Postfailure Behavior of Buried Pipe

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A study of the postfailure behavior and the safety of buried pipe is presented. A method based on soil-structure interaction is developed for the postfailure analysis. This method is applied to a deeply buried prestressed concrete pipe after complete loss of prestressing. The analysis is performed at two different cross sections along the pipeline. In one, the pipe is under open water and thus submerged; in the other, the pipe is inland, away from open water. The results of the analysis show that the soil surrounding the buried pipe can provide sufficient support to prevent high compressive stresses and excessive deformations, even after the pipe becomes a mechanism. Consequently, the failed pipe does not collapse.

Deeply buried prestressed and reinforced concrete pipe can fail after installation, and the failed pipe alone may not have the necessary strength to support the design loads. However, the pipe-soil system may be able to support the external loads. The solution to this problem may prolong the use of apparently failed pipelines or ensure the safety of persons working inside to rehabilitate the pipeline.

Buried pipe before failure resists the external loads acting on it by axial and bending strengths. Overload or loss of strength of a buried pipe through loss of prestressing or reinforcing, for example, may result in crack formation in the pipeline. In the case where the cracks first form at the invert and crown of the pipe, the cracking makes the pipe more flexible, and the deflection of the pipe increases. Accompanying the additional deflection of the pipe, the bending moment at the springline increases until cracks are formed at the springline. The pipe, having developed a mechanism, deforms into the soil until either a stable configuration is reached, with the pipe wall stress resultants in the uncracked quadrants below the cracking strength, or new cracks form in these quadrants.

This paper presents a method based on soil-structure interaction to analyze the postfailure behavior of buried pipe and applies the method developed to a practical problem.

METHOD OF APPROACH

The method of approach adopted in this study is based on (*a*) developing a procedure to predict the postcracking behavior of the pipe wall subjected to axial thrust and bending moment and (*b*) developing soil-structure interaction models that can predict the postfailure behavior of the buried pipe. The analysis was performed on a prestressed concrete pipe. The pipe wall construction is shown in Figure 1. The postcracking behavior of prestressed concrete pipe may be predicted using the procedures developed to analyze prestressed concrete pipe and by appropriately modifying the computer program UDP [Unified Design Procedure (*1*)] developed for this purpose. The soil-structure interaction analysis is performed by modifying the finite-element computer program SPIDA [Soil-Pipe Interaction Design and Analysis (*2*)] developed for studying soil-pipe interaction.

UDP computes the stresses and strains in the wall of a prestressed concrete cylinder pipe subjected to combined effects of moments and thrusts. The program considers the tensile softening and cracking of concrete in tension, the nonlinear stress-strain relationship for concrete in compression, cylinder yield in tension, and the nonlinear stress-strain relationship of prestressing wire in tension.

SPIDA discretizes the pipe into beam elements and both the in situ soil and the constructed backfill around the pipe into quadrilateral and triangular elements. The program performs an incremental analysis as backfill is placed in layers. Each soil element has a hyperbolic stress-strain relationship (*3*) that expresses the behavior of the soil up to failure. The values of soil parameters used in the model for each soil type are based on the experimental study of Selig (*4*). The validity of the model has been checked by comparing the calculated horizontal and vertical pipe deflections with the available test results on concrete pipe. [The model with Selig soil parameters was used to develop a new installation design basis for buried concrete pipe (*5*).] The soil types were selected based on the study of the actual soil investigation at the site, including the results of nearly 40 boring logs. The program considers the actual geometry of the trench or embankment, applies the constructed soils in layers, computes the incremental strains and stresses in both the pipe and the soil resulting from each soil layer, and superimposes the increment stresses to obtain the final stresses.

SPIDA was modified to handle postcracking behavior of the previously installed pipe after loss of prestress. Obviously, as the pipe loses prestress, its moment capacity decreases, and cracks develop at its invert, crown, and springline. Consequently, there will be significant redistribution of moments, as well as additional deformation of the pipe wall into the soil at springline. Failure of the pipe-soil system occurs by excessive deformation of the installed pipe.

The following changes were made to simulate the effects of the cracking of the pipe at invert, crown, and springline that may occur after installation is complete and prestress has been lost:

- After the installation of the pipe and introduction of water to the exterior of the empty pipe, if the invert or crown moments exceed the pipe moment capacities, plastic hinges are introduced at the invert and crown. The negative of the dif-

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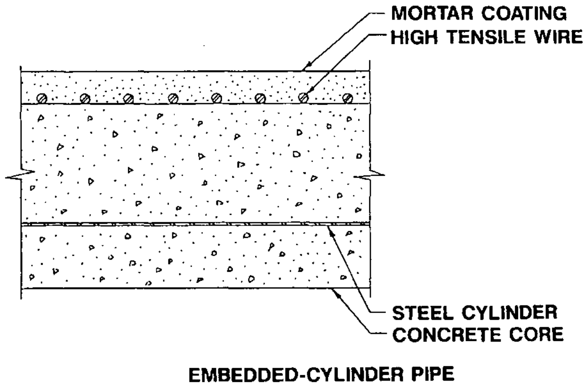

FIGURE 1 Cross section of pipe wall.

ference between the uncracked moment and moment capacity of the section for the existing thrust is applied to the pipe and the pipe-soil system is analyzed. This load increment will increase the springline moment and pipe deflection.

- If the moment at the springline exceeds the pipe moment capacity, new hinges are introduced at the springline and the negative of the difference between the uncracked moment and moment capacity is applied to the pipe in nine load increments and the resulting pipe-soil systems are analyzed. Because the pipe with four hinges is a mechanism, significant soil movement is expected to take place. Under these conditions, the thrusts at the crown and invert will increase as the pipe moves into the soil at the springline; simultaneously, the thrust at the springline will decrease. A large number of increments is used to prevent the numerical problems that result from excessive soil deformation.

In addition to the above changes, SPIDA was modified to incorporate the effect of water outside an empty pipe after the installation. In particular, the following changes were made:

- The soil weight was reduced to account for the buoyancy effect.
- The pipe weight was reduced to account for the buoyancy effect of the solid cross section of the pipe.
- The negative effect of water weight was applied to account for the emptiness of the pipe in water.
- A uniform water pressure was applied to the exterior of the pipe to account for the effect of the water height above the pipe.

APPLICATION

The foregoing procedure was applied to analyze an empty 2743-mm (108-in.) diameter embedded-cylinder prestressed concrete pipe. The pipeline was deeply buried and submerged and passed under a channel. The pipe had a 178-mm (7-in.) thick concrete core, a 16-gauge embedded steel cylinder with an outside diameter of 2858 mm (112.5 in.), and a 25-mm (1-in.) thick mortar coating applied on the exterior of core after prestressing.

The pipeline suffered one or two failures. An inspection of a limited part of the pipeline at the failure site revealed several 1.3-mm (1/20-in.) wide, 0.6-m (2-ft) long longitudinal cracks. Based on these observations, it was concluded that prestressing may have already been lost over a significant part of pipe circumference and length. A 55-m (180-ft) segment of the pipeline under the channel was subjected to internal inspection by a remotely controlled video camera. The inspection revealed a score of 0.6-m (2-ft) long longitudinal cracks at or near the invert, crown, and springline and one circumferential crack.

The pipe was subject to a hypothetical assumption of total loss of prestress, but the embedded steel cylinder was intact and watertight. The pipe, having lost all prestressing, would develop cracks wherever the moment exceeded the moment capacity. The results of analysis for two sections of the pipeline are presented here: one under the open water of the channel (Station A) and the other inland (Station B).

Moment Capacities of Pipe Wall after Loss of Prestress

A prestressed concrete pipe wall cross section at the invert or crown subjected to a fixed axial compressive thrust and a gradually increasing positive bending moment (i.e., producing tension inside the pipe) is considered. The pipe was assumed to have lost all its prestressing wires. The increasing bending moment first causes tension inside the pipe followed by tensile softening and microcracking and finally by visible cracking of the inner core. The steel cylinder, initially under compressive residual stresses resulting from creep and shrinkage of the core, would lose its prestress with increasing bending moment. With sufficient bending moment, the cylinder would go into tension, straighten, and detach from the outer core. From then on, the inner core and the cylinder did not contribute to the stiffness or to the strength of the section. The moment capacity was derived mainly from the eccentricity of the thrust within the pipe wall cross section.

The moment capacities at invert and crown were computed for different compressive axial thrusts at these sections. The variation of the bending moment at the onset of tension in the cylinder and the ultimate strength after the cylinder had pulled away from the outer core were computed and are shown in Figure 2. The variation of the ultimate moment capacity at the springline was computed based on the compressive strength of the inner core, accounting for the tension in the cylinder. The results are shown in Figure 3. The moment capacity increased with the compressive axial thrust at the springline.

Analysis of Submerged Pipe at Station A

The installation condition of the pipe at Station A and the soil types used in the model and compaction levels are shown in Figure 4. The major characteristics of this installation were as follows:

- The pipe invert is at Elevation −22.0 m (−72.0 ft).
- The in situ soil in the trench walls and under the pipe bedding was very stiff clay.
- The bedding consists of crushed stone or processed gravel, or a combination thereof, that was sized to be retained on a 10-mm (3/8-in.) sieve and to pass a 19-mm (3/4-in.) sieve.

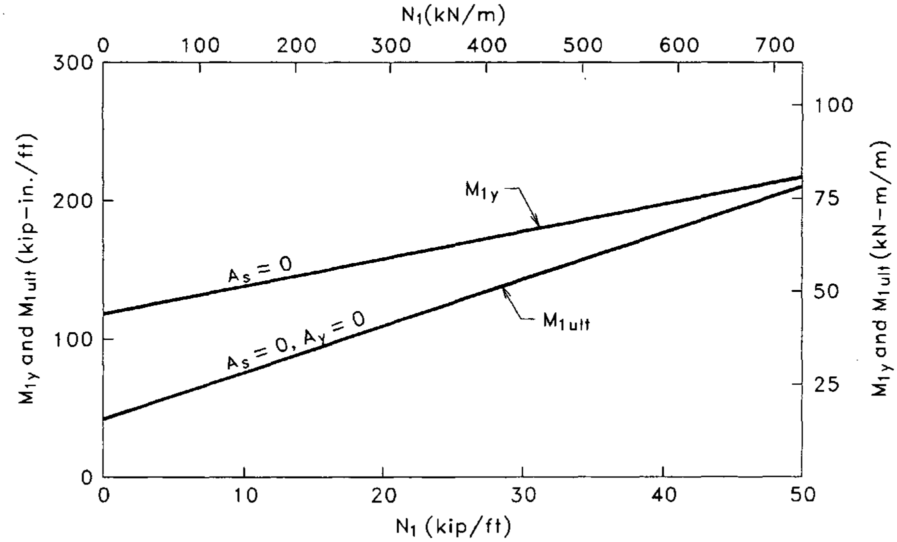

FIGURE 2 Variation of bending moment at onset of tension in steel cylinder, M_{1y}, and ultimate moment capacity, M_{1ult}, with axial thrust at invert and crown, N_1, calculated for the special case of zero wire area, $A_s = 0$, and zero steel cylinder area, $A_y = 0$.

- The backfill in the pipe zone is natural or processed sand with no more than 15 percent passing a No. 200 sieve and 100 percent passing a 10-mm (⅜-in.) sieve.
- A soft soil support was assumed to exist in the haunches of the pipe.
- A 0.15-m (6-in.) thick concrete mat was placed over the backfill.
- The rock fill placed over the concrete mat in the trench was well graded, 25 mm (1 in.) to 305 mm (12 in.) with a minimum of 50 percent to be retained on a 152-mm (6-in.) sieve.
- The bedding, the backfill in the pipe zone, and the rock fill were placed by the tremie method.
- The mud was assumed to extend from the top of rock fill to Elevation −3.0 m (−10.0 ft), that is, about 16 m (52 ft) above the top of the pipe.
- The water level was at Elevation +0.9 m (+3.0 ft).

The results of analysis for the empty pipe with total loss of all prestressing wires are summarized in Tables 1 and 2. The results show that both the invert and the crown of the pipe, after the loss of all prestressing wires, developed cracks. The cylinder would go into tension, straighten, and then separate from the outer core. The installation bending moments in excess of the moment capacity at the invert and the crown would shift to the springline and cause the pipe wall to crack

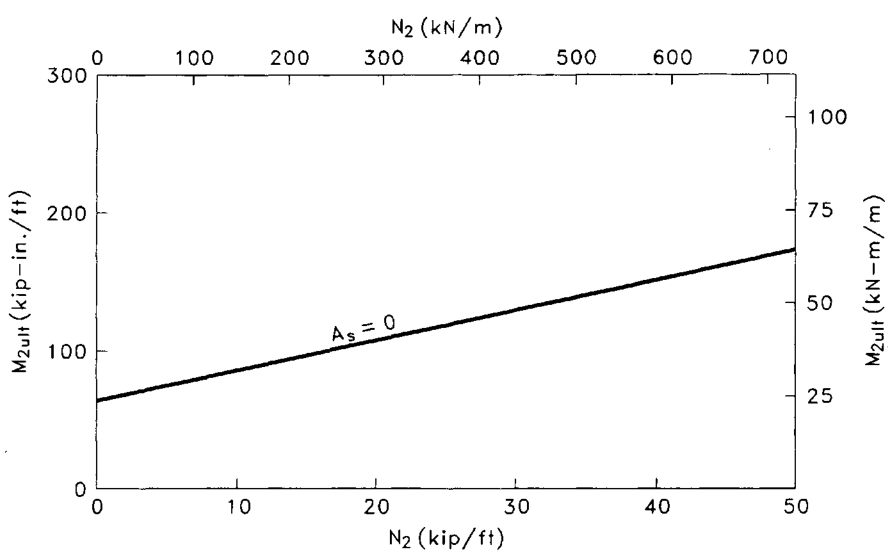

FIGURE 3 Variation of ultimate bending moment capacity, M_{2ult}, with axial thrust at springline, N_2, for the special case of zero wire area, $A_s = 0$.

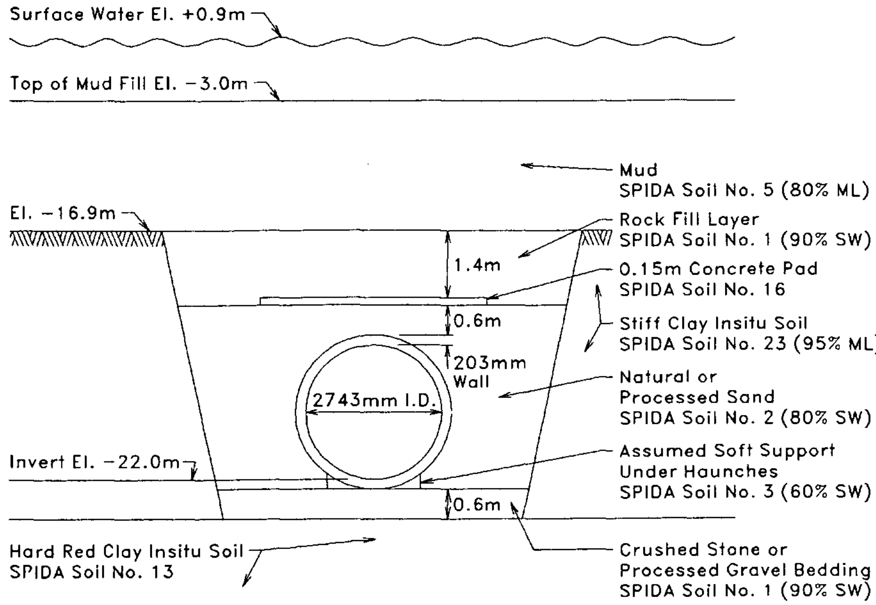

FIGURE 4 Installation condition of submerged pipe at Station A (standard proctor compaction values and soil types are shown in parentheses).

TABLE 1 Calculated Pipe Deformations at Stations A and B Before Cracking (with Prestress) and After Cracking (with No Prestress)

	At Station A		At Station B	
	Vertical mm (in.)	Horizontal mm (in.)	Vertical mm (in.)	Horizontal mm (in.)
Before cracking	14 (0.56)	13 (0.52)	5 (0.21)	5 (0.20)
After cracking				
Without concrete mat	29 (1.13)	101 (4.00)	–	–
With concrete mat	37 (1.46)	64 (2.52)	34 (1.35)	47 (1.85)
After backfill migration into bedding	39 (1.53)	82 (3.21)	–	–
With softer insitu clay for saturation effect	47 (1.85)	74 (2.91)	38 (1.49)	47 (1.86)

TABLE 2 Calculated Pipe Deformations at Stations A and B Before Cracking (with Prestress) and After Cracking (with No Prestress)

	At Station A		At Station B	
	Thrust kN/m (kip/ft)	Moment kN-m/m (kip-in./ft)	Thrust kN/m (kip/ft)	Moment kN-m/m (kip-in./ft)
Before Cracking				
Invert	393 (26.9)	198 (534)	66 (4.5)	70 (188)
Crown	354 (24.2)	149 (399)	115 (7.9)	53 (144)
Springline	703 (48.1)	138 (371)	245 (16.8)	58 (156)
After Cracking				
Invert	454 (31.1)	56 (150)	88 (6.0)	24 (65)
Crown	428 (29.2)	53 (143)	139 (9.5)	28 (75)
Springline	639 (43.7)	60 (162) 71 (132)	240 (16.4)	38 (100)

1 k/ft = 14.612 kN/m; 1 k-in./ft = 0.3711 kN-m/m

at the springline. As cracks developed at the springline, the pipe deformed into the soil; the thrusts at the invert and the crown increased from 393 and 354 kN/m (26.9 and 24.2 kips/ft) to about 454 and 427 kN/m (31.1 and 29.2 kips/ft), respectively, and the thrust at the springline decreased from 703 kN/m (48.1 kips/ft) to about 639 kN/m (43.7 kips/ft). In this process, the pipe underwent diametrical deformation of about −37 mm (−1.46 in.) vertically and +64 mm (+2.52 in.) horizontally. (The plus sign indicates an increase in the diameter of the pipe.) Note that the calculated pipe deflections do not account for the creep of pipe material, the creep of backfill and in situ soil, and the migration of backfill material. The effect of the creep of pipe is expected to be negligible. The backfill is sand and is not expected to creep. A discussion of the effect of migration of the backfill into the gravel bedding follows separately.

The moment capacity at the invert, with a thrust of 454 kN/m (31.1 kips/ft), was about 56 kN-m/m (150 kip-in./ft). The moment capacity at the crown, with a thrust of 427 kN/m (29.2 kips/ft), was 53 kN-m/m (143 kip-in./ft). The moment capacity at the springline, with a thrust of 639 kN/m (43.7 kips/ft), was about 60 kN-m/m (162 kip-in./ft). After moment redistribution, the bending moment just below the springline was 71 kN-m/m (192 kip-in./ft) and therefore exceeded the moment capacity of 60 kN-m/m (162 kip-in./ft). Additional cracking was expected just below the springline. The additional redistribution and the resulting increase in the horizontal diameter of the pipe are not reported here for the sake of brevity.

The gravel bedding may allow the sand backfill to migrate away from the soil and loosen the sand support underneath the pipe. To investigate the sensitivity of the installed pipe to migration of backfill underneath the pipe into the gravel bedding, the compaction level of the column of the soil underneath the pipe and just outside of the assumed standard soft haunches was reduced to 60 percent of the maximum density, as tested by the Standard Proctor method (ASTM D698-64T). The results show that under such a condition, the diametrical deformation of the pipe increased in magnitude from −37 mm (−1.46 in.) to −39 mm (−1.53 in.) vertically and from +64 mm (+2.52 in.) to +82 mm (3.21 in.) horizontally.

The concrete mat over the pipe played a very important role in diverting the earth load away from the pipe. In the absence of the concrete mat, the diametrical deformation of the pipe would be −29 mm (−1.13 in.) vertically and +102 mm (+4.00 in.) horizontally. Note that by omitting the concrete mat, the resulting increase in the horizontal deformation would have been 59 percent.

Because the saturated condition in the stiff clay may lower the soil modulus, a sensitivity analysis was performed by reducing the in situ soil modulus from that which corresponds to 95-percent maximum density, as tested by the Standard Proctor method to 90 percent, while the constructed soil moduli remained unchanged. The results show that the deflection of the pipe increased in magnitude from −37 mm (−1.46 in.) to −47 mm (−1.85 in.) vertically and from 64 mm (2.52 in.) to 74 mm (2.91 in.) horizontally. Note that the increase in the horizontal diametrical deformation is 15 percent.

Analysis of Inland Pipe at Station B

A second pipe installation along the same pipeline was analyzed. In this installation because the pipe was under groundwater but not under open water, a rupture of the pipe would not cause a rapid inflow of water, thus endangering personnel in the pipe.

The installation condition at Station B and the soil types used in the model and compaction levels are shown in Figure 5. The major characteristics of this installation were as follows:

- The pipe invert was at Elevation −4.7 m (−15.5 ft).
- The in situ soil in the trench walls and under the pipe bedding was sandy clay or soft sandy clay with silt seams, and organic with clay seams.
- The bedding was 0.9 m (3 ft) total below the pipe invert and consisted of 0.45 m (1.5 ft) of cement-stabilized sand. The cement-stabilized sand consisted of a mixture of 3.2 sacks

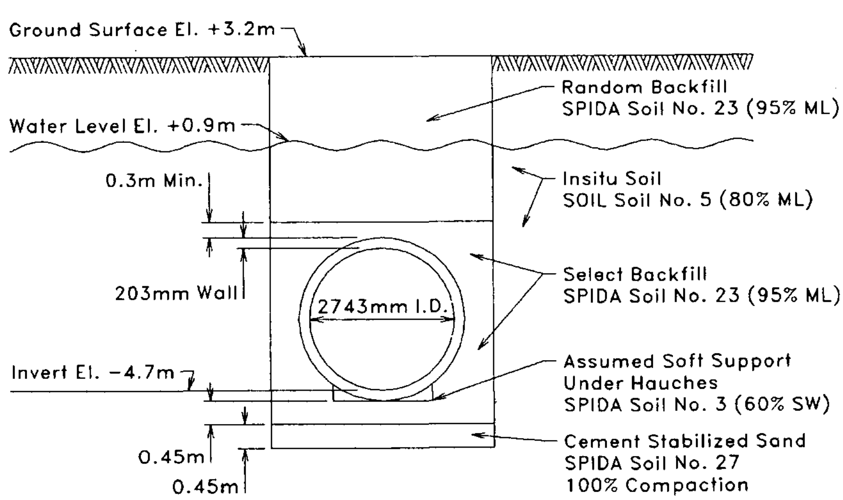

FIGURE 5 Installation condition of in-land pipe at Station B (standard proctor compaction values and soil types are shown in parentheses).

of cement/m^3 (2.5 sacks of cement/yd^3) of natural sand with liquid limit (LL) of 25 or less, plasticity index (PI) of 4 or less, and with less than 50 percent passing a No. 200 sieve. The cement-stabilized sand was applied over the undisturbed trench bottom. The remaining thickness of bedding consisted of select backfill material with LL, PI, and the gradation as described above.

- The backfill in the pipe zone was natural sand with LL, PI, and gradation as described above.
- A soft support was assumed to exist in the haunches of the pipe. This was a conservative assumption made to simulate the probable lack of adequate compaction in the haunches of the pipe, even though the installation was in a dry trench.
- The bedding and backfill material in the pipe zone were placed in loose lifts of 0.2 m (8 in.) or less and were compacted to 60 percent relative density (ASTM D2049-64T) or to 95 percent of maximum density as tested by the Standard Proctor method.
- The random backfill applied over the backfill in the pipe zone consisted of clays, sandy clays, and clayey sands obtained from the material excavated and compacted to 95 percent of maximum density as tested by the Standard Proctor method.
- The water level is at Elevation +0.9 m (+3.0 ft). Below this elevation, the soil weight and the pipe weight were reduced for the buoyancy effect and the external water pressure was applied to the pipe. Above this elevation, the actual weights of the random fill were used.

The results of the analysis for the empty pipe after loss of all prestressing wires are summarized in Tables 1 and 2. The results show that the pipe cracked at the invert and the crown. The cylinder at the invert and the crown went into tension and thus pulled away from the outer core. The installation bending moment in excess of capacity at the invert and the crown shifted to the springline and cracked the pipe wall at the springline. The cracked pipe deformed into the backfill. The thrust at the crown and invert increased from 66 to 115 kN/m (4.5 and 7.9 kips/ft) to 88 and 139 kN/m (6.0 and 9.5 kips/ft), respectively, and the thrust at the springline decreased from 245 to 240 kN/m (16.8 to 16.4 kips/ft).

The moment capacities at the crown and the invert were about 24 and 28 kN-m/m (65 and 75 kip-in./ft), corresponding to the thrusts of 88 and 139 kN/m (6.0 and 9.5 kips/ft), respectively. The moment capacity at the springline, which was about 37 kN-m/m (100 kip-in./ft) for a thrust of 240 kN/m (16.4 kips/ft), was also exceeded. The diametrical deformation of the pipe was −34 mm (−1.35 in.) vertically and +47 mm (+1.86 in.) horizontally. No other cracks were expected to form in the pipe wall between the invert and the springline.

The signs of distress at this station were expected to be similar to those described for pipe at Station A. However, because the compressive thrusts were much less than those at Station A, cracks formed during the service operation may remain open, that is, the compressive thrusts may not be large enough to close these cracks.

To account for the lower modulus of saturated clay, a sensitivity analysis was performed for this installation by reducing the in situ soil modulus from 80 percent of maximum density as tested by the Standard Proctor method to about 65 percent while maintaining the constructed soil moduli. The results show that the diametrical deformation of the pipe increased in magnitude from −34 mm (−1.35 in.) to −38 mm (−1.49 in.) vertically, but remained the same horizontally at 47 mm (1.86 in.).

DISCUSSION OF RESULTS

Pipe deflection; longitudinal cracks at the invert, the crown, and near the springline; and possible separation of cylinder from the outer core at the invert and the crown are the expected signs of distress.

The following types of distress signs are not predicted by this analysis and indicate that the pipeline may be in danger of collapse and that additional safety measures should be considered:

- Increase in horizontal diameter or decrease in vertical diameter that are more than the calculated value of 64 mm (2.5 in.).
- Leakage or water flowing in the pipe, except at joints.
- Cracks or distress on the inside wall of the pipe at the springline in the form of multiple circumferential (vertical) fine cracks that indicate a very high compressive strain.
- Hollow sounds, when the liner is tapped with a hammer near the cracked crown and invert, extending circumferentially for significantly more than 305 mm (12 in.), accompanied by a large vertical deformation. These signs may indicate that water under external pressure is behind the steel cylinder. The buckling process, if it occurs, could lead to rupture.

CONCLUSION

A method based on soil-structure interaction was developed for the postfailure analysis of buried pipe. The failed pipe, having only a limited capacity for bending, may crack and produce a mechanism. The soil surrounding the pipe supports the pipe against excessive deformation and collapse. This method was applied to a deeply buried prestressed concrete cylinder pipe after complete loss of prestressing at two sections along the pipeline: one under open water, the other inland. The results of the analysis show that the soil surrounding the buried pipe can provide sufficient support to prevent the excessive deformation, the high compressive stresses in concrete core, and the collapse of the pipe.

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