

If the stream has flowing water, the parallel approach allows the new barrel to be constructed while the water flows through the original culvert. This is a huge benefit during construction. When the new barrel is completed, the water course can be redirected into the new barrel to allow consumption or rehabilitation work to occur in the old culvert.

With the increased capacity, the inverts in both barrels (new and old) can be in-filled to provide the type of invert required (i.e., flat, notched, or roughened for environmental reasons). A sag in the old culvert can remain or a new invert can be cast to remove the sag because increased flow capacity has been achieved with the new parallel barrel.

Construction of a second barrel allows the work to be completed from whichever end has the best access. In the parallel barrel approach, the work can be completed using pipe ramming, tunneling, and pipe jacking. The parallel barrel can also be installed with auger boring and the pilot tube method.

6. PIPE MATERIAL SELECTION

Pipe ramming, tunneling, or pipe jacking permits removal of the existing culvert and allows the substitution of other materials. Material selection is important for several reasons, including life cycle and safety. If the crossing is located near an active cathodic protection system, the old and any new metal culvert will be experiencing increased corrosion. Replacing a metal culvert or building a new culvert with concrete or plastic materials may provide a longer life cycle. If the culvert is located in a wooded area, which is susceptible to fire, then use of concrete or steel may be preferable as plastic materials are flammable. The selected or preferred culvert material must also be compatible with the contractor's construction method.

7. CULVERT REPLACEMENT DESIGN

The design for culvert replacement using pipe ramming, tunneling, or pipe jacking can include size for size replacement if parallel, but in most cases upsizing is done to increase the cross sectional area for various reasons. In the consumption approach, the size will always be larger to envelop the existing culvert. The new pipe diameter must also include upsizing to factor in any squatting that has occurred and any sagging. The final diameter of the new pipe will also consider the position of the new invert relative to the original invert elevation. When pipe ramming, it is necessary to include a driving tolerance, as the method is not steerable and could drift during

installation. The existing culvert could become an obstruction if the leading edge of the pipe ram ends up drifting into the existing culvert. When tunneling or pipe jacking, there is less of a concern because the shield is articulated and can be steered. The position of the existing culvert is known while the excavation is going on and corrections can be made when needed.

When tunneling or pipe jacking is used, the diameter of the new pipe must be large enough to allow personnel entry. Workers need to enter the tunneling or pipe jacking operation to physically excavate or remove the existing culvert. Space is needed for a rail line to move equipment, supplies, spoils, debris, and personnel. Ventilation lines are needed to feed fresh air for the workers. Typically, tunnels and jacked pipe need to be 60 in. (1,500 mm) or larger to allow effective personnel entry and working space.

If the cover is minimal, a larger culvert must be placed with a deeper invert or the shape of the culvert must be changed; otherwise, multiple parallel barrels will be needed. The drainage flow through the bottom of a lower culvert can be adjusted by casting a new invert that provides the desired flow line. When casting a new invert, the design can include energy dissipation features by adding rocks or an irregular surface in the invert. During construction the contractor needs to monitor the ground surface for lateral ground movement during the installation. This problem is particularly important when pipe jacking.

One advantage of using pipe ramming, tunneling, or pipe jacking is that the same equipment used to replace an existing culvert can be used to add capacity by placing a new parallel culvert.

8. CONSTRUCTION METHODS

8.1 Pipe Ramming

Pipe ramming can be used to consume an existing culvert or install a new parallel barrel. It is used in predominantly soil conditions and does not work in rock. Replacement pipe can be any size, as long as the casing can consume the existing culvert and complete the drive. Typical casing sizes range from 18 in. (450 mm) to 144 in. (3,660 mm). The drive length is subject to many conditions; therefore, the distances are approximate and should only be considered as a guideline. An 18-in. (450-mm) diameter pipe ram can be advanced up to approximately 150 ft (50 m) in length. A 30-in. (750-mm) diameter pipe ram can be advanced up to approximately 300 ft (100 m) in length. A 144-in. (3,660-mm) diameter pipe ram can be advanced up to approximately 200 ft (60 m) in length. A manual of practice on pipe ramming outlines the process in more detail (ASCE, 2008).

Pipe ramming can also be used to install a parallel barrel. Figure 4 shows a 120-in. (3,000-mm) diameter, 197-ft (60-m) long culvert installation in Oregon using pipe ramming (Piehl et al., 2005).



Figure 4. Pipe ramming is used to install a parallel culvert (Piehl et al., 2005): upstream (left); downstream (right).

The pipe ramming method requires the driving of a steel casing. The construction process commences by diverting any water and preventing the workers and work area from flooding. Once the area is safe, the contractor excavates around one end of the culvert, creating sufficient distance for guide rails to be set to grade. On the opposite end, the contractor prepares a receiving area. The sizing of the casing needs to include compensation for any sags. Once the pipe ramming tool, leading edge, and casing are aligned, joined, and set to the proper line and grade, pipe ramming is advanced to engage the ground. The shoe and casing would be sized to completely envelop the existing culvert in its current state. Mechanical cutting tools may be attached to the leading shoe to assist in cutting the culvert. As friction increases, the pipe ram is stopped and the enveloped material, including the original structural culvert material, is removed to a point where the residual material resists inflow. Pipe rams with casings less than 30 in. (750 mm) are extremely restrictive, and personnel entry for material removal is not possible. Once the material is removed, the pipe ramming continues, stopping for interventions until the casing is completely through to the receiving point. Once completed, and the casing is cleared of debris, contact grouting of the casing is performed based upon the project requirements. The steel casing can be left as the finished material. An alternative is to install a carrier pipe to the design line and grade and to grout the carrier pipe in place if a different finish material is needed. In many cases the steel casing may be the final pipe. A lining material would be added for corrosion protection.

8.2 Tunneling

Tunneling can be used to replace most any size of culvert so long as the shield and initial ground support can consume the existing culvert and the new pipe or tunnel liner are sized to allow personnel entry. Although a 42-in. (1,050-mm) diameter is viable, 48 to 60 in. (1,200 to 1,500 mm) is normally considered the minimum diameter. A tunnel can be advanced to any length. However, removing spoil can be slow and expensive beyond 400 ft (120 m). A 96-in. (2,400-mm) diameter tunnel can typically be advanced up to approximately 1,200 ft (366 m) in length with longer lengths possible. As with smaller diameters, removal of the spoil is slower and more expensive in longer tunnels. Transportation of materials and supplies is typically aided with a rail system with hand carts.

The tunneling method requires a shield and initial ground support system. The initial ground support is installed behind the shield and is used to push the shield forward. The initial ground support may be permanent or temporary. Typically initial support systems include liner plate, rib and lagging, or pre-cast segments. Figure 5 shows the process using a liner plate system. The initial ground support has to be designed to resist the jacking loads, construction loads, and traffic loads. The tunnel will be advanced with the old culvert and spoils removed as the tunnel is advanced. The annular space between the liner plate and the ground should be contact grouted to ensure effective load transfer between the ground and the support.

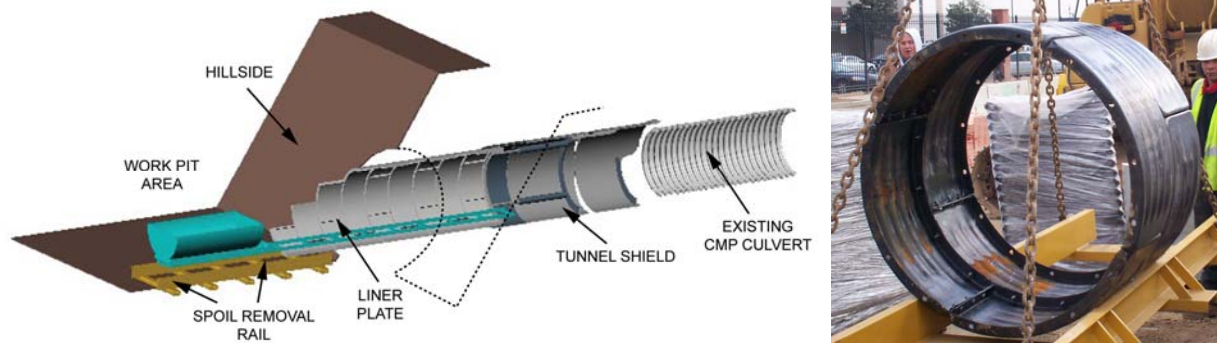


Figure 5. Liner plate is used during the tunneling process to consume an existing culvert (Tenbusch, 2009): tunnel with liner plate illustration (left); assembled liner plate ring (right).

With any of the initial support systems, a support ring is assembled in the tunnel shield. Once completed, the shield is advanced forward. The crew in the tunnel removes either the ground (parallel method) or the culvert in pieces (consumption method) within the protective shield. The shield is advanced by hydraulic cylinders located in the shield that push off the most recently assembled support ring. The shield has steering capability to maintain grade.

Tunneling does not require a jacking unit at the portal. The work area must be long enough to launch the shield and to allow for the safe entrance and exit of personnel and materials.

If the tunnel was constructed with temporary support, the carrier pipe would then be installed to design line and grade. Once the carrier is placed, the volume between the carrier pipe and the temporary ground support is backfill grouted. Both ends of the tunnel can then be finished according to the design.

After completion of the tunnel with the new carrier pipe, the invert may not meet the design flow line. The tunnel can then be cast with a new invert that meets the flow requirements, upstream and downstream design, and environmental concerns.

If additional capacity is being added, then the same construction process can be used in a parallel excavation with the same equipment, thereby reducing the cost of mobilizing a second construction method. The contractor may elect to construct the new culvert first to minimize pumping costs and increase worker safety in the event of flooding. If the existing culvert is replaced first, there may not be a path that allows the water to be pumped around the construction area as temporary pipe cannot be laid across the roadway.

8.3 Pipe Jacking

Pipe jacking can be used to replace almost any size of culvert, as long as the shield and jacking pipe can consume the existing culvert and the new pipe can allow personnel entry. As with tunneling, the diameter must be big enough to act as a work space. The length of the installation is limited by the friction forces that develop on the outside of the pipe during jacking. It is important to include an overcut and lubrication to manage the jacking loads.

Figure 6 shows a shield and pipe jacking being used to consume an existing culvert. New pipe is jacked segment by segment as personnel remove the ground (parallel method) or the existing culvert in pieces (consumption method). All work is done from within the protective shield. The shield has the steering capability to maintain grade. A jacking unit is needed at the portal to push the pipe into place. The jacking unit is substantial and requires a sizeable work pit. The unit must have a stable backstop to push against.

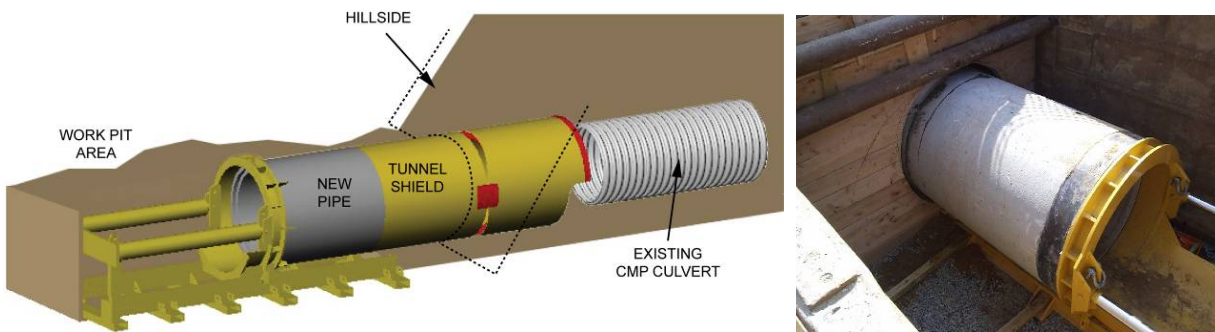


Figure 6. A shield and pipe jacking are used to consume an existing culvert with concrete pipe (Tenbusch, 2009): pipe jacking illustration (left); jacking pipe (right).

Jacking a pipe string requires the use of a lubricant. This lubricant helps reduce the skin friction that the pipe generates. Lubricant becomes more important as the pipe string becomes longer or the diameter larger. When the new pipe string is in place, the annular space must be contact grouted. Jacking pipe materials available for this option include vitrified clay, polymer concrete, reinforced concrete, and steel.

8.4 Contact Grouting

Contact grouting is the injection of cementitious material into the ground: from inside the pipe or tunnel into the fill. It should be performed on all sizes where personnel-entry is possible. This process reduces the long-term potential for ground settlement and eroding of the fine soil fraction out of the bedding, caused by the migration of groundwater. It will also help to improve the ground around the culvert. The contact grout should be injected from

the midpoint of the tunnel to the upstream and downstream ends. By injecting grout from the middle and allowing the pressure to relieve itself on each end, the chances of building pressure that would heave the ground surface improvements are diminished. The surface should be monitored during grouting to ensure the grout does not heave the surface, erupt on the surface, or enter any body of water.

8.5 Comparison of Pipe Ramming, Tunneling, and Pipe Jacking

There are pros and cons to each of these three methods (Table 1). It is important to assess the geology, determine the condition of the original culvert, and consider environmental concerns, hydraulic requirements, and access to determine which is the best method for an individual project.

Table 1. Pros and Cons of Pipe Ramming, Tunneling, and Pipe Jacking

Construction Methods	Pros	Cons
Pipe Ramming	<ul style="list-style-type: none"> • Can be used for consumption or parallel construction • Works best with smaller diameters • Can eliminate sags in the existing culvert • Does not use a lot of equipment (easy to stop and start if the weather changes) • Allows existing stream to flow through the culvert during construction • Initial work is completed with no personnel entry 	<ul style="list-style-type: none"> • Needs to be used in soil conditions • Requires a second liner if the exposed steel is not acceptable • Has to push out old culvert/old materials after the new casing is installed • Cannot see the condition of the backfill materials during the installation process (working blindly)
Tunneling	<ul style="list-style-type: none"> • Can be used for consumption or parallel construction • Excavating as you go allows you to see backfill material • Can be used in soil or rock conditions • Can eliminate sags in the existing culvert • Allows for the construction of different shapes of culvert • Allow longer distances to be installed • Permits larger diameter openings 	<ul style="list-style-type: none"> • Needs more equipment; therefore difficult to stop and start • Requires a larger diameter for personnel entry • Requires a second liner if liner plate or steel ribs are used
Pipe jacking	<ul style="list-style-type: none"> • Can be used for consumption or parallel construction • Allows the direct installation of concrete or other pipe material that does not need a secondary lining • Can eliminate sags in the existing culvert 	<ul style="list-style-type: none"> • Needs to be used in soil conditions • Requires a large diameter for personnel entry • Needs more equipment, including jacking frame and reaction block

9. CONCLUSION

With many culverts reaching the end of their designed life and experiencing structural failure, replacement of culverts is a major issue for various DOTs. Rehabilitation is a viable method of extending the life expectancy of a culvert if it is performed before structural failure of the culvert material or bedding occurs. Rehabilitation is not a good method when sagging has occurred in the existing culvert. Rehabilitation does not increase capacity beyond the improvement of hydraulic flow; it only improves hydraulic flow.

Open trench construction is not normally a viable method to reconstruct a culvert. Trenchless reconstruction methods need to be evaluated if a culvert is undersized, experiencing structural material failure, or experiencing bedding failure. Pipe ramming, tunneling, and pipe jacking are viable methods of:

- Replacing culverts
- Increasing the capacity of culverts through upsizing
- Increasing capacity by adding parallel barrels
- Eliminating sags in culverts
- Eliminating a structural failed culvert and the poor bedding and backfill materials

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