Concrete-Soil Structure Interaction Systems--are recommended.

SUMMARY

The primary use of prestressed pipe to date has been for pressure pipe installations. In Caltrans, it has been limited to special drainage designs and has been considered a semirigid design. The prestressed concrete pipe research reported in this paper, coupled with the reinforced concrete pipe research by Hydro-Conduit using pipes that share common dimension ratios and Ameron prestressed concrete pipe designs, gives further support to the dimension ratio concept.

Prestressed concrete pipe continues to offer an acceptable alternative for special drainage designs--i.e., where there is an unstable soil condition in a potential slide area. Under high fills it is not recommended, since there is admittedly the adverse effect of the earth loads being added to the prestressing forces.

ACKNOWLEDGMENT

The Caltrans Culvert Committee and Ameron cooperated and participated fully in the initiation of the prestressed concrete pipe culvert research at Cross Canyon and the selection of the design parameters to be considered. Walt Creasmon of Ameron contributed significantly to the initiation of the prestressed concrete pipe research proposal and, most recently, to this paper on design summary and implementation.

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Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe

REYNOLD K. WATKINS, RONALD C. REEVE, AND JAMES B. GODDARD

Corrugated polyethylene pipe, developed originally in 4- to 12-in diameters for land drainage, is now manufactured in larger diameters for other uses of buried conduits such as culverts, air ducts, and service conduits. Tests were conducted on pipes with 15-, 18-, and 24-in inner diameter to investigate the structural performance and performance limits of these larger-diameter pipes when subjected to external soil pressures. For pipes in typical native soil backfill, compacted by typical methods to greater than 80 percent standard density (AASHTO T-99), less than 1 ft of soil cover (called minimum cover) was found to be adequate protection against H-20 (32-kip/axle) loads and up to 54-kip/axle "super-loads". The soil envelope does not have to be select material. At less than minimum cover, the performance limit is either (a) excessive pipe deflection or (b) localized reversal of curvature directly under the wheel load. Under high soil cover, both the performance and performance limit are pipe deflection (out-of-roundness), which is a function of the total vertical soil pressure and is equal to or slightly less than vertical-soil strain in the backfill material on both sides of the pipe, herein referred to as sidefill. In compacted soil backfill, pipe deflection is less than 10 percent for either H-20 loads on minimum soil cover or vertical pressures up to 2500 psf under high soil cover. Pipe stiffness is roughly equal to steel and is greater than aluminum in 16-gage, 2-2/3 x 1/2 corrugations.

Corrugated plastic pipe is one of the leading pipe materials used for land drainage in the United States. It was introduced in the late 1960s, beginning with small inner diameters (ID) (3 and 4 in), which were used primarily for agricultural land drainage. During the 1970s the uses for corrugated plastic pipe greatly increased. Sizes up to 15-in diameter were developed, and applications were extended to highway drainage and to various residential and commercial construction uses, including foundation drainage, home sewage disposal, and grain aeration. With the introduction of 18- and 24-in pipe in 1981, the uses for corrugated plastic pipe again expanded to a still wider range of applications, including mining, culverts for roads and driveways, and other types of entrance and ditch crossing applications.

In 1979, field loading tests were conducted at Hamilton, Ohio, to evaluate the structural performance of 12-in corrugated polyethylene pipe for various types of culvert installations (1). With the recent development of the larger pipe diameters (18 and 24 in), the following additional questions arise.

Are there any structural limitations pertaining to these larger-diameter pipes when they are subjected to heavy external soil pressures? Subdrainage pipe is often backfilled with gravel or similar material that provides a filter for the inflow of ground water but also provides radial support for the pipe. If the pipe is used for purposes other than subdrainage (i.e., culvert), a select backfill material is not needed as a filter. But is it needed as support for the pipe? Most drainage pipe is installed in trenches and at shallow depths that can be excavated by a backhoe or wheel trencher or plowed in with a drainage plow. The most critical pipe loadings are surface wheel loads usually no heavier than H-20 truck loads, the highest legal highway wheel loadings. Can buried polyethylene pipe, with minimum cover, resist the super heavy wheel loads of construction equipment, off-highway trucks, etc.? Can corrugated polyethylene pipe be buried under very high embankments or in very deep trenches? What about pipe stiffness?

To answer these questions, field tests were conducted at London, Ohio, by Utah State University (USU) in cooperation with Advanced Drainage Systems, Inc., to investigate the effect of heavy loads passing over shallow buried corrugated polyethylene pipe. An additional series of tests conducted at USU used a pressure soil test cell to simulate the effect of great depths of cover, which in some cases can result in very high soil pressures. Comparative tests were conducted by the Wadsworth Testing Laboratory of Canton, Ohio, and by USU on the stiffness of functionally equivalent corrugated pipes of steel, aluminum, and polyethylene.

NOTATION

The following notation is used in this paper:

- D = nominal pipe diameter = inside diameter (in),
- d = depth of corrugation (in),
- Dm = mean diameter of pipe = D + d (in),
- B = width and height of select soil envelope, usually gravel (in) (in this study, width and height were equal),
- H = height of cover above the top of the pipe (in),
- H/D = ratio of height of cover to nominal pipe diameter (dimensionless),
- Δy = vertical pipe deflection (in),
- $\Delta y/D$ = ratio of decrease in vertical diameter to the original circular diameter (dimensionless),
- γ = soil density based on AASHTO T99, applied to native soil in situ, or after compaction of soil backfill (pcf),
- P = vertical soil pressure at the top of the pipe (psf),
- ε = vertical soil strain (in/in), and
- $F/\Delta y$ = pipe stiffness (lb/in of length ÷ in of deflection).

MINIMUM COVER TESTS

Procedure

A test course of seven pipe runs was set up at a site near London, Ohio, as shown in Figure 1. Each pipe run consisted of two 20-ft sections coupled together at the midpoint (the midpoint was not a measurement point). The objective of the testing program was to determine, for buried corrugated polyethylene pipe, the relation of pipe deflection to height of soil cover under large wheel loads at various backfill densities.

Loads

A single-axle H-20 load, 16 kips/dual wheel, was used as the basic load, but "super-loads" up to 27 kips/wheel, as might be applied by heavy off-highway equipment, were also investigated. The standard truck H-20 rear axle load of 32 kips was simulated by use of a John Deere model 762 scraper. The front wheels of the loaded scraper (16 kips each) were centered directly over the pipe as shown in Figure 2.

Deflection

The pipe deflection under each wheel was measured by using a spring-loaded, direct-reading deflectometer (see Figure 3). Deflection was measured to the nearest 1/16 in at five loading positions at 3-ft spacings on each side of the midpoint of each 40-ft pipe run, which made a total of 10 measuring points/pipe. As the testing proceeded, it became apparent that deflections were less than 5 percent even when the height of cover was less than 12 in. To obtain a wider range of deflections, it was decided to remove cover from the shallow end of each pipe run and to test the pipe with the H-20 load at zero cover.

Cover

The pipes were installed in sloping trenches and backfilled to the original soil level (as shown in Figure 1) to provide a continuously decreasing height of cover from one end of each pipe run to the other. The height of cover was determined from elevations taken along the pipe before and after backfilling.

Materials

Three sizes of corrugated polyethylene pipe were tested: 15-, 18-, and 24-in diameters. The recently developed 18- and 24-in-diameter pipes are manufactured with a slightly angled helical corrugation of approximately 2°. These sizes were compared with the annularly corrugated 15-in-diameter pipe manufactured by the continuous extrusion and corrugating process. The pipes used in the tests were representative of standard production material. The high-density polyethylene resins used in the manufacture of the pipes complied with the requirements of Type III, Class C, category 5 as defined and described in ASTM D1248. The pipe stiffness values recorded on the test specimens exceeded the proposed minimum pipe stiffness requirements of large-diameter pipe of 40 psi at 5 percent deflection and 30 psi at 10 percent deflection.

As shown in Figure 1, the testing was designed for three soil densities: 75, 85, and 95 percent American Association of State Highway and Transportation Officials (AASHTO) standard density. The native soil at the site was used as backfill on six of the seven pipe runs. Uncompacted gravel backfill (AASHTO coarse aggregate 57, uncompacted) was used on run 3. The backfill soil was a mixture of two strata: a 2.5-ft stratum of sandy clay silt (Unified Soil Classification CL) and a sandy silty clay from below that depth (CL).

The soil backfill around the pipe was compacted by mechanical power tampers as shown in Figure 4. For pipe runs 1, 2, 5, 6, and 7, the soil was compacted in successive lifts of about 6-10 in each, depending on the desired degree of soil density. More lifts and more passes achieved greater density. The soil backfill for pipe run 4 (75 percent specified density) was dumped on and around the pipe with a loader and spread with a dozer blade; there was no compaction except the slight compaction due to the D-6 crawler dozer passing over the completed backfill with a track pressure less than or equal to 3 psi. A specified density of 75 percent usually indicates uncompacted or very lightly compacted soil. The density of the soil was checked with a Troxler nuclear densitometer at several stations along the pipe and at various levels as the backfilling progressed.

Results

The results of the tests for minimum cover on 24-in-diameter pipe subjected to H-20 loads are shown in Figures 5 and 6, where $\Delta y/D$ is plotted as a function of both height of soil cover in inches and the dimensionless soil cover term H/D. The dashed curves are power curves of the form ($y = bx^m$) that represent the best-fit curves of the data for the 24-in pipe at the three average soil densities of the field tests--95.8, 91.8, and 75.0 percent. Because the soil densities attained on pipes 5 and 7 were nearly equal, the data were combined for analysis.

For purposes of design, plots of 95 percent confidence levels were evaluated by using the 24-in pipe data for soil densities of 75, 80, 85, 90, and 95 percent standard AASHTO density. These are shown in Figure 6. The 95 percent confidence level plot is that plot below which 95 percent of all test data fall. The test data for pipe 3, uncompacted gravel

Figure 1. Minimum cover test layout at London, Ohio.

PIPE Run No.	D (in.)	Backfill	Density Specified (%)	Density Achieved (%)	HEIGHT OF COVER H_1 (in.)	DIA. (in.)	H_2 (in.)
1	15	soil	85	85.7 ±2.7	5	15"	20
2	18	soil	85	85.2 ±1.5	8	18"	20
3	24	gravel	uncompacted		8	24"	24
4	24	soil	75	75 ±3.5	6	24"	30
5	24	soil	85	90.8 ±1.3	6	24"	24
6	24	soil	95	95.8 ±3.4	6	24"	24
7	24	soil	95	92.5 ±1.5	16	24"	40

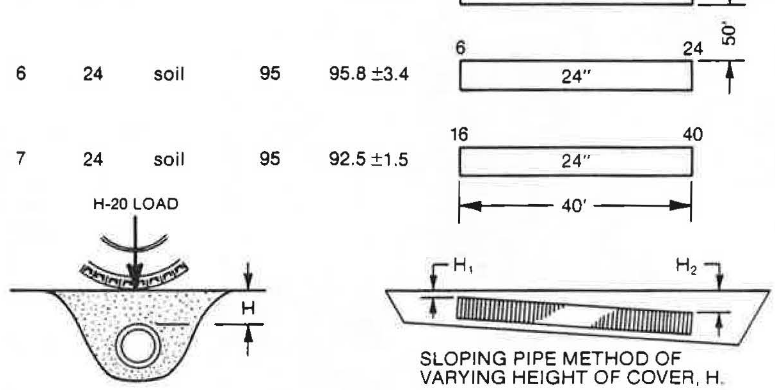


Figure 2. H-20 standard truck load (32-kip axle load), simulated with John Deere scraper, being positioned for deflection measurement.

backfill, are also shown in Figure 6. These data fall within the range of cover from 20 to 30 in. The performance of the gravel backfill was similar to that of soil backfill at 95 percent density.

For most pipe installations, the maximum allowable ratio of deflection would be set at $\Delta y/D$ = 10 percent by the design engineer. This includes a safety factor of 2 based on an assumed performance limit of $\Delta y/D$ = 20 percent. Thus, the safety factors inherent in Figure 6 for 24-in pipe are generally adequate for design.

For comparison of all three diameters, Figure 7 shows the 95 percent confidence levels for minimum

Figure 3. Spring-loaded, direct-reading deflectometer.

cover at 85 percent soil density for all three diameters under H-20 loads. The apparent reversal of positions of the 15- and 18-in curves left of H = 16 in indicates that localized anomalies begin to affect the deflection at very low soil cover. It was observed that with less than a foot of soil cover the deflection is sensitive to tire tread and tire pressure, surface finish (cut by blade after compaction or filled, i.e., backraked by blade), surface soil type, moisture content, etc. This is to be expected since at very shallow heights of cover live loads are not uniformly distributed to the underground conduits. It is also noteworthy that to the right of H = 16 in the 24-in-ID plot is lower than the other two, which indicates that a 24-in-ID pipe is relatively deeper in the pressure bulb under an H-20 dual wheel than are the smaller pipes. For the H-20 load, separate plots of $\Delta y/D$ versus H for each pipe size are proposed as shown in Figure 7. Further details concerning the effects of loads are given by Watkins and Reeve (2).

Figure 4. Compacting backfill with powered tamper.

Based on the assumption that the effects of the backfill density on the 24-in pipe are similar for the 15- and 18-in sizes, a curve-fitting technique was used to interpolate the relation between percentage deflection and height of cover for intermediate soil densities of 80, 85, and 90 percent. These relations for 15-, 18-, and 24-in pipes are given in Tables 1-4. The values in Tables 1 and 2 are average values from the best-fit curves. The values given in Tables 3 and 4 are at the 95 percent confidence level. Tables 1 and 3 give percentage deflection for various heights of cover, and Tables 2 and 4 give height of cover for various percentage deflections. Tables 3 and 4, at the 95 percent confidence level, should be used for design.

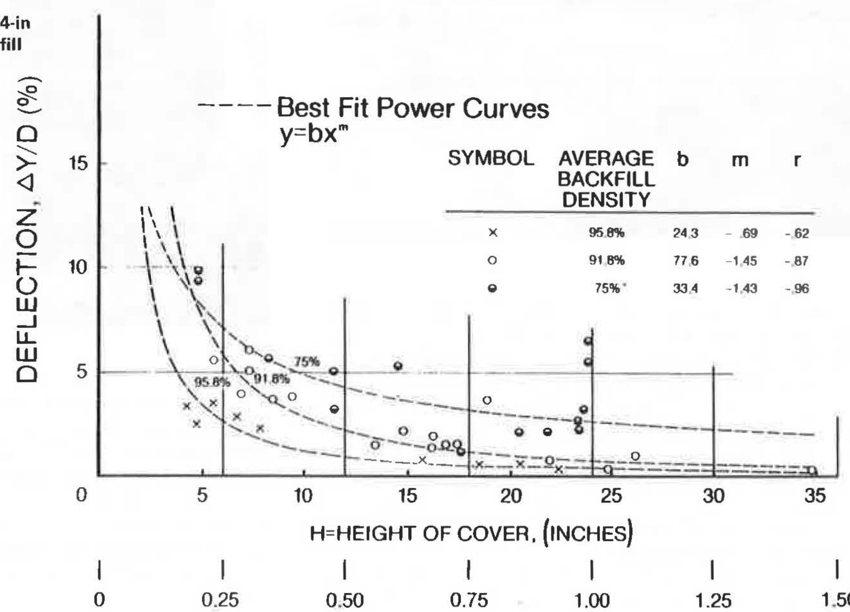
Super-Loads

In some applications, loads from off-highway-type vehicles, such as large scrapers, may need to be taken into account in the design process. A superload of 54 kips on one axle was achieved by teetering a loaded John Deere model 762 scraper on its blade. This was done by using the blade as a fulcrum to raise the tractor axle off the ground with the machine's hydraulic system. The blade bore on timber blocks cut to simulate single-wheel imprint areas of 12x24 in each. Where the soil cover was less than 6 in, the 27-kip wheel loads sheared through the pipe. For pipe 4 at 75 percent soil density and soil cover ranging from 20 to 24 in, the pipe deflection ranged from 3 to 7.5 percent. Where the cover exceeded about 12 in, the pipe deflection was not significantly greater than that for the H-20 standard AASHTO truck loading.

HIGH SOIL PRESSURE TESTS

The USU soil pressure test cell (see Figures 8 and 9) was used to evaluate the structural performance of 4-ft-long test sections of the 15-, 18-, and 24-in-diameter corrugated polyethylene pipe sizes

Figure 5. Deflection versus cover height for 24-in pipe under H-20 loading at three average backfill densities.



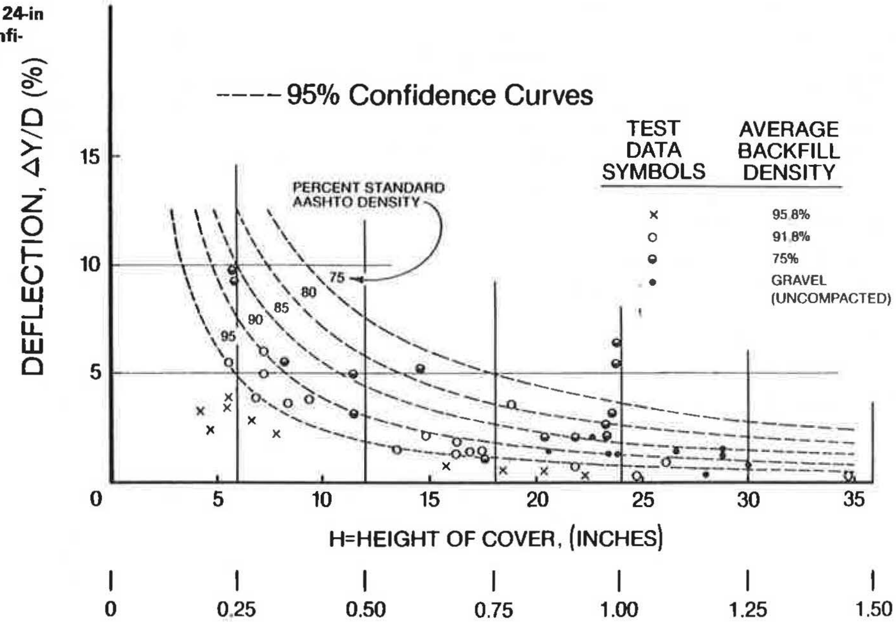


Figure 6. Deflection versus cover height for 24-in pipe under H-20 loading with 95 percent confidence level curves for five backfill densities.

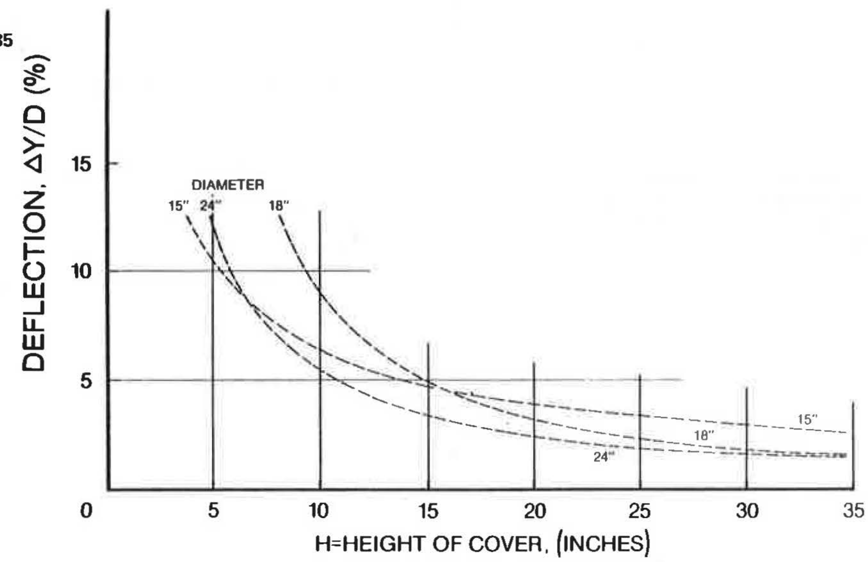


Figure 7. Plots of 95 percent confidence values for deflection versus cover height at 85 percent soil density under H-20 loading.

Table 1. Average deflection values by cover height for 15-, 18-, and 24-in pipe diameters and 80, 85, and 90 percent backfill densities.

Cover Height (in)	Avg Deflection (%) 15 in 80%	15 in 85%	15 in 90%	18 in 80%	18 in 85%	18 in 90%	24 in 80%	24 in 85%	24 in 90%
3		12	10						
4	11	9	8						10
5	9	8	7				11	10	7
6	8	7	6				9	8	6
7	7	6	5			10	8	7	5
8	6	6	5	13	11	8	7	6	4
9	6	5	4	11	9	7	6	5	4
10	5	5	4	9	7	6	6	4	3
11	5	4	4	8	6	5	5	4	3
12	5	4	3	7	6	4	5	3	3
13	4	4	3	6	5	4	4	3	2
14	4	4	3	6	4	3	4	3	2
15	4	3	3	5	4	3	4	3	2
16	4	3	3	5	4	3	3	2	2
17	4	3	3	4	3	3	3	2	2
18	4	3	3	4	3	2	3	2	2
19	3	3	2	4	3	2	3	2	1
20	3	3	2	3	3	2	3	2	1

(the USU tests are referred to as high soil pressure tests). In the test cell, performance limits were identified and related to corresponding vertical soil pressures that may be associated with high earth fill in typical cohesionless soils. The objective of this testing was to find the relation between deflection and high soil pressures at various soil densities with and without select soil (gravel) envelopes immediately around the pipe.

The test schedule was as follows:

Test No.	Pipe ID (in)	Envelope B (in)	Soil Backfill Density (%)
1	24	None	85
2	24	None	75
3	15	27x27	75
4	18	27x27	75
5	18	27x27	85
6	18	27x27	95
7	15	None	75

Procedure

High vertical pressure was applied in the soil cell by hydraulic rams that had sufficient capacity to simulate depths of soil cover to more than 100 ft. The load was applied in increments, and observations

Table 2. Minimum cover height versus pipe deflection for 15-, 18-, and 24-in pipe diameters and 80, 85, and 90 percent backfill densities.

	Minimum Height of Cover (in)								
Deflection (%)	15 in			18 in			24 in		
	80%	85%	90%	80%	85%	90%	80%	85%	90%
1	95	75	63	44	36	30	55	32	25
2	38	30	25	28	23	19	28	18	14
3	22	18	14	21	18	15	18	13	10
4	15	12	10	17	15	13	14	10	8
5	11	9	7	15	13	11	11	9	7
6	9	7	6	13	12	10	9	8	6
7	7	6	5	12	11	9	8	7	5
8	6	5	4	11	10	8	7	6	5
9	5	4	3	10	9	8	6	5	4
10	4	4	3	9	8	7	6	5	4
11	4	3	3	9	8	7	5	5	4
12	3	3	2	8	7	6	5	4	3

Table 3. Pipe deflection at 95 percent confidence level versus cover height for 15-, 18-, and 24-in pipe diameters and 80, 85, and 90 percent backfill densities.

	Deflection (%)								
Cover Height (in)	15 in			18 in			24 in		
	80%	85%	90%	80%	85%	90%	80%	85%	90%
3			12						
4		12	10						12
5	13	10	8					12	9
6	11	9	7				13	10	7
7	10	8	6			13	11	8	6
8	9	8	6			10	9	7	5
9	8	7	5		11	8	8	6	5
10	8	6	5	12	9	7	7	6	4
11	7	6	5	10	8	6	6	5	4
12	7	6	4	9	7	5	6	4	3
13	6	5	4	8	6	5	5	4	3
14	6	5	4	7	6	4	5	4	3
15	6	5	4	6	5	4	5	3	2
16	5	5	4	6	5	3	4	3	2
17	5	4	4	5	4	3	4	3	2
18	5	4	4	5	4	3	4	3	2
19	5	4	3	4	3	3	4	3	2
20	5	4	3	4	3	2	3	2	2

Table 4. Minimum cover height at 95 percent confidence level for 15-, 18-, and 24-in pipe diameters and 80, 85, and 90 percent backfill densities.

	Minimum Cover Height (in)								
Deflection (%)	15 in			18 in			24 in		
	80%	85%	90%	80%	85%	90%	80%	85%	90%
1									
2	66	53	43	32	27	23	32	24	17
3	38	19	23	25	21	17	22	17	13
4	25	20	15	20	17	15	17	13	10
5	19	14	11	18	15	13	14	11	8
6	14	11	8	16	13	11	12	9	7
7	12	9	6	14	12	10	10	8	6
8	10	7	5	13	11	9	9	7	6
9	8	6	4	12	10	9	8	7	5
10	7	5	4	11	10	8	7	6	5
11	6	5	3	10	9	8	7	6	4
12	6	4	3	10	8	7	6	5	3

Figure 8. USU high vertical soil pressure test cell, showing setup for testing corrugated plastic pipe.

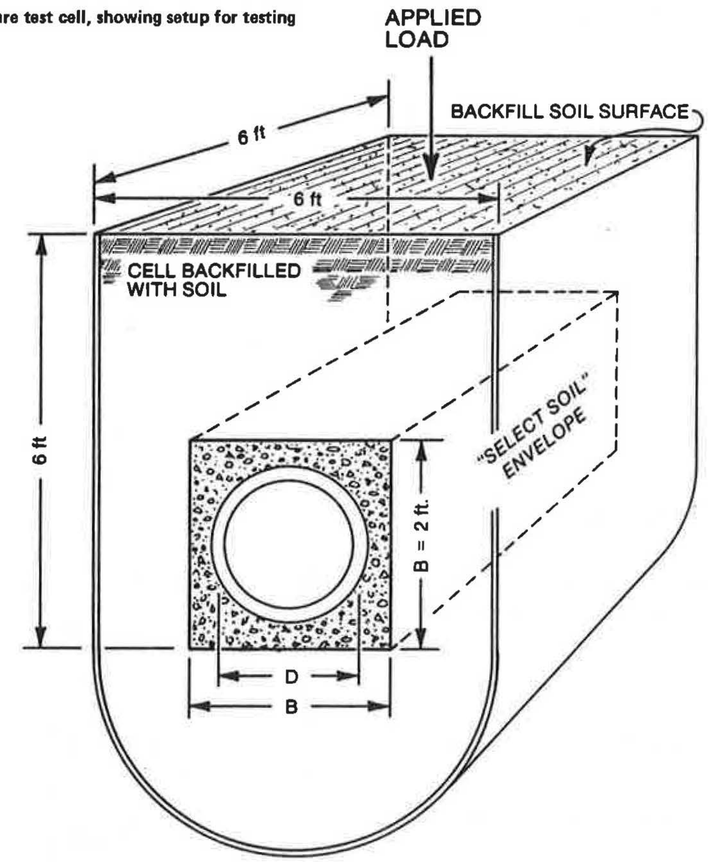
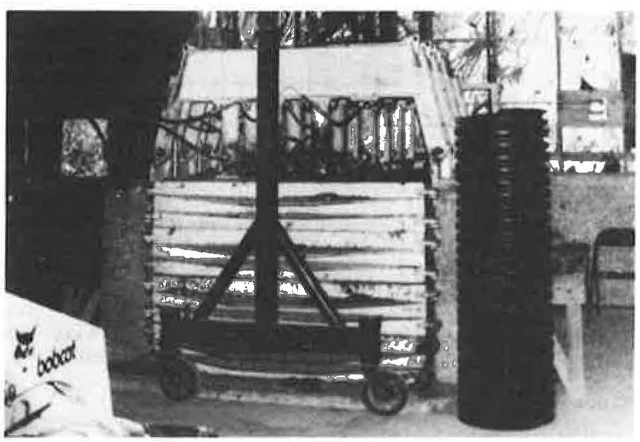


Figure 9. USU high vertical soil pressure test cell in operation.



such as visual distress and deflection were recorded at each increment of load.

The native soil used in these tests was fine sand with about 20 percent silt. The select soil envelope was gravel with some coarse sand, all less than 0.5-in sieve mesh. The soil densities in the laboratory were measured with a densitometer in a procedure similar to that used in the field tests.

Results

The tests produced the following results and general observations.

Deformation

The performance limit was ratio of deflection $\Delta y/D$. No wall buckling, wall crushing, cracking, or tearing occurred. At deflections greater than about 25-30 percent, a longitudinal dimpling in the inside crests of corrugations could be detected at nine and three o'clock. As a performance limit this was discounted in favor of prior deflection of 20 percent, proposed by Spangler as "failure". That no wall crushing occurred under these extremely high pressures in the soil cell is remarkable. This confirms recent observations that polyethylene pipes do not fracture under constant strain (constant deformation) because stress decreases (stress relaxes) faster than strength decreases. In this case, the soil envelope assured constant deformation at each load increment.

Deflection versus vertical soil pressure for 24-, 18-, and 15-in pipe, respectively, is shown in Figures 10-12. Silty sand backfill was used in the tests, with a 0.375- to 0.5-in gravel envelope for the 24- and 18-in pipes and with and without a gravel envelope for the 15-in pipe.

Flexible Pipe Ring

Corrugated polyethylene pipe has a flexible cross section (ring) despite the corrugations. Therefore, under load, deflection is essentially equal to vertical soil strain:

$$\Delta y/D = \varepsilon$$

where $\Delta y/D$ is the ratio of vertical decrease in diameter to nominal pipe diameter and ε is vertical soil strain. The corrugations serve to hold the shape of the pipe ring during placement of the sidefill. But, as vertical soil pressure is applied, the flexible ring simply conforms with the soil. The only exception occurs in loose soil (75 percent density). The slight hump at the lower end of each

Figure 10. Vertical deflection versus vertical soil pressure for 24-in pipe in high pressure soil cell.

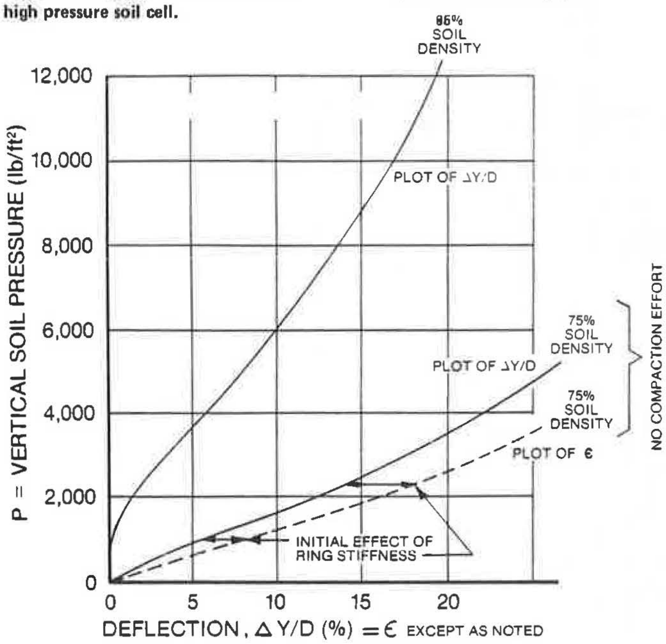
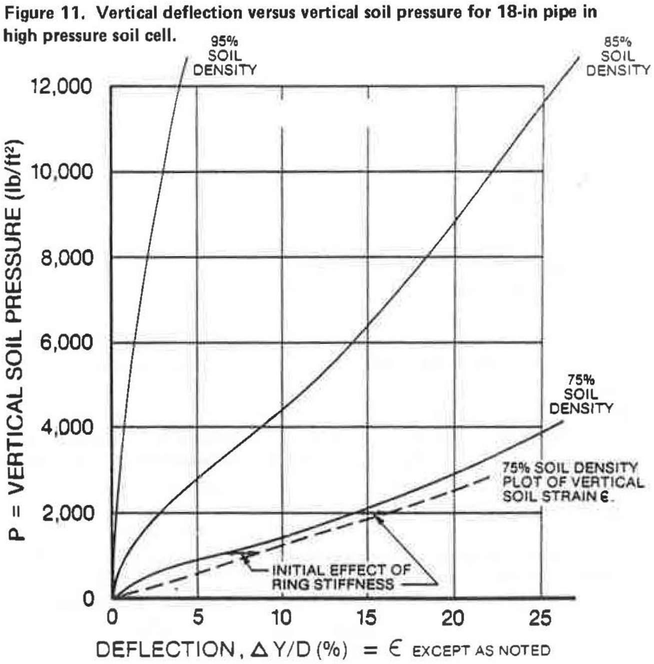


Figure 11. Vertical deflection versus vertical soil pressure for 18-in pipe in high pressure soil cell.



deflection plot indicates some initial resistance by the corrugations before the soil is dense enough to dominate deflection.

Select Gravel Envelope

The select gravel envelope reduced deflection slightly in very loose soil (see Figure 13). If the B/D ratio is roughly 1.8--or, say, 2--then the maximum reduction in deflection achieved by using a select gravel envelope is less than one-third. There is some benefit in using a gravel envelope to reduce deflection but only if the native soil is unusually compressible and if the B/D ratio is 2 or greater. On the other hand, where the entire backfill is

Figure 12. Vertical deflection versus vertical soil pressure for 15-in pipe in high pressure soil cell.

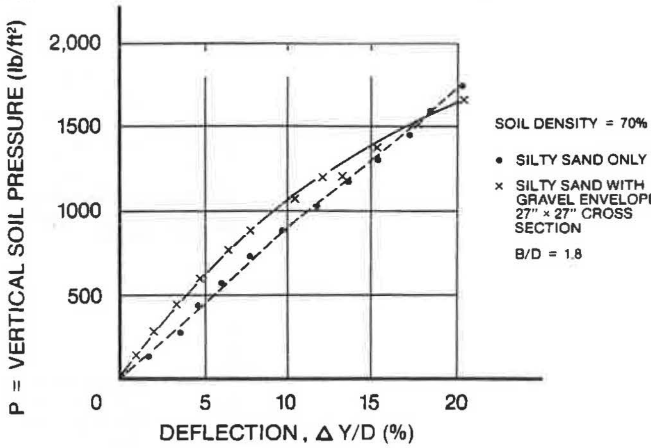
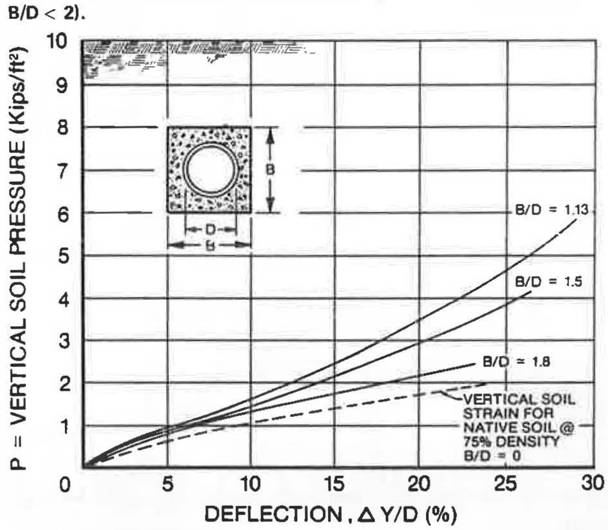


Figure 13. Effect of B/D on deflection (not significant in loose soil for B/D < 2).



gravel, the high internal friction of the gravel forms a semirigid structure and carries virtually the total load with minimal pipe deflection. The response of total gravel backfill is essentially the same as native soil backfill at 95 percent density.

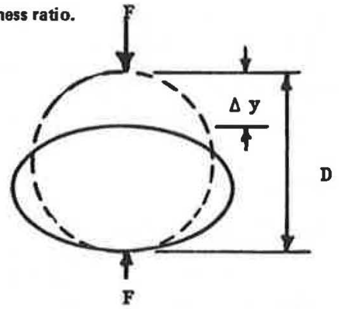
Minor Variables

Observations indicate that minor variables that influence pipe performance are (a) pipe diameter and (b) select soil envelope.

Pipe Diameter

The data plots in Figures 10 and 11 show a tendency toward steeper plots for the 24-in pipe than for the 18-in pipe. All other conditions appear to remain equal. This does not mean that pipe stiffness is significantly greater for the 24-in pipe nor that pipe stiffness has significant effect on deflection. In fact, all deviations in pipe deflection for any soil density and pressure are within one standard deviation of vertical soil strain at the same density and pressure for all diameters. Uniformity of soil density may be a modifying factor. The wider corrugations of the 24-in pipe may allow higher soil densities between the corrugations. The larger pipe

Figure 14. Pipe stiffness ratio.



diameter may also permit more compaction lifts--i.e., more uniformity--on each side than a smaller pipe. Certainly, the relative positions of soil lifts to pipes are not identical for the 18- and 24-in pipes.

Select Soil Envelope

Figure 13 shows how much the pipe deflection is resisted by the select soil (gravel) envelope for various values of B/D. However, the deviation of these plots from each other is not statistically significant. Standard deviations due to other major variables are greater than the deviation of the three plots from their mean. In fact, the apparent influence of B/D on $\Delta y/D$ is just the reverse of what would be anticipated. A larger sample is needed if significance is to be tested. But the more important observation is that the gravel envelope where B/D is small serves little purpose structurally in maximum cover design except to ensure integrity of the soil support about the pipe, including the spaces under the haunches and between the corrugations.

COMPARATIVE PIPE STIFFNESSES

Pipe stiffnesses were measured for functionally equivalent corrugated pipes of aluminum, steel, and polyethylene in diameters of 15, 18, and 24 in. The metal pipes were 16-gage, 2-2/3x1/2 corrugations. The following can be concluded from the tests:

1. The differences between calculated and measured values of pipe stiffness are so great that the use of calculated values for design is suspect. It is recommended that the industry adopt measured values of pipe stiffness $F/\Delta y$ for design except in cases where it is proved that calculated values, such as $F/\Delta y = 53.77\ EI/D^3$, are essentially the same as measured values.
2. Pipe stiffness at 5 percent deflection is greater than pipe stiffness at 10 percent by roughly one-third; i.e., 52 pii at 5 percent and 37 pii at 10 percent. For design, it is recommended that pipe stiffness at 5 percent be used.
3. Pipe stiffnesses vary as much as three to one between aluminum and steel. Pipe stiffness for polyethylene is about the same as for steel. Ultimate loads follow roughly the same ratios. It is noteworthy that pipe stiffness is of value in maintaining the shape of the pipe ring during construction and in resisting heavy surface loads under minimum soil cover.

The question arises, Does creep reduce the pipe stiffness of polyethylene? The answer is yes. However, creep does not occur during short periods of load such as those experienced during installation or under live surface loads. The strength in resisting sudden loads is not reduced by creep. At constant pipe deformation, stresses decrease (relax) at a faster rate than strength. Therefore, polyethylene pipes supported by good soil are not prone to structural failure as a function of time of service. This would not be true in plastic soil. Service life (50-year) strength should be used for design in this case.

The differences between measured and calculated values of pipe stiffness can be explained by the following.

Longitudinal Seams

If the seam can rotate as a longitudinal hinge, then the pipe stiffness ratios ($F/\Delta y$ no hinge to $F/\Delta y$ hinge) are as follows (see Figure 14):

Location of Single Seam (hinge)	Pipe Stiffness Ratio
Top or bottom	2.4
Springline (either one)	1.6

These values are limiting cases because seams are not hinges. However, they do show the sensitivity of pipe stiffness to a longitudinal seam that does not develop full resistance to moment. Even when a plastic hinge starts to form, the partial rotation allows a reduction in $F/\Delta y$. Corrugations do not nest perfectly in overlap. Rotation of seams in buried pipes is often observed in the field.

Locked-In Stresses near Yield Point

Because corrugated metal pipes are cold-formed, circumferential stresses can be high enough that with little deflection the yield point is exceeded, especially at the springlines when outside locked-in stress is in tension. Even without a locked-in stress, a 21-in-diameter aluminum pipe reaches a yield point of 35 ksi before the deflection reaches 3.4 percent. The same pipe in steel reaches yield point, 40 ksi, at only 1.4 percent. Clearly, $F/\Delta y$ measured at 5 percent deflection and greater is less than the calculated value, $F/\Delta y = 53.77\ EI/D^3$.

In order to form a fully developed plastic hinge, a moment of $M_p = 1.44\ M_e$ is needed. M_e is the elastic moment at which the yield point is just reached. It is the start of a plastic hinge. In other words, if the elastic yield point is reached in aluminum at the top and bottom when the deflection is 3.4 percent, then plastic hinges form at top and bottom when deflection is 1.44 (3.5) = 5 percent. Plastic hinges are incipient on the springlines at deflections no greater than 9 percent; i.e., 5 percent (M_B/M_A) = 5 percent $[\pi(\pi - 2)/2]$ = 9 percent. At 9 percent deflection, the specimen will collapse under the parallel plate load because four plastic hinges cause instability. Pipe stiffness drops to zero at collapse.

Deflection

The deflection itself causes moments that increase at a greater rate than the applied parallel plate load. Due to elliptical pipe deformation, the pipe stiffness at 10 percent deflection is only 90 percent of the pipe stiffness for a circle.

Because this effect combines with the plastic hinge effect, locked-in stress, and longitudinal seam effect, the low measured values of $F/\Delta y$ compared with the traditional $F/\Delta y = 53.77\ EI/D^3$ are readily understood.

Nonelliptical Pipe

First-mode deflection of a pipe in soil is the ellipse. The ellipse causes the least circumferential stress for any given deflection. Unfortunately, the ellipse is ideal but buried pipe is not. The parallel plate test is even less so. Because the pipe is not elliptical, stresses are greater for a given load and pipe stiffness is less than for an ellipse.

DISCUSSION OF RESULTS

The minimum cover tests were designed to evaluate the localized effect of large asymmetrical loads on the pipe-soil structure. The high soil pressure tests were designed to evaluate performance under uniformly applied vertical pressures.

For buried pipe that is confined by considerably more than the minimum soil cover, the distribution of pressure on the pipe is uniform for live load as well as dead load. The deflection is symmetrical. This is not true at soil cover equal to or less than the minimum soil cover. For practical pipe design under super-heavy surface loads, methods of evaluating vertical soil pressure P on the select soil envelope are available. For Cooper E-80 locomotive loading, the values are listed in the Handbook of Steel Drainage and Highway Construction Products (3, p. 87). For heavy off-highway wheel loads, the Boussinesq method of analysis is adequate.

Performance Criteria

Considerable importance is attached to the finding in these tests that polyethylene pipe has structural qualities quite unlike those of concrete or metal pipes.

First, polyethylene pipe is flexible. It conforms with the soil around it. The density of the sidefill material is important. Under load, the deflection of the pipe equals the vertical compressive strain of the sidefill material. If the sidefill material is compacted to a high density at time of installation, any increased strain due to the applied load is minimal. So also is the pipe deflection. Note the results for 95 percent soil density at high pressures in Figure 11: At 12 000 psf the deflection was less than 4 percent.

Second, polyethylene does not have a definite yield point as do metals. For metal pipes, once the yield point is reached, permanent set occurs with wall crushing and/or buckling. As demonstrated in the high-pressure tests on polyethylene pipes, there was no wall crushing or buckling. At these extremely high pressures, the failure mode was pipe deflection, which was equal to vertical strain or settlement in the sidefill soil.

The constraining influence of the sidefill material on pipe performance is illustrated by field deflection measurements after skimming down to zero cover and application of a 16-kip wheel load. The deflections at zero cover, for the 24-in pipe at sidefill densities of 75, 90.8, and 95.8 percent, were 7.2, 4.2, and 3.3 percent, respectively. For the 15-in pipe at a sidefill density of 85.7 percent, deflection was 13.3 percent. For the 18-in pipe at a sidefill density of 85.2 percent, deflection was 12.5 percent. Removal of the top cover did not substantially affect the pipe deflection. The sidefill material at the installed density still performed in restraining the pipe and in supporting the applied load.

Design Considerations

For a non-specification-type application, such as driveway culverts or other entrance crossings, a usual practice is to push the native soil backfill into place and give little attention to sidefill compaction. For loosely applied backfill in most soils, densities will be no more than about 75 percent. It has been demonstrated that with a little care the sidefill density can be increased to around 80 percent by simply "walking in" the sidefill material in 6- to 8-in lifts.

For specification-type installation, the 95 percent confidence values given in Tables 3 and 4 should provide a basis for design with adequate safety factor. The pipe deflection can be held within an allowable limit by adjusting the height of the cover and/or sidefill density.

Corrugated polyethylene pipe is manufactured with corrugations deep enough to hold its circular cross section during installation. After experience with many installations, the manufacturers have developed pipe stiffness comparable to that of functionally equivalent corrugated steel pipes.

Creep is the relaxation of stress with time. This is a favorable property in that any stress concentrations during installation tend to relax. The slip of riveted seams in metals accomplishes a similar favorable relaxation. Under constant stress, polyethylene yields. If some long-term surface load follows the pipe down, or if the soil envelope is fluid, then the allowable stress must be based on the 50-year-service-life strength of the yielding polyethylene.

Of course, polyethylene cannot resist high bearing stresses resulting from large rocks lodged against it.

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