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Structural Rehabilitation of Rigid Pipes

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Abstract

This paper discusses a method of structural rehabilitation of rigid pipes with PVC and cementitious grout liner materials. A design procedure for the structural rehabilitation of rigid pipes is proposed and discussed .

Introduction

The subject rehabilitation system consists of a spirally wound profiled PVC liner which is grouted in place by filling the annulus (0.5 - 3.0 inch) with a high strength cementitious grout. The grouting is accomplished through holes in the crown of the PVC liner every 5 - 10 feet and is performed in several lifts to minimize the stresses on the liner during the grouting operation. Once the grout is in place and cured, it integrates the PVC and host pipe into a composite structure (Ahmad and McAlpine 1994); this integration is accomplished through mechanical locking to the host pipe (via joints, cracks, and rough surfaces) and to the "T"s of the PVC profile. Use of a superplasticizer allows the use of a cement rich mix with low water content (i.e., high strength) while achieving excellent flow characteristics which insures complete fill of all voids in the annulus, including cracks and joints in the pipe. If structural demands require, the grout may be specially blended (e.g., polymeric mix) or steel wire mesh may be placed in the annulus before installing the PVC liner and grouting. In very large diameter pipes (≥ 84 ") the system can be installed in panels arched across the corroded top portion of the pipe only. This design flexibility allows the system to address a wide range of structural rehabilitation situations.

Most rehabilitation of gravity flow sewer and storm drains is in rigid pipes such as concrete or brick structures as opposed to flexible pipes such as ductile iron or steel pipes. This paper discusses the rehabilitation of rigid buried structures and more specifically, circular concrete pipes. Further, this paper addresses only the case of "fully deteriorated" rehabilitation design (see ASTM F 1698); that is, designing a rehabilitation system to restore the required load carrying capacity to the deteriorated host structure. Note that this approach is true rehabilitation of the host structure and not a "pipe within a pipe" (although this approach is also possible

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with this system of rehabilitation). Also note that, strictly speaking, the host pipe cannot be structurally "fully deteriorated" as it is successfully carrying its load at the time of rehabilitation; otherwise, the structure would have collapsed. The operative portion of the ASTM F 1698 definition is that the host pipe "...is expected to reach this condition over the design life of the rehabilitated pipe.", or if left unrehabilitated it will eventually become, truly, "fully deteriorated". Standard industry practice is to use the terms "partially deteriorated" and "fully deteriorated" to describe host pipe conditions and this then dictates appropriate rehabilitation design. These terms were adopted for use principally by flexible plastic liners but are now pipe rehabilitation industry standard terms.

This paper describes a rehabilitation method that results in a rigid composite of PVC/grout/existing pipe which, according to its ASTM installation standard practice (F 1698), "should have strength at least equal to that required to sustain the loads (with safety factor) specified by the applicable project specifications.". As each project is unique in the way the pipe has deteriorated and the extent of deterioration, it is not possible to generalize about the specific rehabilitation design; e.g., whether or not to include new steel reinforcing in the rehabilitation process. Thus, the specific design for each project should be customized in cooperation with the owner's engineer.

Concrete Pipe Deterioration

Concrete pipes in need of structural rehabilitation normally have experienced severe corrosion of the concrete, usually in the crown above the daily high flow level, may be cracked and slightly oval ($\leq 10\%$). In severe situations in reinforced concrete pipe (RCP) the corrosion will extend to or beyond the depth to the inner reinforcement. Once the steel reinforcement in RCP is exposed, its corrosion is rapid and its moment carrying capacity is unreliable at best. If the pipe is carrying moment generating loads, which must be assumed, the pipe will eventually fail. The rigid pipe fails in flexure at the points of maximum flexural stress; that is, at the crown on the inner surface and at the springline on the outer surface of the pipe. RCP will continue to carry its loads after flexural cracking until the load reaches the ultimate strength of the existing pipe wall, which may be considerably less than its specified magnitude. This assumes that the corrosion is limited to the upper half of the pipe and has not yet caused the reinforcement to become ineffective either by removing the concrete anchoring the steel or by eating through the steel itself.

Once the rigid pipe fails (load exceeds its ultimate strength) the pipe will begin to deflect, acting as a hinged circular-sectioned structure with the crown moving down and the springlines moving out (Serpente 1994). This deflection is resisted only by the surrounding soil. Clearly, the job of rehabilitation is to prevent flexural failure (and the resulting deflection) of the rigid pipe. The method to accomplish this rehabilitation under discussion here is to replace the missing concrete (and steel if required and possible) and then protect from corrosion with a plastic barrier to the corrosive environment.

The rehabilitation system being discussed results in a composite pipe wall structure consisting of concrete, steel (for RCP or where it is installed as part of the rehabilitation process in man-entry sized structures), cementitious grout, and plastic (PVC). The plastic is mechanically anchored in the grout and the grout is (adequately) bonded/anchored to the host pipe wall. Insuring adequate bonding/anchoring of the grout to the pipe wall requires that the pipe surface be cleaned to remove all corrosion products and expose competent concrete. This can be accomplished by high pressure (5,000 - 15,000 psi) water jetting; in larger diameter pipes (≥ 60 " ID) this may have to be done using manually directed hand-held jet nozzles. If needed, water jetting may be supplemented with mechanical scraping to handle particularly difficult situations.

The water jetting also flushes the exposed surface removing residual corrosive acid, increasing the pH toward the desired neutral value of 7.0. Due to small amounts of acid in the pores of the cement paste, and to a lesser degree in the aggregate, the surface pH may remain in the range of 6.0 - 7.0. Considering the small total volume of acid present and the high pH (≥ 12.5) of the large volume of cement rich grout to be added at this surface, this slight surface acidity should present no problem. This rehabilitation system and this cleaning process has been evaluated in controlled experiments and in actual field demonstration with periodic inspections and found to be successful (Redner, Hsi, and Esfandi 1994). No evidence has been found of deleterious effects of residual acid. The field demonstration in 600 feet of 78" RCP with a surface pH = 2 has been inspected periodically since its installation in January 1991. This system was first installed in Australia in 1984 and in the USA in 1989.

This surface cleaning normally leaves a very rough surface consisting of exposed large aggregate which is still well anchored in the pipe wall. The fluid grout easily flows into this rough surface producing a mechanical bond/lock, insuring that any movement of the pipe surface is directly transmitted to the hardened grout; thus future strains in the pipe wall will be resisted by the grout and the entire structure will act as a composite material. In those cases in which the host pipe's rebar has been damaged by acid corrosion, the installation of steel welded wire fabric with mechanical anchors into the pipe wall will provide additional mechanical anchoring of the grout to the pipe.

Composite Material Analysis

The analysis of this structure requires the use of the transformed-section method of engineering mechanics as is depicted in Figure 1. The basic operation of the transformed-section method is to convert all materials into one material by transforming the actual areas of each material into an equivalent area with a common modulus of elasticity. For example, if we assume the modulus of elasticity for concrete is $E_c = 4 \times 10^6$, steel $E_s = 30 \times 10^6$, grout $E_g = 3 \times 10^6$, and plastic $E_p = 3 \times 10^5$, and we transform all materials to concrete, the area of concrete

is unchanged, steel area is 7.5 times the physical area, grout area is 3/4 the physical area and the area of the plastic is reduced by a factor of 3/40. This is accomplished by changing the width of each material so as to maintain their centroids unchanged in the geometry of the problem. The example of Figure 1 assumes that the corrosion has removed 1.0 inch from the inner wall in the top half of the pipe and has exposed the rebar; the rehabilitation replaces the missing concrete and adds another 1.0 inch of 5000 psi grout, plus the plastic of 0.36" moment of inertia equivalent thickness of the profile. The addition of the rehabilitation materials has two primary effects on the stress levels: 1) the neutral axis (NA) is shifted toward the inner surface, and 2) the composite moment of inertia I_{comp} is increased. The following equations formalize the analysis (using 48" ASTM C 76 Class II, Wall B RCP: 5" wall, 1" cover over both steel cages, inner cage area = 0.18 in²/ft, outer cage area = 0.11 in²/ft, assume spacing of 4" for rebar separation, $f_c = 4000$ psi).

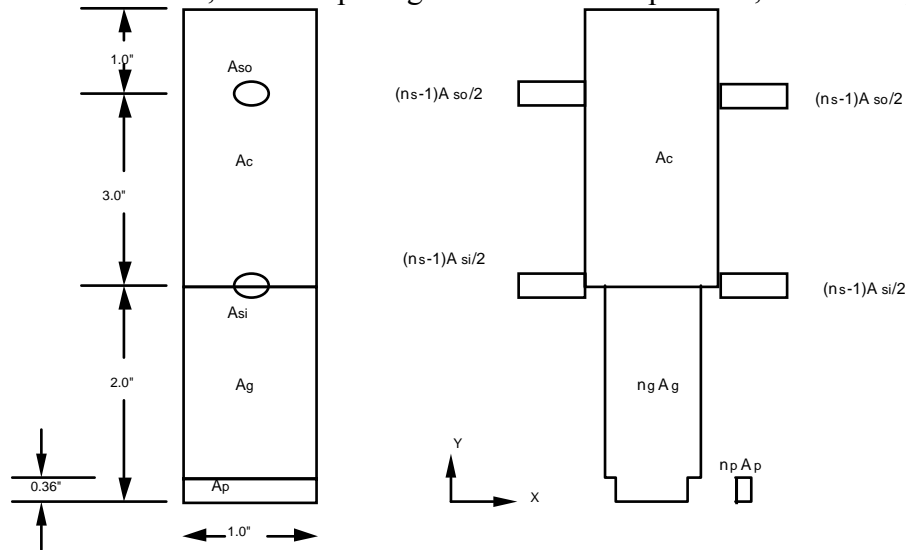


Figure 1 Transformed-section Method for RCP

$$Y_{NA} = (\sum Y A) / \sum A = 3.114" \quad (1)$$

where Y_{NA} is the distance to the neutral axis from the X axis of the coordinate system (inner surface of PVC) and Y is the distance to each centroid of each transformed area $A = n_X A_X$, $n_X = E_X / E_C$.

$$I_{comp} = \sum I'_X = 16.415 \quad (2)$$

where

$$I'_X = \text{moment of inertia of transformed material} = n_X I_X + (Y_{NA} - Y_C)^2 n_X A_X,$$

$$Y_C = \text{distance from X axis to centroid of area.}$$

It is assumed that the cross section of the wall remains a plane while bending, and the materials obey Hook's law; the strain varies linearly from the neutral axis and the flexural stress at a distance y from the neutral axis due to moment M is given by

$$\sigma_x = n_x M y / I_{comp} \quad (3)$$

Repeating the transformed-section method for the deteriorated host pipe (no grout or PVC) yields $Y_{NA} = 1.928$ and $I_{comp} = 5.722$.

Table 1 compares the responses of the two structures to moments by tabulating values of σ_x/M at maximum values of y_x .

<u>Material</u>	<u>Maximum y_x</u>	<u>Deteriorated</u>	<u>Rehabed</u>	<u>Reduction Ratio</u>
	Deteriorated; Rehabed	σ_x/M	σ_x/M	
Pipe Concrete	2.072; 2.886	0.3622	0.1758	0.485
Outer Cage	0.964; 1.886	1.2640	0.8619	0.682
Inner Cage	-1.790; -0.976	-2.3455	-0.5090	0.217
Grout	- ; -3.114	-	-0.1258	-
PVC	- ; -3.114	-	-0.01423	-

Table 1 Structural Responses to Moments at Pipe Crown

The benefit of the rehabilitation is evident from the reduction in the stress response to future additional flexural loads (moments) at the crown of the pipe. The stress response at the springline can be determined by applying a -M; i.e., pipe concrete and outer cage reinforcing are in tension (- stress), inner cage and grout/PVC are in compression (+ stress). The above analysis ignores the thrust forces which add to the compressive stress and subtract from the tensile stress; further this analysis is only valid if the pipe concrete has not cracked under tensile stress due to flexural loading. After cracking, the analysis of stress assumes all tensile forces are carried by the tension reinforcement and the compressive forces are carried by part of the compression portion of the section.

Once the magnitude of the load induced moment M has been determined then the state of stress of the deteriorated host structure can be determined. For example, assume $M = +1000$ in-lbF/in at pipe crown and -1000 at springline: the critical value is at the springline where the tension stress in the outer concrete is -362 psi, which is approaching the modulus of rupture of the 4000 psi concrete ($7.5\sqrt{4000} = 474$). An additional 112 psi of tensile stress in the rehabilitated structure, bringing the total tensile stress to the 474 psi modulus of rupture, would be produced by $112/0.1758 = 639$ in-lbF/in additional moment. Thus the -1000 in-lbF/in moment at the springline is being carried with a safety factor of 1.639; without rehabilitation the safety factor would be $474/362 = 1.309$. This analysis is based on the failure criteria being flexure cracking of the concrete; this is not true failure in terms of collapse and most undeteriorated reinforced concrete pipe has ultimate load capacity of about 50% more than the load producing concrete cracking. However, an elementary but tedious algebraic exercise to determine the shift in the neutral axis and the stresses after concrete cracking at the springline ($M = -1309$) shows that the tensile stress in the outer cage reinforcements is about 81% of the assumed yield strength of the steel (65,000 psi) or a safety factor over

ultimate load of 1.23. After rehabilitation as described above, the safety factor is increased to 1.42. Increasing the grout thickness and compressive strength will give a small increase in the safety factor. Current design practice (ASCE 15-93, 1993) for factory made RCP uses a load factor of 1.3 and strength reduction factors of 0.95 for reinforcement tensile yield and 0.9 for concrete radial tension; $1.3/0.9 = 1.44 =$ safety factor for 0.01" crack and $1.3/0.95 = 1.37 =$ safety factor for ultimate strength.

Of course, the calculated safety factors for the deteriorated pipe are illusory because the deterioration is on-going and the pipe will eventually fail if no action is taken to stop the deterioration. Further, the effectiveness of the rehabilitation in securing a satisfactory safety factor depends on effecting the rehabilitation while there is still load capacity in the host structure, i.e., adequate safety factor. Clearly, the first contribution of rehabilitation is the halting of the deterioration which preserves the structural capacity then existing; enhancing that capacity is an added bonus.

Rehabilitation Design

In general, the rehabilitation situation (pipes installed 25 -150 years ago) is highly uncertain in the knowledge of burial and soil conditions and pressure distributions and does not support or justify detailed assumptions and loading analysis. In fact, it is rehabilitation industry practice to calculate loads on buried flexible pipes using prism loads in Eq. A.20 of AWWA C950-88, which may not be appropriate for rigid pipes (or rigidly encased flexible pipe either). It is clear, however, that the rehabilitation must preserve and enhance moment handling capacity (i.e., flexural strength) of the deteriorated host concrete pipe if it is to remain a rigid structure.

Making conservative simplifying assumptions appropriate to the rehabilitation situation, the recommended design method for rehabilitation is as follows:

- Compute vertical loads on the structure (using prism loads (WRc 1990, page III/40) unless better information is available).
- Apply the calculated loads to the structure assuming uniform horizontal and vertical pressure distribution over full diameter of pipe with $K =$ horizontal pressure/vertical pressure; usually $K = 0.4$ (WRc 1990, page III/45). Again, if better information is available, use appropriate model (moments may vary by as much as a factor of 4 to 1.0, depending on assumptions about K and bedding of rigid pipe).
- Complete a structural analysis using transformed-section method, both before and after rehabilitation.
- Design wall thickness and grout compressive strength to achieve required safety factors by iterating the analysis for different combinations of grout thickness and strength.

This is a reasonable design method for the following reasons:

° The assumed pressure distribution allows reasonable modeling of soil side support and moment generating conditions.

° Using the modulus of rupture of the grout (alone) as the flexural strength to resist bending stress on the inner surface at the crown is 50 - 100% less than the flexural load carrying capability of the PVC/grout composite with reasonably small strains; see Figure 2.

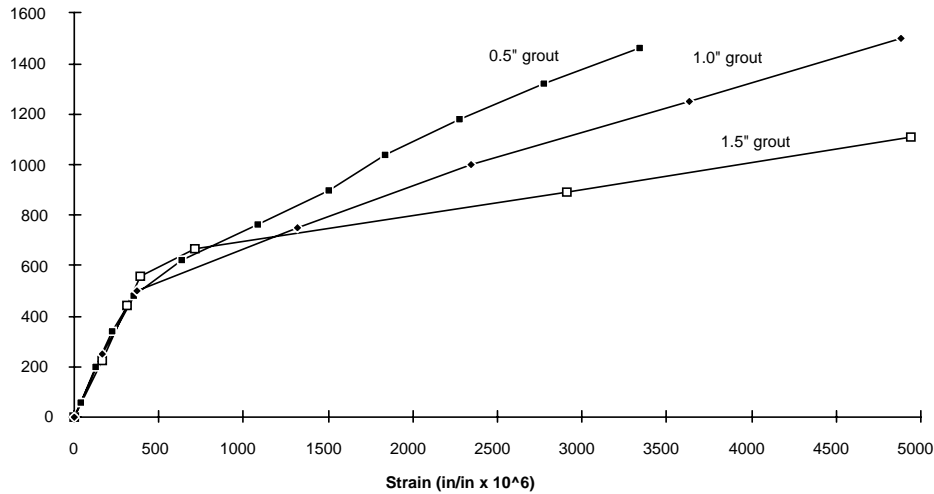


Figure 2 Flexural Stress/Strain for PVC/Grout Composite Beams

The data for Figure 2 are from laboratory tests following ASTM D 790-92 for three point loading and measuring beam deflection versus load. The composite beams consisted of 6" wide, 24" long PVC profile 0.5" high ("T" height) with 5000 psi (nominal) grout filling the space between the "T"s (0.5" grout case of Figure 2) and solid grout above the top of the "T"s. The "1.0" grout" and the "1.5" grout" cases of Figure 2 had 0.5" and 1.0" of grout, respectively, above the top of the "T"s. The composition of the cross sectional area was 75% grout and 25% PVC for the 0.5" grout case. The load was applied to the grout face of the beam (Ahmad and McAlpine 1994) which would be consistent with flexural loads on the liner system at the crown of a rehabilitated pipe.

° Compressive strength and flexural strength (modulus of rupture) used are based on 28-day values. The *Standard Handbook for Civil Engineers* (Merritt 1983, page 8-3) states "Concrete may increase significantly in strength after 28 days, particularly when cement is mixed with fly ash. Therefore, specification of strengths at 56 or 90 days is appropriate in design." This is true for both the grout and the pipe concrete.

The assumption is made in this design method that the grout does replace missing concrete in the host pipe wall and fills cracks that may have been acting as hinged joints, thus making the structure act as a homogeneous rigid pipe. The reasonableness of this assumption has been demonstrated in D-Load and Large Soil Cell tests (Ahmad and McAlpine 1994).

Conclusions

A design method has been presented for the structural rehabilitation of rigid pipes using high strength cementitious grout in conjunction with a plastic (PVC) liner which serves as formwork for the grout and a chemical barrier to prevent corrosion. The design variables are the thickness and strength of the grout; when needed, steel wire mesh can also be used in man-entry size pipes. Although this paper discusses only concrete pipes, the method should be applicable to other rigid structures such as circular brick pipe; non-circular structures may require modifying the details of the method or using an appropriately modeled finite element analysis.

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