Failing Culverts – The Geotechnical Perspective

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Introduction

The economic stimulus program has brought significant attention to the need to maintain and improve our nation's infrastructure. Noteworthy is the high failure rate of flexible pipe culverts, most of which are corrugated metal, under our federal, state, and local highways. Some recent failures have been catastrophic as highways collapse without warning, and most occur in high traffic volume areas. With today's economic realities, it is more important than ever to closely scrutinize these failures and develop long term, cost effective, site appropriate, solutions. To do this it is necessary to consider the fundamental modes of culvert failure and possible solution options from a geotechnical perspective.

Three important events that shaped the use of flexible corrugated metal pipes since the beginning when James Watson and Stanley Simpson were granted a U.S. Patent for corrugated metal pipe (CMP) around the turn of the century (late 1890s):

1. Starting in the 1930s, Merlin Spangler, the father of buried flexible pipe design provided a standardized method for installing buried pipe and showed that structural pipe bedding could provide structural support for flexible pipes such as CMP and the overlying pavement.
2. June 29, 1956, America began in earnest to build highways (and culverts) when President Eisenhower signed the Federal-Aid Highway Act of 1956. Corrugated pipe, and in particular, CMP, was generally the material of choice on these low bid projects because of relative low cost for a given strength of the pipe. The corrugation added strength while permitting a reduction in wall metal thickness resulting in lower pipe material cost per foot of pipe.
3. In 1976 the introduction of the Federal High-Way Administration (FHWA) sponsored CANDE (Culvert ANalysis and DEsign) program provided a rational design method for culverts that acknowledged the significant effects of soil to structure interaction in the stability of buried culverts and the overlying pavement. Results showed that for CMP applications, the structural soil fill surrounding the pipe and the pipe form a co-dependent composite structure.

Unfortunately, elevated failure rates should be expected as many of the 50s vintage culverts age and highway maintenance funds have been redirected to tasks other than maintenance of culverts. Like other highway structures, flexible culverts have a given lifespan starting at their time of installation depending on design and installed conditions. Initially, the life cycle can be economically extended by relatively low cost routine maintenance such as headwall and pavement maintenance and by cleaning. As the culvert ages, the components start corroding or deteriorate by abrasion and structural fill properties can deteriorate. Pipe damage that has not compromised the soil support system can still be cost effectively maintained and rehabilitated. Rehabilitation options include invert paving and slip lining with an array of different pipe products along with grouting the annular space. In areas where fire is not a possibility, these liners can include different plastic products such as cured in place epoxy composites or a fold and form liner. However, once the culvert and soil structure have both been compromised or a failure has occurred, the structure has reached the end of its service life and must be replaced.

What many see as simply a flexible pipe failure is much more – it is the failure of the soil/pipe structure. This paper will examine fundamental elements associated with failure of flexible buried culverts. It is expected that those who are facing the challenges of replacing or repairing the failing culverts will readily recognize the realities of the failure mode explanations laid out here and the need for addressing both the pipe and the supporting soil to both restore the failed culvert and maintain the integrity of the overlying pavement. Let us start by examining the work of those who went before us in the construction of the culvert system.

Installation specifications called for over excavation under the pipe and placement of a sound layer of bedding material that would serve to support the pipe and provide drainage for the surrounding soil to reduce the potential corrosion from groundwater. The pipe was then laid on the sound bedding. Free draining structural fill was then installed along the haunches and compacted in a manner so as to not heave the pipe by forcing material under the haunches. When the well drained structural fill was installed and compacted in lifts to a level near the top of the pipe, the final backfill lift over the crown was placed, and the final compaction effort finished the job. The remaining trench was then backfilled to final grade and in some areas where there was to be an embankment – work began to build the embankment to the final grade. These are the conditions under which most culverts start their life and where aging begins.

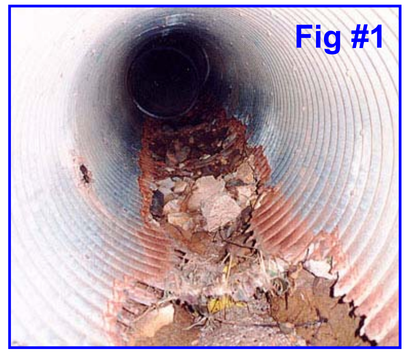
Culvert aging is a function of the impact of environmental factors on the culvert and soil composite system. These impact factors change the structural properties of the pipe and/or the surrounding supporting soil that make the composite system stable. Deterioration of the properties of these structural elements leads to mechanical failure such as seam separation, buckling failure of the invert or crown as pipe material or supporting soil structure weakens, or catastrophic removal of structure components by erosion or physical damage such as by fire.

Buckling is probably the most common of the failure modes and bares additional explanation regarding the soil and pipe system interaction to understand the meaning of why the flexible pipe and soil are considered to be a composite structure. Spangler discovered the effectiveness of soil support at the sides of flexible pipe. Failure of pipes with applied external loads is typically by unconstrained buckling of the pipe. Providing external support to the pipe enhances the pipe resistance to buckling. The installed corrugated pipe strength is significantly enhanced by external support provided by the structural fill bedding. Research has indicated that this well placed structural fill can enhance the buckling resistance of the composite system by up to 7 times resulting is significant reduction in pipe material cost relative to plate pipes. Newer engineering models and research strongly supports the concept that the soil structure interaction is the main component of the flexible culvert system's strength and stability. Thus damage to the structurally supporting soil can reduce the buckling capacity of the culvert system to that of an unsupported pipe.

Fundamental Geotechnical Factors Affecting Culvert Aging

The following geotechnical factors can adversely impact the flexible pipe/soil composite system over time and accelerate the culvert aging process.

1. Corrosion – Pipe metal corrodes from reactions with water and soil, which removes the metal from the pipe. The result is reduction in pipe material strength and eventual loss of the soil protection provided by the pipe material for the structural fill.

   Corrugated pipe strength is a product of pipe material, wall thickness, and the geometry of the corrugations. The basic design premise for corrugated pipe is to use geometry to reduce metal thickness while maintaining design strength. Maintaining the strength is done with corrugation geometry by applying higher stresses in the metal at the peaks of the corrugations. However, higher stresses can accelerate corrosion and reduce the amount of additional stress that the metal can tolerate before failure of the structural shape, the corrugation. This means that it takes less corrosion to result in failure of a corrugated structure than for a metal plate pipe of the same strength.

   Corrosion was recognized early on as one of the major factors in determination of a CMP service life. Early corrosion protection was provided by galvanized or asphalt coatings applied to the metal and more recently by aluminum coatings. The coatings deteriorate at a slower rate than the pipe metal and thus extend the life of the metal pipe. Presently, most states design major highway culverts for a 50 to 75 year lifespan and require corrosion protection. However, a Missouri Department of Transportation study indicates that a coated corrugated metal pipe lifespan can be less than 20 years because of invert corrosion damage. Coating and pipe chemical corrosion occurs on the outside of the pipe from ground reaction and on both the inside and outside of the pipe by road salt contaminated surface water and chemically active groundwater. Physical damage to coating that leads to pipe corrosion occurs from bed load abrasion and by traffic or environmentally induced mechanical abrasion between soil and the culvert (see Fig #1 above).

2. Mechanical instability of the local ground – Local ground instability may be caused by unanticipated or unaccounted for increased traffic loads, increased loads from increasing the height of embankment, increased water pressure from fluctuations in the water table, or changes in the underlying soil. The instability can result in unanticipated relatively slow movement or dynamic ground movements. Slow movements result when the bearing strength of the soil is exceeded causing compaction of granular soils, consolidation of cohesive soils, or internal soil shear failure. Slow movements increase loads applied to the flexible pipe system. Relatively fast movements can apply dynamic loads to the system such as from a landslide or can mechanically abrade the pipe coating or pipe material due to a sanding effect caused by the dynamic movements within the

granular soil fill acting against the pipe coating. The dynamic sanding effects are typically limited to relatively shallow installations and high traffic loads.

Highways, by their nature are constructed over many types of ground, some more capable of supporting the highway than others. Poorer quality soils for supporting loads are often located in lower areas forming surface and groundwater drainage routes. Water further reduces the ability of soil to support overlying loads by reducing the soil strength, which is the soil's ability to resist compaction, consolidation, or to bear loads. Water runs down hill and is often transported under highways through culverts in these areas of poorer quality soils. The result is the increased potential for ground instability around culverts which may consist of highway embankment settlement into underlying compressible soil or lateral spreading of an embankment as underlying weak soil has insufficient bearing strength to support the embankment. This ground instability may be slow and steady as with settlement, intermittent as ground and surface water fluctuates, or as a sudden embankment failure.

The result of instability includes embankment movements that can place sufficient tension along the pipe to pull a culvert apart at joints or it can place additional unplanned vertical or horizontal loads on the pipe as the structural fill supporting the pipe is displaced, or it can reduce the lateral support capacity of the structural fill supporting the pipe as it is displaced.

3 Erosion – Initially at the downstream end, erosion removes the structural fill supporting the flexible culvert, reducing the strength of the culvert/soil composite system. The structural fill provides bearing for supporting the culvert. Structural fill also provides lateral support to the flexible pipe that is providing the enhanced strength to the composite system. Removal of the bearing soil causes the pipe material to deflect like a beam either from its own weight or from a load applied by the overlying soil or vehicles. When deflections exceed the joint strengths or the pipe shape strength, then the pipe pulls apart at the joints or it buckles. Eventually, erosion will remove the entire embankment and culvert.

4 Surcharge Hydrostatic Pressure – Increased upstream development results in increased peak flows and therefore unanticipated surcharges. Unanticipated surcharge hydrostatic pressure applies additional water loads to the pipe and structural fill. The additional water loads can cause buckling of the culvert pipe by water pressure acting on the outside of the culvert pipe, which is a water barrier. Additional water pressure can reduce the stability of the structural fill by buoyancy effects. Additional water pressure also increases the groundwater flow velocity within the soil structure of the granular fill thus increasing pressure against the soil grains which reduces the capability of the soil grains to remain in one positions within the soil mass.

5 Environmental impacts – Soil strength can be reduced by environmental factors. Soil strength for granular soil is in part a function of density. If density is reduced, then the strength is generally reduced. The result of the soil damage is that the pipe no longer has the enhanced lateral support provided by the soil to remain stable and eventually it can buckle under a reduced load based on the strength of the pipe alone.

Environmental soil damage can occur in different ways:

- Frost action or internal soil movement such as occurs from traffic loadings for shallow culverts reduce soil density.
- Loss of soil such as through cracks and holes in the pipe.

Flexible Culvert Failure Mechanics

Failure for this paper is defined as any gap in the pipe that includes movement of the structural soil bedding immediately outside the gap. Failure elements do not operate in isolation but act together to deteriorate the culvert. Consideration of the geotechnical perspective of culvert system aging factors has made it possible to investigate the failure mechanics of a composite flexible pipe system. When the pipe deteriorates, it ceases to protect the bedding that is an integral part of the structure. As the culvert deteriorates the bedding deteriorates and the viscous circle ends in a complete failure. Once failure begins, there is no way to predict the moment of complete failure. Note - it is for this reason that once the culvert has begun to fail, it is unsafe for entry by inspection personnel.

The following are examples of situations that can result in failures:

Example 1 - Buckling resulting from a reduction in culvert structure components

Structural failure of corrugated pipe is typically due to buckling. It might be helpful here to point out that there are basically two modes of buckling failure:

1) The invert deteriorates by corrosion or abrasion removing the hoop shape of the culvert, which is a source of the pipe strength. This break in the hoop allows the pipe to close in – effectively reducing the circumference of the pipe (Fig #2) thus removing the confinement for the structural fill allowing the fill to loosen and in some cases the bedding fill can become eroded again allowing the pipe to move in. As the pipe support is removed, the bottom of the pipe buckles upward, the sides of the pipe buckle in, and the top of the pipe will then buckle downward.

2) The pipe sidewalls and joints deteriorate and allow the bedding material to migrate through gaps in the pipe; this is aggravated by hydrostatic pressure reducing the structural fill strength. This allows the pipe to deflect outward at the springline, which effectively removes the arch structure supporting the top. (Fig #3).

Example 2 - Hydrostatic Pressure Develops at the Upstream End of the Culvert and Reduces Soil Strength

Substantial development throughout our country during the last fifty years has increased the peak flow rate as surface water traveling over the modified ground now reaches existing culverts faster. The result is that many of the older culverts that serve our communities are now undersized. Undersized culverts, during rain events, result in backwater at the culvert intake. As the culvert is typically bedded in well drained structural fill, substantial hydrostatic pressure can occur from the backwater at the upstream end of a culvert that will be applied along the culvert length through the backfill. Obstructed culverts can result in the same condition. The hydrostatic pressure is not typically included in design loads but is a real load exerted on the pipe and it will apply a real internal pressure to soil surrounding the culvert reducing the effective stress in the surrounding soil resulting in reduced soil strength. The increased hydrostatic load combined with a reduction in soil strength can lower the enhanced stability of the soil structure to a point below that needed to resist buckling as further explained in the next section.

Example 3 – Erosion

Granular bedding is permeable and provides an excellent conduit for groundwater migration. Granular bedding is always a function of the locally available materials. The one common denominator is that it always has a low plasticity index, little silt content, and except for sandy areas, it has relatively high permeability compared to the adjacent native materials. Consequently the bedding will act as a "French drain" and will readily drain any groundwater that might be present. Add the differential head between the upstream and downstream end of a culvert as discussed earlier and you have water flowing through the structural fill similar to flow through an earth dam. Unlike earth dams, culvert design practices do not typically involve soil stability analyses under pressure heads. Hence, structural fill for culverts are not typically designed as a mineral filter system to prevent soil migration when the differential water pressure exceeds the soil ability to withstand the pressure. Thus unconstrained structural fill can start to erode at the downstream end of the culvert as the soil become "quick" and will continue to erode upstream until the water pressure is reduced. The loss of the structural fill removes the enhanced structural capacity of the culvert, which will result in a reduced capacity to resist buckling. Additionally, soil surrounding the trench can become unstable and erode into the structural fill. This instability of the soil surrounding the trench can also occur when the soil remains saturated after a flood event and drains into the trench fill. This drainage can reduce the soil particle stability resulting in migration into the trench fill thus reducing the density of the fill supporting the overlying structure such as the road.

Example 4 - Bedding affected by the condition of the pipe.

This is a well-documented phenomenon in sanitary and other underground piping systems. When there is a leak in a sanitary piping system, groundwater infiltrates into the pipe resulting in additional volume in the sanitary stream thus increasing the load at the treatment plant. With culverts the same is true. The only difference is the additional water volume is unimportant; however, the water intrusion into the culvert through holes and separated seams washes in the structural fill and the culvert water flushes the intruded material from the culvert. This lost material results in a void in the structural fill with loss of support for the pipe. If the conditions persist and the culvert does not collapse by buckling, the void will grow toward the water source or along a seam of more erodible soil forming voids and preferential flow channels in the surrounding soil. Increased hydrostatic pressure upstream will accelerate this process. This phenomenon results in significant erosion of the surrounding soil removing support for overlying soil and structures. The result can be a sudden sinkhole developed at the ground surface above the culvert hole. If the process is stopped by lining the culvert, the ground conditions will persist and create a legacy potential for a collapse in the future as the overlying soil will continue to collapse during rainfall or high groundwater events and migrate upward.

Example 5 - Bedding affected by compaction and internal dams.

It is important to remember that storm water conduit bedding must resist the effects of hydrostatic pressure on the downstream end, which can be substantial from time to time. If the bedding is compacted sufficiently, and if it is restrained by a solid downstream headwall, and if there is a hydraulic dam at the upstream headwall, then the structural fill may not readily carry enough volume or pressure of water to cause a problem. The corrugated metal pipe manufacturers considered this early on and developed what is known as an anti-seep collar. These collars are strapped onto the pipe at intervals and inhibit the migration of groundwater along the skin of the pipe. These backfill improvements have had questionable results. The trench plugs must surround the pipe without any layers of granular soil in the mix, and the anti-seep collars must extend into the virgin soils beyond the trench line. When the pipe deteriorates, the usefulness of these improvements is negated. *This failure starts at the discharge end of the culvert and works upstream.*

Example 6 - Granular soil ground movements.

This type of ground movement is not necessarily associated with groundwater migration. One significant attribute of granular soil such as used in structural fills around culverts and in overlying embankments that support roads is that dense granular soil must dilate (get looser) to move or erode. The soil mechanics of this process can result in "chimney" features in granular soil (Fig #4). These features can result in a looser soil zone around the pipe thus reducing pipe support resulting in pipe failure or if the pipe does not collapse, they


Fig #4

can continue to the surface and cause a sinkhole collapse. Once soil mass has been lost into the culvert and if the soil mass has not been remediated to the design density, the void will fill with looser soil that ravels from the top of the void. As the raveled soil gets deeper it compacts under its own weight thus resulting is a void at the top of the loose soil. This void will progressively work upward until there is sufficient arching within the soil mass to support the overlying soil or until the void reached the ground surface and forms a sinkhole (Fig #5). *The progress of this process is not predictable and may take several years before the results are realized.* Additionally, the surface water running through the system or the wet/dry cycles of moisture change within a granular soil which continues the void migration upward will not compact the soil that filled the void around the original hole in the culvert resulting in a weakened zone around the pipe that can significantly reduce the local buckling resistance of the existing culvert or of a liner.

Fig #5

Example 7 - Differential foundation support movement or lateral embankment movement.

Both of these conditions result in differential movement along the culvert that will result in tensile loads imparted to the culvert structure. The result is a loosening of the structural fill surrounding the culvert with subsequent reduction in buckling resistance and tensile forces that will open gaps at joints in unrestrained joint pipes that will provide an erosion path for trench and embankment fill material.

FAQ’s

As we stated in the introduction - if the backfill/bedding has not failed, then a pipe may be rehabilitated by a lining system within the existing pipe. However, a lining system will not rehabilitate the surrounding structural fill and if the fill has been damaged then the damage will remain, and with periodic increases in hydrostatic pressure due to rain events, it will become worse.

To further illustrate some of the different conditions and their ramifications the following “frequently asked questions” are presented below –

Q - Can the existing pipe be lined?
A - Lining is a great fix if the bedding has not been compromised by the failure of the pipe. If the pipe shows signs of failure, the bedding has therefore been compromised and it is too late for lining – the bedding must be removed and the pipe replaced.

Q - The invert has begun to deteriorate and has rusted through in some places; can we pave the invert with new concrete and at least buy a little time?

A - Once the water flow has been allowed to erode the bedding under the pipe, the hydrostatic pressure that the bedding will see from time to time will begin to force water migration through the bedding. The bottom line is - it is too late. The bedding must be removed and the pipe replace. Figure #1 above, is a good example of this problem.

Q - We are currently lining the existing CMP with new smaller CMP and then grouting the annular space. The calculations show that the new pipe is extremely strong, and when the inside CMP deteriorates the flow will have to erode the concrete grout before any failure can occur.
A - If the existing pipe showed failure – the bedding has been moving and therefore it is not capable of withstanding any substantial upstream hydrostatic pressure. See the next question for another slant on this subject.

Q - We sometimes line an existing pipe where we suspect that the bedding has lost its compaction and the pipe has shifted. We predrill holes in the existing pipe, and when we grout the annular space between the new sliplined pipe and the existing pipe, the grout goes through the holes and into the uncompacted bedding material.
A – There are two things to consider here.

1- You cannot know for sure where and to what extent the bedding has shifted and is now porous.
2- If you develop enough pressure with the grouting operation to expect that the grout has flowed to where it is needed, you may heave the road above or you may collapse the new sliplined pipe.

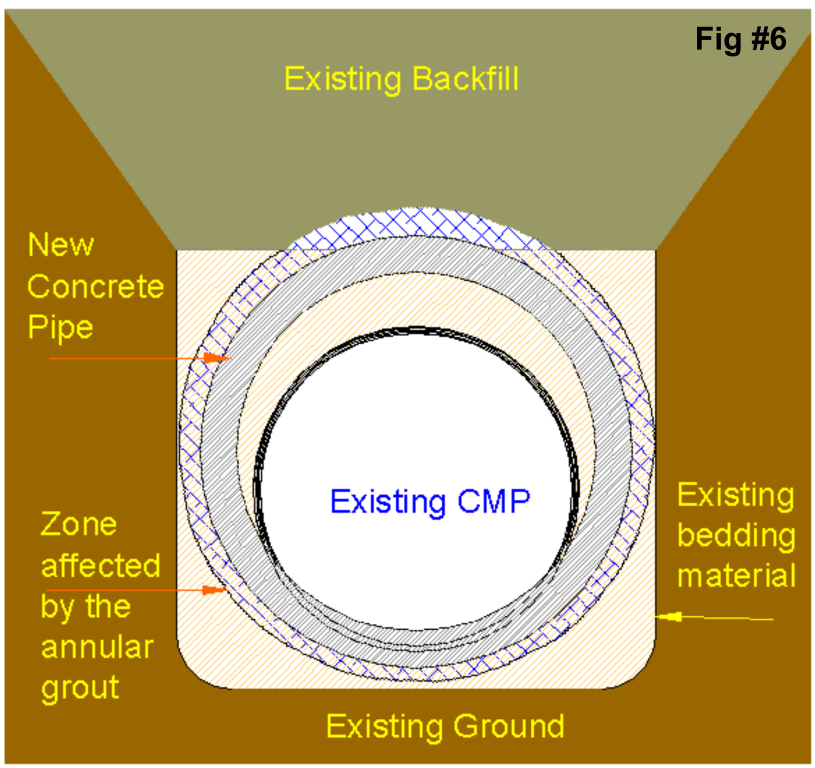
Q – We are considering replacement of the existing culvert by tunneling. However, there are signs of settlement on the surface above the failing CMP culvert. We cannot ask the contractor to assume any risk for the settlement that has already occurred or that will occur with the passage of time. Therefore we are going to install a new conduit by tunneling near the old crossing and then fill the existing pipe with concrete.
A – This sounds good but you have not dealt with the fact that the bedding has become loosened and porous and is carrying groundwater from the upstream side to the downstream side. This phenomenon will not be addressed by the pipe full of concrete. If the existing pipe is removed as a new rigid pipe is installed by tunneling, two things will occur – 1) the loosened granular bedding will be removed during the tunneling operation, and 2) when the annular space around the new pipe is grouted, the groundwater migration near the pipe will end. Now, the settlement can be addressed as it occurs, knowing that the settlement will not continue endlessly.

Solution Options

Solution options of failed flexible culverts are as follows:

- Open cut - Low traffic area crossings especially those that are shallow, may be rehabilitated by open cutting and replacement of the pipe and the bedding.
- Tunneling – When an existing culvert is replaced by tunneling, the existing pipe is removed along with the surrounding soil to accommodate the outside diameter of the new pipe being inserted into the tunnel. The raveling of the granular fill around the existing pipe is mitigated by the shield crowding the face during tunneling. As can be seen in the diagram below, during the process of tunneling most of the original bedding is removed. After the new pipe is installed, the annular space is grouted. The grout will permeate, to some extent, the granular bedding material that remains. In this way the opportunity for groundwater migration along the new pipe is severely limited.

What many see as simply a flexible pipe failure is much more – it is the failure of the soil/pipe structure. The only appropriate fix for a failed culvert is to remove and replace not just the pipe but also the structural bedding around the pipe to support the new culvert and the overlying pavement. Typically, this has been done by open cut construction. However, today's traffic loads and urbanization have resulted in high social and construction cost for open cut construction. Under these conditions tunneling provides a cost effective method to remove the old pipe and it's bedding and replace it with new flexible or rigid pipe.



Tunneling cross section – new RCP through the existing CMP

The figure above illustrates how the existing bedding/granular fill has been removed during the tunneling operation.

Let's look at how tunneling solves some of the original concerns generated by the failure conditions of the original pipe.

- ✓ Chimney features in the soil above the original pipe. If the original pipe is replaced by open cut, the soil above the pipe will be replaced and compacted properly. If the existing pipe is replaced by tunneling, the base (the zone that is causing the chimney feature) will be replaced and annular grout will be installed. The settlement above can then be dealt with as it occurs at the surface knowing that it will not progress indefinitely.
- ✓ Granular bedding that has become uncompacted in the pipe zone. Most of the material will be removed in the tunneling process as shown in the diagram above.

In addition to dealing with the existing problems above:

- The new jacking pipe has superior structural strength.
- During the tunnel operation it is common to use bentonite lubricant to cut down on skin friction around the new pipe as it is being pushed. The bentonite will soak into any granular material that is available to it and further reduce water migration.
- When the annular space is grouted, the area available for groundwater migration is all but closed off.
- Tunneling also typically brings a significant decrease in the carbon footprint of the culvert replacement construction, which may be very desirable in today's culture.
- Because the line can easily be upsized by tunneling – the engineer can now address the need for increased capacity.

Conclusion

This paper has discussed various components, including the geotechnical parameters that lead to aging and failure of the flexible culvert system.

The traffic along this highway was not affected as the existing 48" CMP culvert was replaced with new 54" Concrete Pipe. **FIG 7**

Findings and conclusions indicate that flexible culvert system replacement must address the complete structure including pipe and supporting material. Ultimately culvert failure is due to corrosion and the degradation of the soil-pipe structure. The only fix for a failing conduit that is supported by a granular structure is replacement of the failed granular material. If we are determined not to repeat history, the pipe will be replaced with a long design life pipe that does not depend on the bedding structure for strength.

Many culverts, whether they are federal, state, or local, are located in high traffic areas or in deeper fills. Rehabilitation of these culverts has become a national problem, as there are few alternatives that do not impact traffic flow and local commerce (see Figure #7 above). Traditional tunneling methods have been found to be an economical and effective method of removal and replacement of theses failing culverts as they can address both the damaged surrounding soil and the culvert material and significantly reduce the construction carbon footprint with the reduction in size and quantity of equipment. This alternative also allows the owner to upsize the existing capacity. Tunnelling allows for the replacement of the existing pipe without upsetting any other existing utilities. This geotechnical perspective has shown that there are several elements or mechanisms of pipe failure that work in concert to affect the total failure of the culvert. Tunneling creates a new structure with a new long design life material and a very long life expectancy.