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Large Diameter Gravity Sewer Rehabilitation Design

V. Firat Sever, PhD, PE, QuakeWrap, Inc., Tucson, Arizona

1. ABSTRACT

This paper provides an overview of the design principals for gravity sewer rehabilitation. When designing a new pipe, an engineer can calculate the loads based on the soil profile and other live loads, and then select the correct type of pipe using manufacturer data and safety factor required for the project. In a rehabilitation project, however, condition of the existing conduit should be factored into the design. Unfortunately, it can be quite expensive, if it is possible at all, to determine the material properties of existing pipes and manholes with high confidence levels. Determining the residual strength of an existing sewer is a complex problem due to degradation in material over time, missing mortar and brick layers (for brick sewers), and the effect of geometric deformation, mainly due to compressive (ring) stresses along these pipes. As such, a good deal of engineering judgment is needed for most rehabilitation projects, particularly for larger and deeper sewers. The author will discuss condition assessment methods that can be implemented within reasonable costs, and how those data can be utilized for a feasible and economical rehabilitation design using techniques including cured-in-place-pipe (CIPP), fiber reinforced polymer (FRP), and cementitious and polymeric spray applied pipe liner (SAPL). The paper will include different design methods and examples.

2. INTRODUCTION

Pipeline rehabilitation using trenchless technology has gained momentum over the past couple of decades and new methods are developed on a continuous basis. Unfortunately, many of the design practices are based on unsound approaches resulting in projects achieving much less than these technologies are capable of, thereby negatively impacting the reputation of trenchless pipeline rehabilitation. The primary reason for that is the practice of designing a lining system to withstand all the loads exerted originally on the host pipe. This approach, for most cases, results in overdesign and lower or no cost savings for the project versus conventional (open-cut) replacement. As a rehabilitation method that has been around for more than four decades, cured-in-place-pipe (CIPP) has a set of empirical equations (listed in ASTM F1216) that have been successfully applied – and modified – over the years. Nevertheless, even with much experience, the CIPP design divides the liner design approach into two as “fully” or “partially” deteriorated pipe condition. While the fully deteriorated design approach is somewhat straightforward, the partially deteriorated design approach assumes that the liner will not see any loads unless there is a hole or gap on the host pipe, thereby basing the liner design on groundwater pressure which would be exerted on the liner directly for such a case. As such, even the most established method of sewer rehabilitation design to date entails crude assumptions and does not quite factor in the actual site conditions or residual strength of the host conduit. (Think about a case where the host pipe is severely corroded but there is no groundwater pressure.)

It is important to implement the following design practices and avoid over/under design and costly solutions in rehabilitating large diameter sewer mains:

1. Understand the condition of the host pipe as deterministically as possible. (Use inspection techniques that are applicable and available.)
2. Identify the actual loads exerted on the conduit – avoid "crude" assumptions.
3. Obtain soil data
4. Develop a design approach factoring in the type and material of the host pipe (e.g., rigid versus flexible).
5. Identify the feasible lining solutions, and decide on the material upon an evaluation.
6. Select the design equation appropriate for the rehabilitation system. This step may have to be customized due to:
    a. Lack of a standard design equation
    b. Novelty of the rehabilitation system used
    c. Host pipe condition
    d. Host pipe geometry
7. Where feasible, obtain test data on the rehabilitation system selected, and validate the design approach/equations. For most cases, ring stiffness with respect to external loads is the key.
8. Determine the safety factor or reduction factor (LRFD) to be used in the design equation

To date, a number of equations have been developed for rigid/flexible pipes as well as well-established lining systems such as CIPP. In fact, the empirical equations included in ASTM F1216 for CIPP design are commonly, and erroneously used for other types of flexible lining systems.

Each design approach should be specific to site/host pipe conditions and the properties of the proposed rehabilitation solution. Sometimes an iterative procedure may have to be followed where an explicit equation is not available. An example of an iterative approach would be starting out with an estimated liner thickness (usually a conservative/thicker than expected value), and then check that thickness against applicable stresses/strains, and calculate the safety factor. If the safety factor is significantly higher than required, then the thickness can be reduced; otherwise, it should be increased until the safety factor calculated is neither lower nor substantially higher than the set value (typically 2.0). This process is helpful when the design equations are implicit due to lack of liner dimensions (mainly thickness).

The design of a trenchless pipeline rehabilitation must take into account the stresses/strains on the host pipe and liner as a result of the loads exerted. The main stresses that play a role on large diameter gravity sewer and liner failure can be listed as follows:

1. Buckling stresses in the hoop direction – this is the most common failure mode for flexible liners and pipes and often times dictates the design. Ring stiffness of the liner and host pipe plays an important role in the buckling resistance of a lined system. A flexible liner design driven by ring stiffness, without factoring in the host pipe (usually rigid) results in an excessively high liner thickness.
2. Membrane tension – more pronounced in situations where groundwater pressure is directly exerted on a flexible liner
2. Axial stresses due to bending – another common mode of failure, particularly affecting rigid pipes (e.g. concrete). Flexible liners will have a good deal of tolerance to bending and ideally there should be no bending in a well bedded and haunched trench with appropriate backfill, but that is rarely the case.

3. Transverse shear stress – Shear cracking may occur in rigid pipes due to differential settling of the pipe resulting from uneven loading and soil support. This is not a common failure mode for flexible liners or pipes.

The first step in large diameter gravity sewer rehabilitation design – or in any infrastructure rehabilitation project for the matter – is understanding the properties of the site and host pipe condition. It is important to note that a gravity sewer is a system of pipe and soil and should be treated as such.

3. CONDITION ASSESSMENT

A rehabilitation system should be designed around three main parameters:
1. Structural integrity
2. Hydraulic capacity
3. Economics

The second and third factors are outside of the scope of this paper. The first two can be approximated by compiling existing data on particular pipe segments and overall system. Then the data/information should be supplemented with inspection and further data acquisition to make meaningful decisions on the rehabilitation design (Sever et al., 2017).

Common methods for large diameter gravity sewer inspection include CCTV, laser, sonar, and, of late, utilizing other non-destructive techniques such as ultrasound. The first three are usually deployed on the same device known as a multi-sensor (Figure 1).

Figure 1. Multi-sensor inspection device (crawler type).

Another relatively new technology used for large diameter sewer inspection is a proprietary technique called the “Pipe Penetrating Radar’ (PPR by SewerVue®). This is essentially an application of the ground penetrating radar (GPR) technology from inside of the sewer to measure wall thickness and identify any gaps around the sewer pipe (Figure 2). Measuring the remaining wall thickness on a host conduit helps determine its residual strength and voids around sewers can result in higher than anticipated stresses due to soil pressure concentrating over a smaller area of the pipe exterior.

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As a conventional method, man-entry inspection is still a reliable and relatively deterministic method in evaluating a large diameter sewer pipe. In addition to visually inspecting a pipe, some simple measurements and tests can be conducted while in the pipe. These measurements would include pipe dimensions, ovality, flow rate, and even basic material properties via hardness and Schmidt hammer tests.

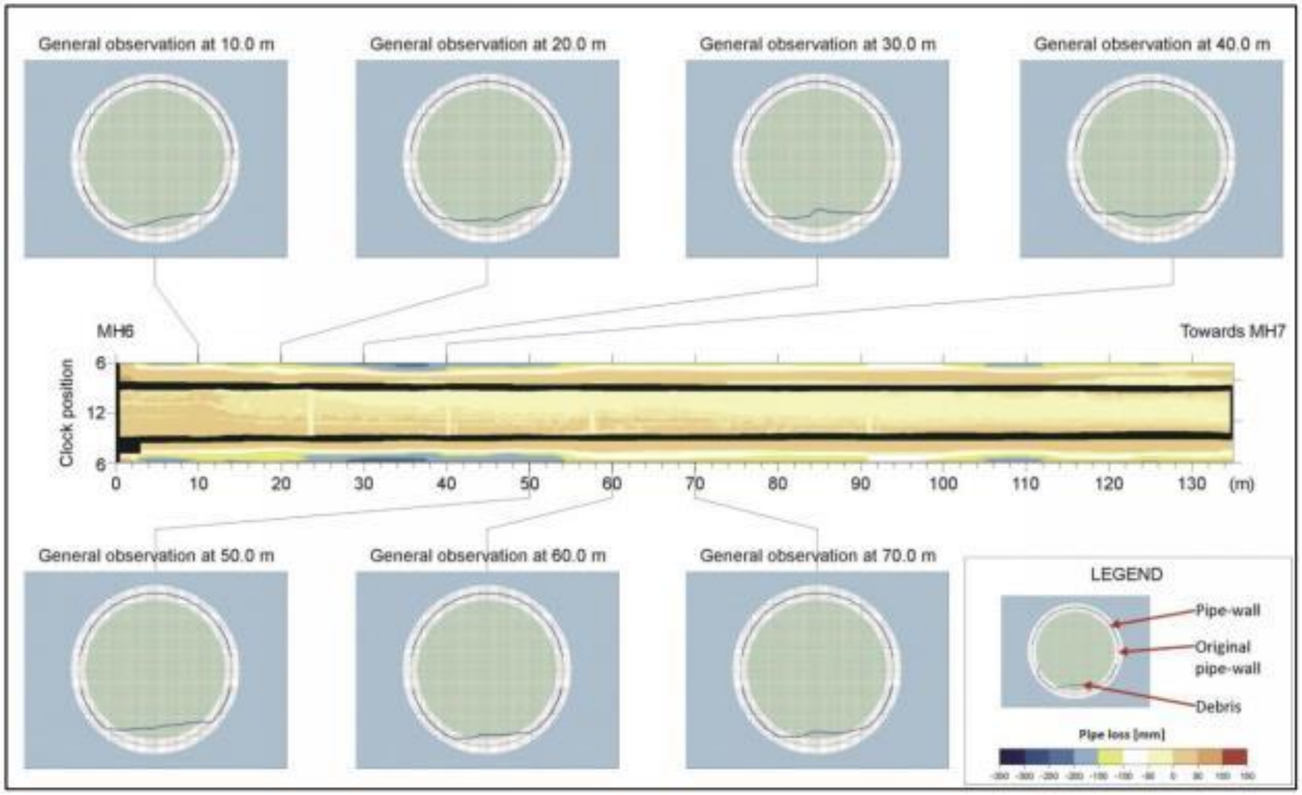

Figure 2. PPR inspection plot that shows the pipe geometry and actual wall thickness (Source: SewerVue).

Nevertheless, a man-entry inspection is most useful if carried out by engineers or senior level technicians resulting in higher costs. Man-entry inspections are also influenced greatly by flow conditions in the pipe, safety measures that must be taken, and maintenance of traffic, where necessary.

4. REHABILITATION DESIGN

Rehabilitation design for a pipeline can often times be more challenging than designing a new pipeline, unless it is oversimplified by taking the same approach as a new pipe design. The latter practice can be detrimental to the rehabilitation industry by substantially inflating the costs. In fact, the majority of the underground infrastructure does not require a stand-alone (fully structural) rehabilitation. As such, it is important to keep the concept of semi-structural rehabilitation in mind. Nevertheless, this concept can be complex and might require some assumptions on the strength of the existing conduit where there is not sufficient data.

Watermain Rehabilitation Classifications

For instance, in the drinking water industry, AWWA M28 classifies water main rehabilitation into four categories. Detailed descriptions of the AWWA water main rehabilitation classification is currently being revised, and will be published as a separate AWWA standard. The classification, as it stands, can be summarized as follows:

1. Class 1: Non-structural rehabilitation for corrosion protection. Examples include thin applied spray applied coatings (cementitious or polymeric).
2. Class II: Semi-structural rehabilitation capable of spanning small holes and gaps. Examples include thicker spray applied linings (cementitious or polymeric).
3. Class III: Semi-structural rehabilitation capable of taking external loads (groundwater pressure) in addition to ability to span small holes and gaps.
4. Class IV: Fully-structural rehabilitation capable of taking all internal (pressure) and external loads on the pipe.

Manhole Rehabilitation Classification

To the best of author’s knowledge, there is no widely accepted such classification on the gravity sewer side. A research project (EPA/WERF INFR1R12, 2012) sponsored by the Water Environment Research Foundation (WERF) as a part of a nationwide EPA program, outlined a simplified version of the AWWA classification for manhole rehabilitation:

1. Class A: Non-structural rehabilitation for stopping leaks and corrosion protection, if applied to the entire manhole.
2. Class B: Semi-structural rehabilitation partially relying on the host structure residual strength.
3. Class C: Fully-structural rehabilitation as a stand-alone solution capable of taking all the loads exerted on the manhole once installed and cured.

Cured-in-Place Pipe Design Assumptions

Since the first installation in 1970 in the UK, the CIPP liner has grown to the point where it is now among the most established methods of gravity sewer rehabilitation. CIPP has been applied with great success over the years, particularly on small diameter sanitary sewers. There are several ASTM Standards used as a reference to design and install CIPP. One of them is ASTM F1216- Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube, which provides two sets of design equations for CIPP (2009 version):

Partially deteriorated condition:

$$P = \frac{2KE_L}{(1-\nu^2)}\frac{1}{(DR-1)^3}\frac{C}{N} \qquad [1]$$

Where P is the groundwater pressure, K is the enhancement factor of the soil and existing pipe adjcent to the new pipe, E_L is the long-term modulus of elasticity for the CIPP, C is the ovality reduction factor, ν is the Poisson ratio (0.3 for CIPP), DR is the dimension ratio, and N is the safety factor.

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The partially deteriorated condition equation is solely based on groundwater pressure exerted directly on the liner due to a hole or gap on the host pipe. The CIPP liner relies on the host pipe for soil pressure and traffic loads as they apply. This approach assumes the host pipe will not fail or deteriorate to a level that its residual strength will be negligible and the liner itself will not have to withstand the soil pressure. While designing a liner for groundwater pressure could result in a good deal of support to the host pipe for any other external loads, for a case where there is no necessarily significant groundwater pressure (think about the arid west) the liner design could result in a CIPP thickness that would practically have no benefit to the host pipe. For such a case, if the condition, for instance the remaining wall thickness in a concrete sewer, is known, then a semi-structural design approach that would factor in the residual strength of the host pipe plus the CIPP would make the most sense. Nevertheless, there is no established design equation for this. A common practice is to come up with a liner thickness that is equivalent to the wall loss on the host pipe. This approach has its shortcomings however:

1. The host pipe may be over or under designed, in that case, the lined pipe will be over/under designed as well.
2. It will be misleading to convert a rigid pipe thickness, to a flexible liner just based on stiffness of the two (EI). Rigid and flexible pipes have different design principals; i.e., flexible pipes do not have to bear as much load as rigid pipes do.

The first pitfall listed above can be overcome by looking into the original design loads, thereby determining what the host pipe thickness should be. It should be also noted that the owner may assume responsibility on the host pipe condition, and request that a liner be designed to a thickness that is equivalent to, for instance, 25% of the host pipe wall loss.

Unfortunately, there is no simple solution to the item 2 listed above. If a flexible liner is to be used to rehabilitate a rigid pipe as a fully-structural solution, then it may make sense to use the flexible pipe load distribution over the liner. However, in reality, the rigid pipe will be absorbing higher loads and stresses until it fails, and at that point, the energy (and deformation) will be released to the flexible liner. It is advisable to utilize powerful computational techniques such as the finite element analysis that will factor in the flexible and rigid properties of the host pipe/liner as well as the contact mechanism between the two under the loads exerted. Nevertheless, using the finite element method often times requires expensive software programs and engineers with extensive experience with computational modeling, and these additional costs may not be justified if a project is small.

The second set of equation provided in ASTM F1216 is for the fully-deteriorated condition, meaning that liner is designed to be stand-alone:

$$q_t = \frac{1}{N}\left[32R_w B' E'_s C\left(\frac{E_L I}{D^3}\right)\right]^{1/2} \qquad [2]$$

Where q_t is the total external pressure applied on pipe, R_w is the water buoyancy factor, B' is the coefficeint of elastic support, I is the moment of inertia of the liner, D is the mean internal diameter of the CIPP liner.

Equation 2 has been widely accepted and used over the past decades, and now there is a "less conservative" modified version published in the latest ASTM standard. It has become so popular that engineers started to use it for other types of polymeric liners (such as spray applied epoxy and polyurethane) and even for manhole rehabilitation. This is a highly flawed approach simply because Eq. 2 is an empirical formula that applies to CIPP only.

To illustrate how F1216 cannot be a fit for other types of liners, a sample design exercise is presented below.

Host Pipe = Concrete (fully deteriorated)
Soil cover depth = 16 ft.
Soil unit weight ≅120 pcf
Ovality ≅1%
Coefficient of elastic support = 1/(1+4e-.065H) (lbs-in.)
Long-term modulus of liner (StifPipe®) = 4,500,000 psi
Water buoyancy factor ≅ 0.75
Internal diameter = 66 in.
Safety factor = 2

Based on Eq. 2, ASTM F1216 calls for a minimum thickness determined by the following equation (Imperial units):

$$\frac{EI}{D^3} = \frac{E}{12(DR)^3} \geq 0.093 \qquad [3]$$

Plugging in the values for the design example presented above results in a maximum DR of 159 or a minimum thickness of 0.41 inches.

Figure 3. Installation of .57 in. thick StifPipe® inside the 66-inch RCP.

5. CASE STUDY COMPARING TIMOSHENKO VS. MODIFIED IOWA FORMULA

The design example presented above from a real 66-inch RCP rehabilitation project recently completed in Edison, New Jersey except the type of liner used was not a CIPP; it was a patented composite liner (StifPipe® by QuakeWrap, Inc.) comprised of carbon, glass fiber, a proprietary 3D core fabric saturated with epoxy resin (Figure 3).

Timoshenko Method

The design approached used for the actual project was governed by buckling due to external pressure utilizing the equation provided in the draft AWWA C305, which is a modified version of Timoshenko's buckling formula:

$$Pc = \Phi \frac{E}{(1-\nu_{LT}\nu_{TL})}\left(\frac{t}{D}\right)^{2.2} \qquad [4]$$

Where Φ is the reduction factor to account for material degradation and installation flaws and ν is the Poisson's ratio (in longitudinal and transverse directions).

Note, Eq. 4 is based on Load Resistance Factor Design (LRFD), and does not require a safety factor due to the reduction factors incorporated into Φ. The total thickness calculated utilizing Eq. 4 for the project was 0.57 inches. Although, this is still within the margin of safety and reduction factors, the thickness calculated utilizing the approach specifically developed for CFRP systems, and backed by experimental data applied on StifPipe®, yields a total thickness that is 39% more than the thickness calculated using the F1216 equation. While a sensitivity analysis has not yet been performed on this comparison, it is more than likely that the difference is due to two design approaches fundamentally different from each other in addition to a lining system that is comprised of three different layers and is highly anisotropic.

Modified Iowa Formula

Another design approach applied for flexible pipes and liners is the modified Iowa formula (Marston, 1930), which is a deflection based design:

$$\Delta Y\% = \frac{T_f 0.07\gamma h + 10W_L}{\frac{EI}{r^3} + 0.061E\prime} \qquad [5]$$

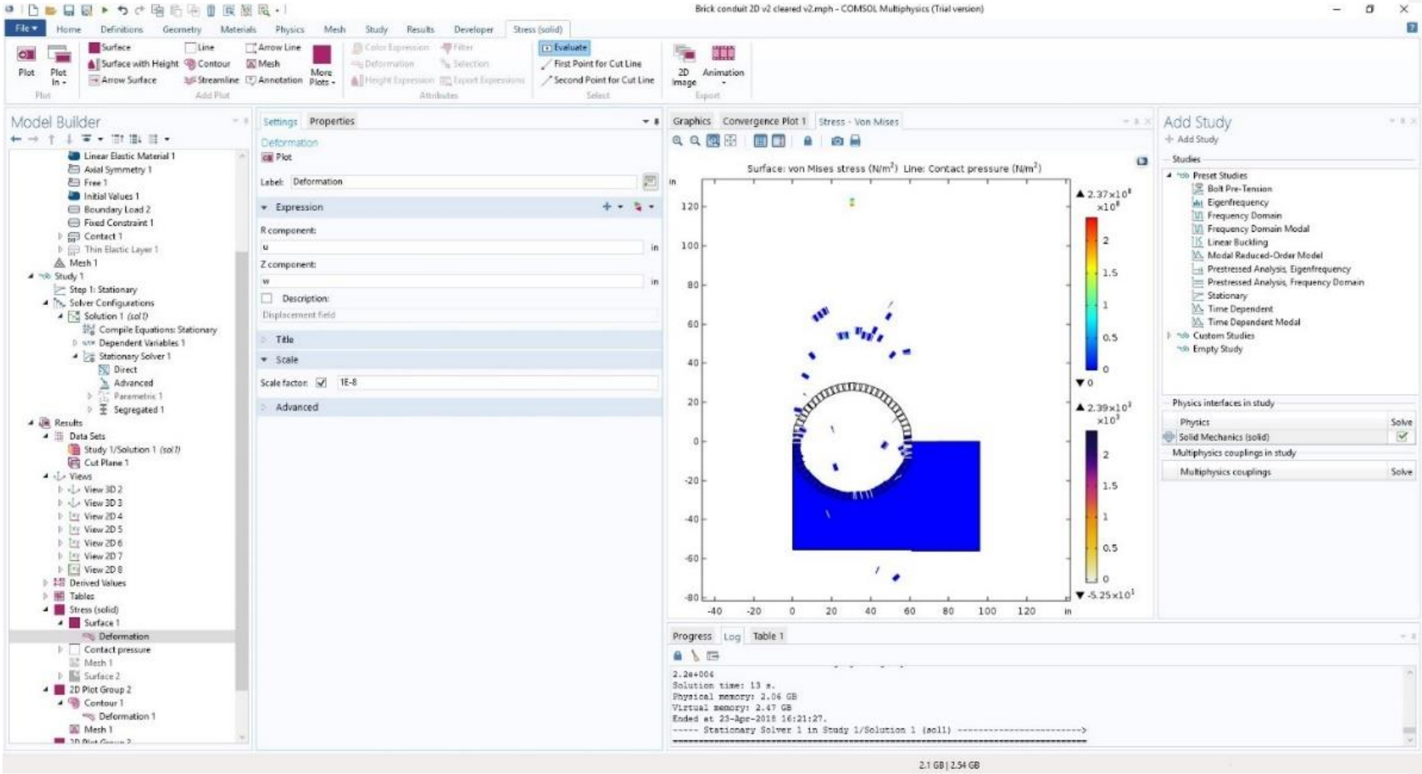
Where ΔY is the horizontal deflection, T_f is the time-lag factor, γ is the unit weight of the soil, h is the cover depth, r is the pipe/liner radius, W_L is the live (traffic) load on the pipe per linear foot.

It is important to note that Eq. 5 is also an empirical one, and often times returns misleading results particularly for flexible composites with high stiffness. This discrepancy is more pronounced for large diameter flexible pipes or liners. The primary reason for this is that the Iowa formula approach suggests deflection on a flexible pipe is rather driven by the depth and the support provided by soil than the stiffness of the pipe or flexible liner.

The flexible liner design approach alternatives above outline the importance of choosing the right equation specifically developed for the type of liner. Unfortunately, such equations yet do not exist for a number of materials used today; and in fact, even for the conventional materials such as cement-mortar liner, different design approaches persist.

Using Finite Element Analysis (FEA)

A powerful tool to design a lined pipe system, particularly the more economical semi-structural design is finite element analysis (FEA). FEA can be also quite helpful when the pipe geometry is unusual and/or



Deformation

Label: Deformation

R component: u

Z component: w

☐ Description: Displacement field

Scale factor: ☑ 1E-8

```
2.2e+004
Solution time: 13 s.
Physical memory: 2.06 GB
Virtual memory: 2.47 GB
Ended at 23-Apr-2018 16:21:27.
----- Stationary Solver 1 in Study 1/Solution 1 (sol1) ----------------------->
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Figure 4. Failure of a single ring brick sewer depicted in an erroneous 2D FEM.

loads, support conditions, as well as material properties are not constant. Nevertheless, using the right type of finite elements as well as making reasonable assumptions for the parameters where no data are available are among the important factors that will turn a FEA model into a success vs. colorful plot that are esthetic, but practically have no meaning; or even worse, could lead to bad design decisions.

For instance, the author of this paper created a FEA model (Comsol) to analyze stress and strain distribution over a 54-inch diameter brick sewer that had sections of single layer (ring) brick and partially lost the mortar among the bricks likely due to hydrogen sulfide induced corrosion. With the crude assumptions made for the model (such as 50% of residual mortar strength and trench load on the pipe regarded as rigid) the model results suggested this conduit should have failed (Figure 4). In reality, although at a high risk of failure, this pipe is still in place probably due to more than anticipated remaining binding strength among the bricks as well as the ignored increased soil support on the pipe over time due to the positive arching effect.

6. CONCLUDING REMARKS

The design overview for large diameter gravity sewers provided herein suggests a standard approach or following suit on an empirical equation will be misleading, and can cause detrimental effects. While we all strive for practical and fast ways of solving engineering problems, sometimes the solution is not straightforward, and may require a good deal of data collection, analysis, and testing prior to reaching an acceptable design solution. A multiple step approach is recommended for design engineers with respect to large diameter sewer rehabilitation design:

1. Conduct condition assessment
2. Identify the design needs (i.e., semi or fully-structural)
3. Determine the lining method
4. Identify available equations
5. In absence of a widely accepted design equation:
    a. Develop an approach based on equations used for similar problems
    b. Use material properties from independent test data
    c. Verify modified design approach by testing, preferably on a pipe segment rather than coupons. Ring stiffness is the key.
    d. Utilize computational modeling with FEA where there is a lack of design equation or a unique site and loading situation. Avoid broad or crude assumptions; collect the necessary

7. REFERENCES

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