Presented At
The ASCE Materials Engineering Conference On Infrastructure: New Materials And Methods For Repair
San Diego, California
November 13-16, 1994

Structural Characteristics of the Danby Pipe Renovation System

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Abstract

This paper describes a pipe renovation system and its structural characteristics which results in a PVC liner mechanically bonded to injected cementitious grout which in turn bonds to the inner wall of the host pipe.

Introduction

The Danby Pipe Renovation System produces a PVC liner mechanically bonded to the host structure by cementitious grout. Grouting of the annulus between the liner and the old pipe is an important (and integral) part of the Danby process in all applications. Annulus grouting not only provides important structural properties (the main topic of this paper), but also may produce some level of repair to the old pipe by filling cracks and voids. Figure 1 shows a sample of the PVC and grout while Figure 2 shows a core sample taken from a 54" RCP with PVC and grout.

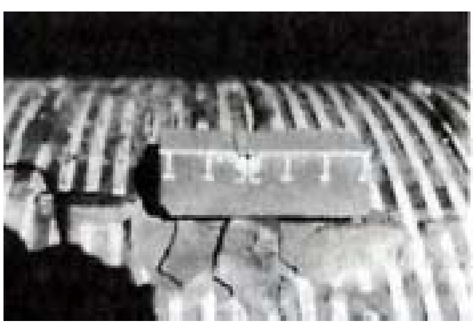

Figure 1. PVC/Grout Sample

Figure 2. Core Sample of Lined RCP

Recent tests have provided information on the structural properties of the Danby rehabilitation process. A test in the large soil cell at the Buried Structures Laboratory at Utah State University (Watkins, 1993) was performed to compare the strengths of two

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strings of broken, unreinforced, concrete pipes, one lined with the Danby system and the other unlined. Vertical pressure was applied and load-deflection data were recorded on both strings of pipe. In another test, two 8 foot sections of deteriorated (corroded), single steel ring reinforced concrete pipes were cut into four 4 foot sections; one 4 foot section from each 8 foot section was lined with the Danby system and the other half was tested as a control to provide baseline data. Two different configurations of Danby lining and the two corresponding control sections were then D-load tested under the supervision of staff from the County Sanitation Districts of Los Angeles County.

While the tests in Utah and California showed that the Danby system significantly increased the strength of the deteriorated pipes, it was felt that more fundamental data on the characteristics of the Danby materials themselves (PVC/grout) would be needed to fully understand how the system contributes additional strength to its host structure. Thus, tests were conducted at North Carolina State University to determine the flexural properties of beams made from grout only, PVC profile strip only, and PVC and grout together as found in field applications. Although the full range of these latter tests have not been completed as of this writing, beam tests completed have provided data which correlates well with the earlier pipe tests and helps explain the mechanism of strength enhancement the Danby system provides its host pipe.

The remainder of this paper deals in detail with these three tests, the analysis of the results, and the development of a reasonable engineering model of the physical system's behavior based on these test results.

Pipe Tests

Soil Cell Test (Utah State University) Ten 30 inch ID unreinforced concrete pipes were banded and broken into four quadrants with cracks at 9:00 and 3:00 and 12:00 and 6:00 o'clock. The sections were four ft. long with tongue and groove joints. They were placed in two parallel pipelines of five sections each in the large USU soil cell. Cracks were oriented. Dry silty sand was placed around them in lifts to just above the springlines. The bands were cut so that the backfill soil was all that held the broken pipes in conduit shape. Backfill was then continued in layers to six inches above the tops of the pipes. Except for personnel walking on the soil to place and level it, the soil was not compacted. One of the pipelines was lined with a 27" ID Danby liner and grouted in the annular space between the liner and the host pipe. The grout was allowed to cure for thirty days at which time it attained a strength of 8.6 ksi. Backfill was then continued on up to three feet above the tops of the pipes, and the load beams were pinned into place. Vertical soil pressure was applied in increments. After each increment of soil pressure, the diameters of the pipes were measured and the condition of each of the pipes was observed.

Figure 3 is the test results. Percentage ring deflections, $d = 100\ \Delta ID/ID$, are plotted as functions of vertical soil pressure, P. The upper graph is the Danby lined pipe. The lower graph is the unlined pipe.

The pressure, P, at zero ring deflection of the unlined pipe indicates a bit of precompression of the soil due to walking on it while placing and leveling the backfill layers by hand. The greater initial pressure, P', at zero ring deflection of the lined pipe includes the additional strength of about 3.1 ksf provided by the grouted liner.

Once the pipes begin to deflect under soil pressure, the ratio of slopes of the pressure-deflection graphs is about 1.4 to 1. This represents the greater ring stiffness of the lined pipe compared with the unlined pipe. Of course, the unlined pipe has no stiffness except that which is provided by backfill soil support.

Effects of Liner

Increase in Strength at d = 0,
P' - P = 3.1 ksf

Increase in Stiffness
Ratio of Slopes = m'/m = 1.4
or
m' - m = 8 ksf

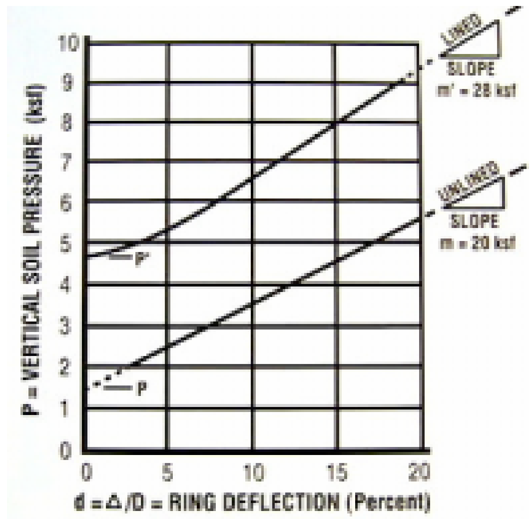

Figure 3. Utah Load-deflection Data for Lined and Unlined Pipes

After the test was completed, a postmortem was performed by uncovering the pipe and prying the quarter sections of the broken pipe away from the liner (see Figure 4). The visual evidence clearly showed that the grout had sheared along the top of the PVC profile T's but otherwise remained, for the most part, intact in two parts; one part, that between the top of the T's and the pipe wall, still firmly bonded to the pipe wall and the second part still within the PVC profile, between the T's. Further, close inspection revealed little cracking of the grout which remained within the profile except along the hinge line at the sides of the pipe (roughly at 3 and 9 o'clock). Although this shearing action could not be visually observed during the test, it was distinctly heard as loud "popping" noise as the lined pipe started to deflect. Obviously, this noise also accompanied the cracking of the grout bonded to the host pipe along longitudinal lines at the top and bottom, and possibly the sides, as the entire structure began deflecting as 4 rigid quarter sections hinged together at the sides. It is significant that the grout between the T's in the PVC profile remained intact and largely uncracked after almost 20% deflection. Further it is significant that this PVC/grout structure clearly added significant load carrying capacity as it deflected.

Figure 4. Postmortem After Utah Soil Cell Test

D-Load Test (Los Angeles County) Two 8 foot sections of 24" ID, corroded, single steel ring reinforced concrete pipe were cut into four 4 foot sections; one 4 foot section from each 8 foot section was lined with the Danby system. The other 4 foot section from each of the 8 foot sections was tested as the control for the corresponding lined section. The uncorroded wall thickness was 3" and the wall thickness lost to corrosion averaged about 1.25" in the top half of the pipe, with maximum loss at the springlines. There was evidence that the steel cage had begun corroding and was exposed in spots. The Danby system was used to line two of these 4 foot sections; one with lining covering approximately 270° of the interior wall, leaving the 90° in the invert of the pipe unlined and resulting in an internal vertical diameter of 23". The other Danby liner covered the entire inside of the host pipe and had an internal diameter of 20.75". The D-Load figures given below (Table 1) were calculated by dividing the total load on the pipe by 8 (= length x diameter of test pipe).

	Unlined	Lined (270°)	Unlined	Lined (360°)
First Crack (psf)	--	--	--	4250
.01" Crack (psf)	2375	4563 (193%)	2188	4750 (217%)
Ultimate (psf)	2375	4563 (193%)	2313	5250 (227%)

* Percentage of unlined test value

Table 1. D-Load Test Results

Laboratory Beam Tests (NCSU)

Following Test Method I of ASTM D-790 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, load-deflection tests were performed on beams of PVC profile only, and grouted PVC profile. The beams were simply supported 2" from each end of their 24" length while the load was applied at the midpoint where the deflection was measured. The beams were 6" wide and 0.5" deep (height of PVC profile). The beams of PVC and of PVC and grout were tested both with the load applied to the ribbed side and applied to the smooth side of the PVC.

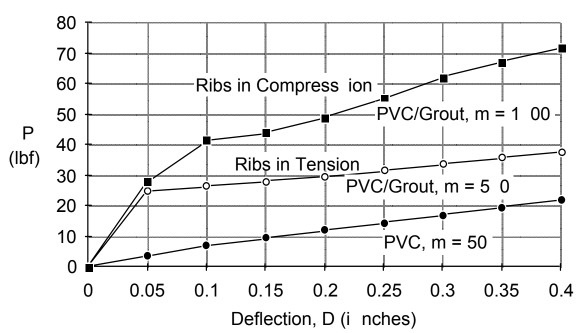

Figure 5. Load-Deflection

Figure 6. Expanded Scale

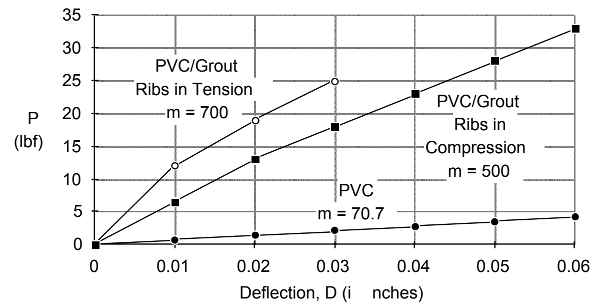

Figure 5 presents the test results for the load applied to the smooth side of the PVC which places the ribs or T's in tension, as well as the surface of the grout between the T's for the composite beam. Figure 5 also presents the load-deflection data for the load applied to the ribbed side of the PVC which places the top of the ribs or T's in compression, as is also the case for the grout between the ribs. Comparison of these two graphs shows the somewhat anisotropic nature of the PVC/grout beams.

It should be noted that the grout used in the tests of Figure 5 was cured only 7 days and had an estimated compressive strength of about 5000 psi (density of 105 pcf) and the data shown in the graphs are the averaged data of two composite (PVC/grout) beam tests. The data for the PVC beams are averaged data of 3 tests. The 0.5" high PVC profile has modulus of elasticity of about 400,000 psi, moment of inertia of approximately 0.004 in^4/in, neutral axis 0.18" above smooth surface face, and cross sectional area of 0.125 in^2/in.

The region of service operation in pipe rehabilitation is the very small deflection region where the slope of the load deflection curves are very steep, i.e. high modulus and high stiffness. Thus, Figure 6 presents the data from Figure 5 on an expanded scale so that these slopes may be more accurately measured and clearly illustrated.

Analysis of Test Data

Beam Tests Due to the profiled shape of the PVC beam and the nonhomogeneous nature of the PVC/grout beam, the equations given in ASTM D 790 can not be directly applied to the analysis of these test data. Rather, the following equation must be used:

$$D = PL^3 /48bEI \qquad (1)$$

from which, can be derived

$$EI = L^3 (dP/dD)/48b \qquad (2)$$

where:
D = maximum deflection of the center of the beam, in.
EI = flexural rigidity = Young's modulus E times moment of inertia I, lbf-in
P = load at a given point on the load-deflection curve, lbf
b = width of beam tested = 6 in.
L = support span = 20 in.
dP/dD = m = slope of the tangent to the initial straight-line portion of the load-deflection curve, lbf/in.

For the PVC and PVC/grout beam tests, EI = 27.8 m. For now the analysis will neglect the composite nature of the beam and estimate the "equivalent homogeneous beam" characteristics. Table 2 summarizes the pertinent characteristics derived from figures 5 and 6. (The transformed-section analysis yields EI = 17,571 in the rigid region.)

Characteristic	Ribs in Tension	Ribs in Compression
Rigid Region		
PVC m (EI)	70.7(1,965)	70.7 (1,965)
PVC/Grout m (EI)	700 (19,460)	500 (13,900)
Flexible Region		
PVC m (EI)	50 (1,390)	50 (1,390)
PVC/Grout m (EI)	50 (1,390)	100 (2,780)

Note: EI = 27.8 m

Table 2. Slope m and Flexural Rigidity EI Estimates

Because the grout used in these tests was relatively "green" (cured only 7 days), there may be significant differences in the compressive strengths in the grouts used in the tests of Figure 5 even though the same mix was used. Thus it may not be appropriate to make detailed quantitative comparisons of the two sets of data. However, some qualitative observations clearly seem justified from the data presented in figure 5:

1. Both beam orientations produce clearly defined regions of rigid (high stiffness) and flexible (lower stiffness) behavior. Note similarity in form to Utah data.
2. Both produce clear evidence that the PVC/grout beams have significant load capacity with small deflection in the rigid regions.
3. Both produce clear evidence that the PVC/grout beams have significant additional load capacity with moderate deflection in the flexible regions.
4. There is a definite difference in the stiffness of the PVC/grout beams in the flexible regions between the two load orientations, i.e., some anisotropy due to the PVC-grout interaction as no such phenomenon is observed for either PVC alone or grout alone.

Concerning the last observation, it may be that when the PVC ribs and the exposed surface of the grout between them are in compression, the opposite grout surface is in tension and the cracking there is impeded by the intimate contact with and confinement by the PVC, resulting in the observed increase in stiffness. No such confinement of the grout by the PVC exist on the opposite face when it is in tension.

It appears highly likely that, like the Utah test, the transition between rigid and flexible structure occurs when there is significant cracking of the grout (in shear or tension or both). This thesis is supported by the fact that the load at which the transition occurs corresponds fairly closely to the estimated flexural strength of the grout, about $7\sqrt{fc} = 495$ psi as well as the measured failure point of the grout beam. This stress occurs at approximately P = 25 lbf for a homogeneous beam, which correlates better with the ribs in tension case than with the ribs in compression case. Of course, once the grout cracks its modulus is reduced and, depending on the restraints placed on the physical movements of the grout particles, may become zero or even negative. (This is evident from a typical stress-strain curve for unreinforced concrete.) As the slope in the flexible region of the load-deflection curve for the PVC/grout beam in Figure 5 (ribs in tension) is approximately the same as the pure PVC beam it can be concluded that the modulus of the grout effectively has been reduced to zero in this case. By similar reasoning, the greater slope (2 to 1) of the PVC/grout beam compared to the pure PVC beam in Figure 5 (ribs in compression) indicates that the grout is still functioning as a structural element with positive modulus, i.e., adds stiffness. Note that even if the grout modulus is reduced to that of the PVC, the effective stiffness would still increase by about 2.6 times due to the higher moment of inertia of the uniform cross section (0.01042) compared to the PVC beam with a profiled cross section (0.004).

D-Load Test Because the D-load test was not instrumented to measure small deflections prior to the cracking of the pipe no load-deflection data is available from which to determine stiffness. However, the stiffness can be estimated by estimating the deflection from the occurrence of the 0.01" crack from the relation $w = t\,\partial$, where w = crack width = 0.01", t = pipe wall thickness in inches, and ∂ = D / pipe ID = deflection / pipe ID. Thus, ∂ = w / t and for the three wall thickness of these tests (1.75", 4", 4.625"), ∂ = .0057, .0025, .0022. The flexural rigidity EI can be determined using

$$\partial = 0.0186\,(Q/D) / (EI/D^3) \qquad (3)$$

where (Q/D) = D-load in psi, and D is the mean diameter of the pipe wall under test. Table 3 gives the values of the parameters from the D-load tests and the calculated flexural rigidities.

	(Q/D) psi	∂	D	EI
Unlined (270°)	2375/144	.0057	28.25	1,213,373
Lined (270°)	4563/144	.0025	26.00	4,143,630
Unlined (360°)	2188/144	.0057	28.25	1,117,836
Lined (360°)	4750/144	.0022	25.375	4,636,325

Table 3. Estimated Flexural Rigidity from D-Load Tests

The increases of the estimated stiffness factors from Table 3 for lined to unlined are 2,930,257 for the 270° lining case and 3,518,489 for the full 360° lining. If we assume that the only effect of increasing the wall thickness with the PVC/grout is to increase additively the moment of inertia (I) of the wall section, the increases in stiffness factors should be 3,189,538 and 6,654,168 respectively (based on 6000 psi compressive strength and 120 pcf grout). While the test result for the 270° lining case is very close to its theoretical increase value, clearly the composite PVC/grout/pipe is failing long before it has developed its full potential for increased stiffness in the full 360° lining case.

Unfortunately, no postmortem was performed on these D-load test specimens so there is no direct evidence of the nature or extent of the grout cracking as a result of the loading. However, it is quite likely that the grout sheared along the top of the PVC ribs as it did in the Utah test; adjusting the theoretical increase in stiffness for this loss of the inside 0.5" of effective wall thickness leads to a value of 3,751,207 for the 360° lining case. This is in very close agreement with the estimated value considering the roughness of this approximation.

Soil Cell Test (Utah State University) The two significant data that came from this test are 1) the PVC/grout lining increased the broken pipe's strength by 3100 psf and 2) it increased the stiffness from 20 ksf to 28 ksf or a 40% increase. Further, the load-deflection curve (Figure 3) clearly illustrates the two regions of rigid and flexible structure behavior (although no data were taken on the region of very small deflections).

To begin the search for theoretical support for the test results we will assume that the lined pipe begins to deflect when the flexural stress in the grouted pipe wall reaches the flexural strength of the grout. (Recall that the host pipe was previously cracked/broken and therefore has little resistance to deflection and would readily rotate in response to bending moments at the cracks <u>unless repaired by the grout</u>.) As stated earlier, the grout had a compressive strength of 8600 psi and a density of 120 pcf; thus the flexural strength can be estimated to be $7(8600)^{1/2}$ = 650 psi and the grout modulus is approximately 4,000,000 psi. Assuming a uniform cross section, and neglecting the effect of the PVC,

$$\sigma_f = 6M/t^2 - kPD/2t \qquad (4)$$

$$M = (1-k)P(OD)D /16 \quad (5)$$

where:
σ_f = flexural strength of grout = 650 psi
M = bending moment, lbf-in. /in.
k = ratio of vertical to horizontal pressures on pipe
t = wall thickness, in.
D = average diameter of wall, in.
OD = outside diameter of wall, in.

Substituting equation (5) into (4) and solving for P gives

$$P = \sigma_f /6 \, [(1-k)(OD)D /16t^2 - kD/2t] \quad (6)$$

and Table 4 gives values of P for four sets of conditions; grout ring only, ignoring presence of pipe, grout ring integrated with pipe wall, and both of these structures with k = 0 and 0.4. The condition k = 0 assumes no side pressure on pipe due to vertical pressure and K = 0.4 assumes good side support with few voids. Note also that (OD) = D + t.

t (in.)	D (in.)	P (psf), k = 0	P (psf), k = 0.4
1.5	28.5	656	1146
4.5	31.5	4457	8357

Table 4. Theoretical Vertical Pressure Required to Cause Wall Cracking

As the test data shows P = 4600 psf just before deflection begins, it is clear from Table 4 that, regardless of the true value of k, ***the grout has effectively integrated the pipe wall into a composite PVC/grout/pipe structure to a significant extent.***

In the flexible region of the load-deflection curve the grout has cracked along the top of the ribs and the PVC/grout structure is interacting with the pipe/grout structure which is being directly loaded by the vertical (and horizontal) soil pressure. The greater slope of the load-deflection curve for the lined pipe is attributed to the stiffness added by the PVC/grout structure. It is important to note that it was observed that the deflecting pipe was loading the PVC/grout structure with essentially line loads at the top and bottom with some indeterminate form of restraint to horizontal movement. (This action is a result of the four pipe fragments remaining as intact rigid structures of roughly quarter circular sections.)

By generalizing equation (3) to $\partial = c P / (EI/D^3)$, where P = Q/D and then it can be shown that $EI = c D^3 m$, where $m = dP/d\partial$ = slope of load-deflection curve. The value of c depends on the assumed restraint on horizontal deflection; c = 0.0186 for no restraint (as in D-load test) and c = 0.00146 for full restraint, i.e., fixed at springlines. Assuming that this relationship can be applied to only the increase in stiffness of 8000 psf (55.5 psi) of the PVC/grout structure whose mean diameter D = 27.5", we have EI = 21,521 for no restraint and EI = 1687 for full restraint. Using the Utah data in the Modified Iowa Deflection Formula yields EI = 14,442 and soil modulus of 228 psi. Also, the transformed-section analysis of the PVC/grout (8600 psi) structure yields EI = 26,901. These values are clearly within the range of flexural rigidity values determined from the laboratory beam test and support the thesis that the PVC/grout structure is capable of supporting significant loads as a rigid or flexible structure. Further, the Utah deflection data indicates that the PVC/grout was acting in its rigid (high stiffness) mode even after the grout cracked along the top of the T's.

Conclusion

This paper has documented test data and a consistent theoretical basis for the structural strength of the Danby pipe renovation system (PVC and grout) acting as a rigid or a flexible structure, depending on magnitude of load applied.

References

1. Watkins, R.K., Utah State University, Buried Structures Laboratory, Civil and Environmental Engineering, "Strength of Buried Broken Rigid Pipes with Danby Liners", Unpublished report to Danby of North America, Inc., December 1993.

SI Conversion Factors

1 psf = 48 Pa 1 psi = 6.9 kPa 1 lbf = 4.5 N 1 inch = 25.4 mm