

Structural Design of Buried Corrugated Polyethylene Pipes

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Test sections of corrugated polyethylene pipe (CPEP) were buried, as in typical drainage installations, in competent, compacted, granular backfill. Both dead load (soil cover) and surface live load (truck dual wheels) were applied. The objectives of the tests were to (a) observe performance of the pipes under load, (b) identify performance limits, (c) resolve some of the questions unanswered by present design methods, and (d) propose improved methods for the structural design of buried CPEP. The objectives were achieved. Experimenters agreed that tests confirmed the complementary interaction of pipe and backfill. Minimum soil cover was investigated under multiple passes of live loads. Conditions for structural stability of the pipe were identified. An analytical procedure was developed for predicting the minimum height of soil cover to assure ring stability under multiple passes of live loads. Maximum soil cover tests confirmed the ring compression analysis as the primary basis for design but also revealed a need to include the effects of ring deflection. An observable performance limit was identified, and a method of design was developed that combined the effect of ring deflection and ring compression on the performance limits of CPEP buried under maximum height of soil cover.

Corrugated polyethylene pipe (CPEP) is used primarily for nonpressurized buried conduits. Structural design must establish the conditions for adequate structural performance of the conduit and must identify the performance limits. Structural performance of a buried pipe is the interaction of the pipe and the soil in providing a useful conduit. If the pipe is flexible, it depends upon the soil to support it. The soil depends upon the pipe to retain the conduit cross section. The basic performance limit is excessive deformation. Excessive deformation could lead to yielding and even to fracture, but for most flexible pipes, excessive deformation is either too much longitudinal beam deflection or too much ring deformation. In the case of CPEP, because of the corrugations, longitudinal beam deflection does not cause pipe damage. Performance limit is simply too much beam deflection either from the standpoint of impeded flow due to beam bending or to sedimentation, or too much differential settlement of the soil surface. Longitudinal deflection is controlled by controlling the soil bedding elevation.

Excessive ring deformation may be so much ring deflection that flow is impeded, or it may be flattening or reversal of

curvature of the ring. Reversal of curvature is considered to be excessive deformation, even though collapse does not occur, because the ring can no longer provide its full contribution to the pipe-soil conduit. Once the ring curvature is reversed, fluctuations in soil pressures can cause progressive ring deformation, sometimes called ratcheting, which could lead to eventual collapse. Soil pressure fluctuations are caused by surface loads and also by cycles of temperature changes, water level variations, freezing and thawing, and earth tremors.

In the summer of 1985, a series of minimum soil cover tests sponsored by Hancor, Inc., was conducted in Findlay, Ohio. The objective was to discover the minimum soil cover needed to protect CPEP. The independent variables were soil density and surface dual-wheel load. The backfill soil was crushed rock passing a 3/4-in. mesh screen and referred to in Findlay as 411 crushed limestone. Soil density was reported for its initially compacted state as a percent standard Proctor density (AASHTO Specification T-99). Except as noted, the load was provided by the single rear axle of a truck trailer with dual wheels carrying about 105-psi tire pressure. In each test, the loaded axle was run back and forth over the buried pipe (passes) in approximately the same tracks. Ruts formed. A graph of approximate rutting is shown in Figure 1, where rut depth H'' is a function of dual-wheel load W and soil density. The values of H'' are conservative, that is, 90 percent of all observed values in the field are estimated to be less than the plots. Rut depth H'' is the depth after the first pass. After the first pass (or up to three or four passes to establish the rut), H'' did not increase significantly, except directly over the pipe at performance limit. The equation from the plots of Figure 1 is

$$H'' = 0.315(\log W - 0.34)(103.9 - \rho)$$

where W is in kips, ρ is in percent, and H'' is in inches of soil cover.

Performance limit was identified as instability; i.e., progressive increase in ring deformation with each successive pass of the load. Multiple passes could lead to pipe damage.

Maximum soil cover tests were conducted on CPEP in a soil cell at Utah State University in Logan, Utah. The soil cell was a container in which a section of pipe was buried and then loaded vertically by 16 hydraulic cylinders to simulate high soil cover. The cell could accommodate pipes up to 2 ft in

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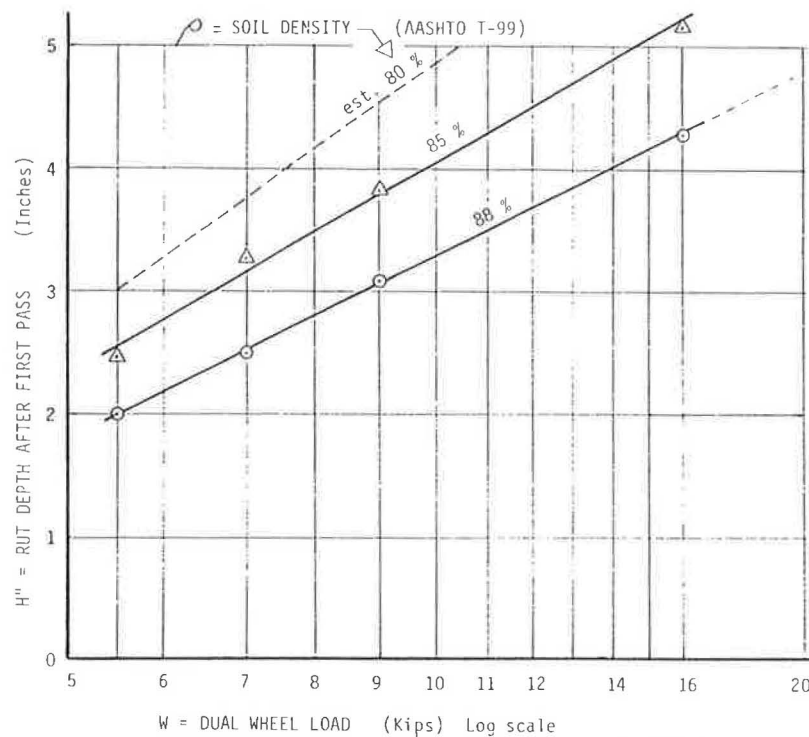


FIGURE 1 Depth of dual-wheel ruts H'' in crushed limestone backfill after the first pass. (Standard deviation of H'' is 0.5 in. The dotted plot for 80 percent soil density is estimated from single-tire ruts.)

diameter in lengths up to 5.5 ft. Soils of various types could be compacted to various densities, and loads in increments up to 16 kips/ft² could be applied to simulate soil loads including surface live loads. (See Figure 2.)

The independent variables were the density of the backfill soil and the vertical soil pressure at the top of the buried pipe. Two different diameters of CPEP were tested to verify similitude. The dependent variables, that is, performances were measured ring deflection and observed dimpling. The test section of pipe was buried in silty sand, Unified Soil Classification SM. Vertical soil pressure in the soil cell simulated high soil cover plus surface loads. After each increment of load, ring deflections were measured.

Performance limit in these tests was identified as vertical soil pressure P at dimpling of the crests of the corrugations at 9 and 3 o'clock as viewed from inside the pipe. The dimpling portended plastic hinging as a result of wall buckling and crushing. Plastic hinges could develop if the vertical soil pressure were increased past the performance limit.

DESIGN

For design, it is traditional to evaluate performance as stress σ and to equate it to strength S as a performance limit. Including sf as a safety factor, $\sigma = S/sf$. In this paper, stress is analyzed as a function of deformation. Strength S is the stress at the limit of deformation, which may or may not occur at yield point. Elastic theory is used because it is generally understood and because it is conservative.

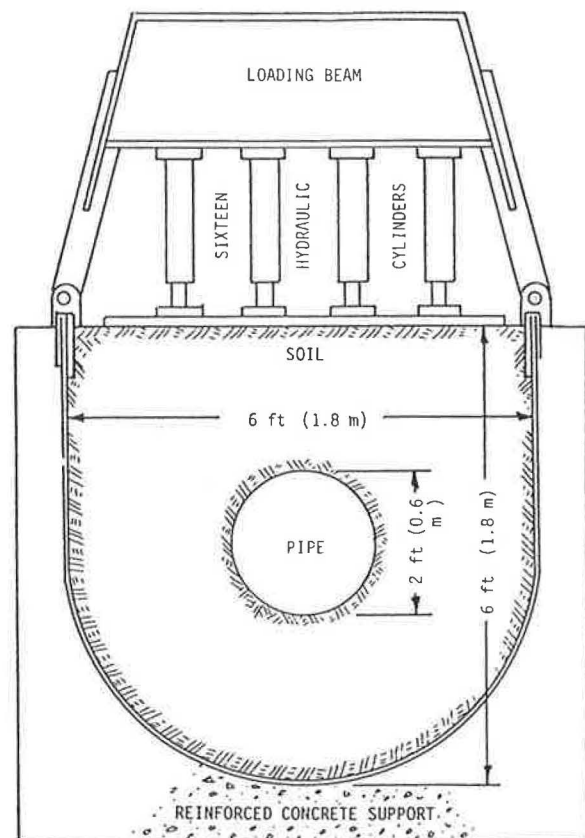


FIGURE 2 Cross section of small Utah State University soil cell in which pipes can be buried in soil and loaded vertically.

PERFORMANCE LIMITS FOR CPEP

In the design of CPEP, two performance limits must be considered: ring deflection and ring buckling. Ring deflection is the change in ring cross section from a circle to an approximate ellipse due to vertical compression of the pipe zone backfill soil. Ring deflection is defined as percent reduction in vertical mean diameter from the original mean circular diameter, that is,

$$\begin{aligned} d &= \Delta/D = \text{ring deflection,} \\ \Delta &= \text{decrease in vertical diameter, and} \\ D &= \text{mean circular diameter of pipe, to the neutral surface of the corrugations.} \end{aligned}$$

Design engineers specify the maximum allowable ring deflection d . A conservative maximum $d = 5$ percent is sometimes specified for culverts and storm drains. A proposed AASHTO deflection limit is 7.5 percent and many engineers permit 10 percent for pipe of this type.

Ring buckling in CPEP is usually identified by the first visible evidence of formation of plastic hinges in the pipe wall. Under maximum soil cover, plastic hinging is incipient when dimples appear on the crests of corrugations at approximately 9 and 3 o'clock. This is called dimpling. Under minimum soil cover with surface wheel loads passing over, this dimpling appears on the outside of the pipe near the crown, at 12 o'clock.

A special case of ring buckling is conduit instability. Under maximum soil cover, if the vertical soil pressure is so great that shear planes form in the soil at 9 and 3 o'clock, or if the ring compression stress in the pipe wall exceeds yield point, then the conduit is unstable. Progressive ring deformation could proceed. Under minimum soil cover, the conduit is unstable if multiple passes of a surface wheel load increase ring deformation with each successive pass. This multiple pass instability is discussed later.

PERFORMANCE OF CPEP

With performance limits identified, analysis must predict the structural performance of the buried CPEP ring under external soil pressures. The familiar stress theory is useful for conservative analysis. Stress is analyzed at performance limits of excessive deformation. Performance limit, then, becomes the maximum circumferential compressive stress developed in the pipe wall by vertical soil pressure P at the top of the pipe when the pipe is at the point of excessive deformation. Two conditions for vertical soil pressure are considered in this analysis: minimum soil cover and maximum soil cover. Under minimum soil cover, an approaching surface wheel load is critical. Under maximum soil cover, the surface wheel load is either negligible or only adds to the dead weight of soil.

Not included in this analysis are the conditions (a) for hydrostatic collapse of the ring, (b) for longitudinal beam deflection, and (c) for indentations or crushed corrugations due to a hard object bearing against the pipe. It is assumed

that specifications for the pipe zone backfill will exclude rocks of such size that an indentation becomes a perforation or an impedance to flow. Usually, specifications exclude rocks over 1.5 in. from bearing against the pipe. It is assumed that intense surface loads such as superhigh-pressure tires over a less-than-minimum soil cover will be avoided.

Minimum Soil Cover

Minimum soil cover over buried CPEP is of concern only when a surface wheel load passes over it. In the following examples, the load is a truck dual-wheel load up to an HS-20 load of 16 kips. Similar analyses could be accomplished for different loads such as those due to tracked vehicles.

Because most buried CPEP is supported by compacted, granular pipe zone backfill, any ring deformation is associated with soil slip along shear planes. In the case of minimum soil cover, if the surface wheel load is applied over a rectangular surface area of width B and length L and if load W is great enough to cause soil compression, then soil shear planes form as indicated in Figure 3, isolating a truncated pyramid of soil. The pyramid angle $\theta = 45^\circ - \phi/2$, where ϕ is the soil friction angle. At depth H , the surface wheel load W is distributed over the base area as indicated in Figure 3(a). For compacted, crushed-stone backfill, the soil friction slope is about 1:2, for which the base area is $(B + H)(L + H)$. The vertical soil pressure on the pipe with soil cover H [Figure 3(b)] is

$$P = W/[(B + H)(L + H)] \quad (1)$$

For a dual-wheel load, the surface area is approximately a 7-by 22-in. rectangle, for which tire pressures vary with load as follows:

Dual-Wheel Load W (kips)	Tire Pressure (psi)
5.5	36
7	45
9	58
16	104

The analysis can be adjusted to different dual-tire contact areas. However, the 7- \times 22-in. contact area gives results in agreement with the Findlay field tests. For such loads, the minimum soil cover is so small (a few inches) that dead load due to soil cover can be neglected.

A useful model for evaluating minimum cover is the following as adjusted by field test results. The geometry is shown in Figure 4 and the notation is as follows:

Notation	Values for 18-in. CPEP
ID = inside diameter of pipe,	18 in.
D = mean diameter of pipe = $ID + 2c$,	19.8 in.
r = mean radius of pipe = $ID/2$ + c ,	9.9 in.
c = distance from the neutral surface of corrugations to the crest on the inside of the pipe.	0.86 in.

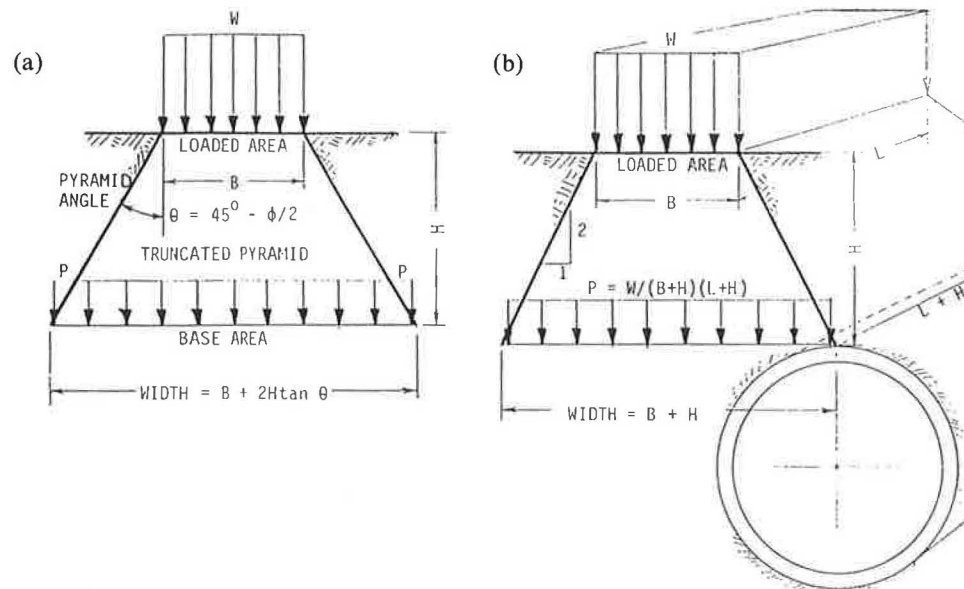


FIGURE 3 Truncated pyramid isolated by the formation of shear planes under a heavy surface load W with minimum soil cover H : (a) Vertical soil pressure P at depth H as load W is transferred through the truncated pyramid to the base area, and (b) approximate pyramid for compacted granular soil cover.

A	=	cross sectional area of pipe wall per unit length of pipe,	0.195 in. ² /in.
I	=	moment of inertia of the pipe wall per unit length of pipe,	0.077 in. ⁴ /in.
S	=	strength of pipe wall material for quick loads such as wheel loads passing over,	3 ksi
H	=	installed height (in.) of soil cover (see Figure 4),	
H'	=	rutted height (in.) of soil cover after multiple passes of load W have stabilized the system,	
H''	=	depth of rut (in.),	
W	=	load on a truck dual wheel crossing over the pipe (kips),	
ρ	=	soil density in percent standard Proctor density (AASHTO Specification T-99) of granular soil cover and pipe zone backfill (percent),	
σ	=	circumferential stress in the pipe wall, and	
P	=	vertical soil pressure at the level of the top of the pipe due to passing dual-wheel load = $W / [(B + H)(L + H)]$ from Figure 3.	

The minimum height of cover is that soil cover H less than which the pipe-soil system is unstable under multiple passes of dual-wheel load W . Instability is incipient when stress equals yield point strength of the pipe.

From Figure 4, values of H are evaluated by $H = H' + H''$. For crushed limestone wet from precipitation, the rut depths H'' for dual-wheel loads W in granular soil cover are as shown in the following table. These values are from the Findlay field tests.

The rutted height of soil cover H' after multiple passes to stability is that cover less than which the stress in the pipe exceeds the quick-load strength of material S . For CPEP, the quick-load strength is usually greater than 3 ksi. So $S = 3$ kips/in.². Quick-load strength is used, rather than 50-year

Soil Density ρ	Rut Depth H'' (in.) W (kips)			
	5.5	7.0	9.0	16.0
80	3.0	3.8	4.6	6.5
85	2.4	3.0	3.7	5.1
90	1.8	2.2	2.7	3.8
95	1.1	1.4	1.7	2.4

strength, because live loads are quick loads. The maximum stress in the pipe wall is less than the sum of ring compression stress and flexural stress due to nonuniform vertical soil pressure. To be conservative, then, the two are added as follows:

$$\sigma = Pr/A + Mc/I$$

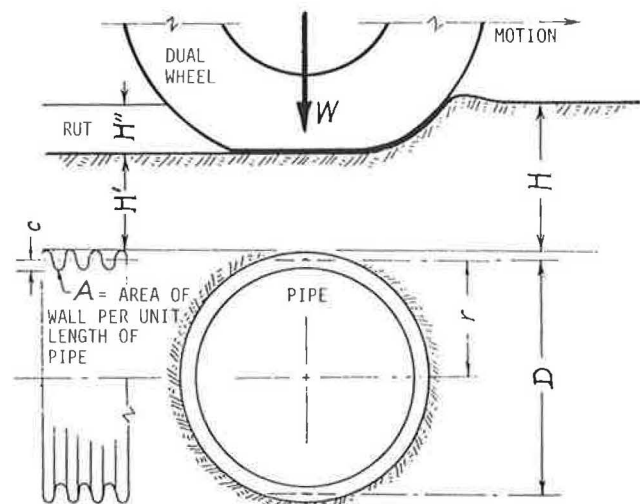


FIGURE 4 Sketch of a dual-wheel load W passing over a buried pipe with granular soil cover of height H .

Moment M can be evaluated by arch analysis. From the Findlay field tests, and from observations of minimum cover failures of flexible pipes, performance limit is identified as incipient plastic hinging that results in reversal of curvature of the pipe. When reversal of curvature does occur, it occurs within the top 80° arc of the ring. To be conservative, assuming 90° of top arch, see Figure 5 where $\alpha = 45^\circ$, with ends of the arch fixed, and with a uniformly distributed vertical soil pressure P approaching from one side as shown,

$$M = 0.022Pr^2$$

The resulting stress equation is

$$\sigma = Pr(1/A + 0.022rc/I) \quad (2)$$

where, by pyramid soil stress analysis under a dual-wheel load distributed over a 7- × 22-in. rectangle,

$$P = W/[(7 + H')(22 + H')] \quad (3)$$

The rutted soil cover H' can be evaluated by substituting Equation 3 into Equation 2 and solving the resulting quadratic equation for H' .

The minimum granular soil cover, conservatively estimated (with 90 percent confidence), but without safety factor, is (see Figure 2)

$$H = H' + H'' \quad (4)$$

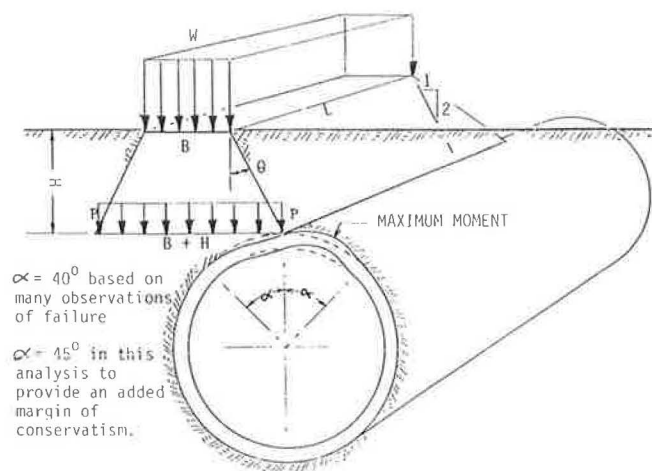


FIGURE 5 Pyramid live-load soil pressure P due to an approaching surface dual-wheel load W crossing over a pipe buried at depth H .

Example: Minimum Soil Cover

Suppose that minimum cover H of granular soil is to be evaluated for 18-in. CPEP in 85 percent dense backfill. Substituting Equation 3 into Equation 2 and including values of r , A , and I/c for 18-in. CPEP,

$$(H' + 14.5)^2 = 25W + 56.25$$

Solutions for 18-in. CPEP are as follows:

Dual-Wheel Load W (kips)	Rutted Soil Cover H' (in.)
5.5	-0.6
7	0.7
9	2.3
16	6.9

The negative value at $W = 5.5$ kips indicates that soil cover is not needed. The pipe can carry a 5.5-kip dual-wheel load even though the ruts expose the pipe. Of course, enough soil cover H should be provided to allow for rutting H'' , to prevent surface rocks from indenting the pipe, and to avoid crushing of corrugations.

For soil at 85 percent density and with multiple passes of a 16-kip dual-wheel load, the minimum height of cover is (from Equation 4) $H = 12$ in. This example yields a conservative minimum soil cover in approximate agreement with field tests. In the Findlay field tests, instability was observed after multiple passes of a 16-kip dual-wheel load over an 18-in. CPEP with 85 percent dense granular soil cover and with an installed height of soil cover of $H = 10$ in. Rutting was found to be about 5 in. maximum after many passes.

This analysis is valid for CPEP up to and including 24-in. diameter. Conditions of similitude should be reviewed for pipes larger than 24 in. in order to consider changes required for installation and possible differences in the properties of the yet-to-be tested large pipes.

For 24-in. CPEP, the equation for rutted height of cover H' becomes

$$(H' + 14.5)^2 = 25.36W + 56.25$$

This result is based on $r = 13.24$ in., $A = 0.2775$ in.²/in., and $I/c = 0.136$ in.³/in. Solutions for 24-in. CPEP are as follows:

Dual-Wheel Load W (kips)	Rutted Soil Cover H' (in.)
5.5	-0.5
7	0.8
9	2.4
16	7.0

These values are essentially the same as for 18-in. CPEP.

Ring deflection under minimum soil cover comprises two components: permanent ring deflection d' and rebound ring deflection d'' . The rebound ring deflection is elastic and so rebounds fully after each pass of the dual-wheel load.

In Figure 6, results are summarized of the Findlay field tests on 18-in. CPEP under the least favorable backfill conditions tested. Backfill was crushed limestone. The soil density was 85 percent of the standard Proctor density (AASHTO Specification T-99), the lowest density tested; the height of soil cover was 7 in., the least cover tested. Two observations are noteworthy from Figure 6:

1. Ring deflection is small, less than 2 percent, for the first pass of the dual-wheel load. Permanent ring deflection and

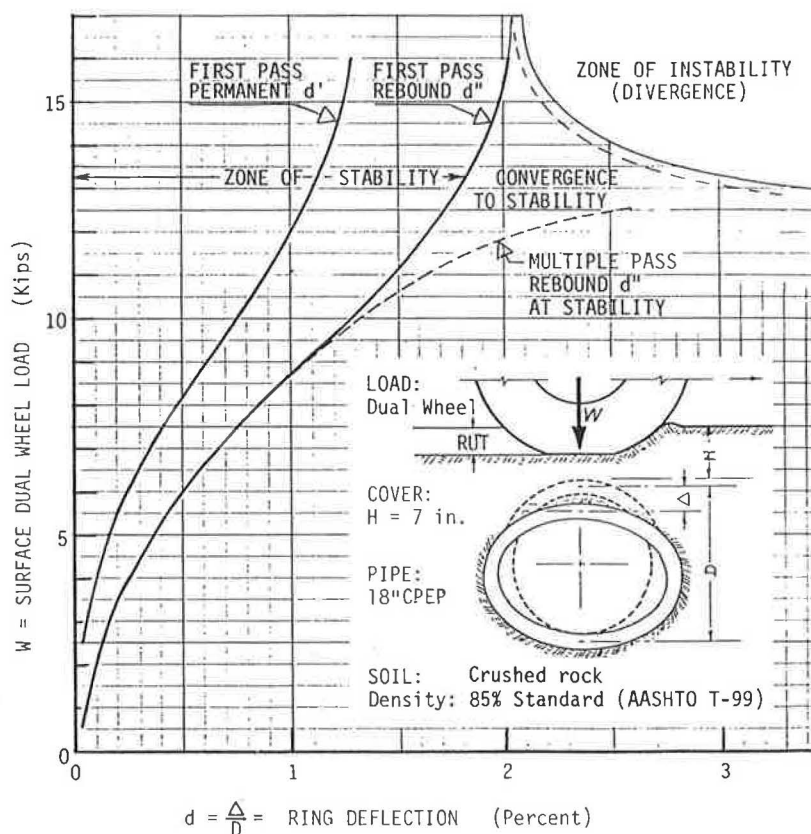


FIGURE 6 Typical load-deflection diagram for 18-in. CPEP under 7 in. of soil cover of 85 percent standard Proctor density (AASHTO T-99), comparing permanent ring deflection d' and rebound ring deflection d'' and showing approximate zone of instability.

rebound ring deflection are both less than 2 percent for dual-wheel loads up to 16 kips.

2. For multiple passes, the rebound ring deflection stabilizes if dual-wheel loads are less than about 12.5 kips. The stabilized ring deflection is greater than the first-pass ring deflection (see the lower dotted graph of Figure 6). At dual-wheel loads greater than about 12.5 kips, rebound ring deflections may increase progressively toward instability.

For minimum soil cover of 12 in., no instability occurred. Ring deflections are much less than 2 percent.

For multiple passes of HS-20 loads over buried CPEP, the recommended minimum soil cover is 12 in. To assure a successful installation, it may be prudent to specify pipe zone backfill up to the ground surface of crushed rock passing the 1.0-in. sieve or less and compacted in 8-in. layers to at least 90 percent standard Proctor density (AASHTO Specification T-99). The 12-in. soil cover includes some surfaces such as asphalt. In fact, a good surface eliminates the rutting. For a reinforced-concrete slab, the minimum cover may be reduced. If the preceding conditions are met, ring deflection is not a performance limit unless it causes unacceptable cracking of the surface over the pipe. Slight cracking of the surface is possible above both rigid and flexible pipes under minimum soil cover. The remedies are to increase the soil cover over the minimum, to use concrete backfill, to densely compact the

select pipe zone backfill, or to cast a reinforced concrete slab on the surface.

For minimum cover, these observations apply to all pipe diameters if all length dimensions are scaled proportionately. Ring deflections d and dimpling remain unchanged for all diameters of pipe under the same soil, density, cover, and load. Pipes larger than 24 in. should be studied further.

Maximum Soil Cover

Maximum soil cover is the height of soil cover H for greater than which ring deformation is excessive. Excessive ring deformation is the basic performance limit. It is identified as either (a) ring deflection d so great that flow is impeded, or (b) visible dimpling of the crests of corrugations at 9 and 3 o'clock inside the pipe. Dimpling portends wall crushing or wall buckling. Both effects can lead to the formation of plastic hinges, a condition for instability.

In terms of stress, dimpling occurs when compressive stress exceeds the strength of material. Critical compressive stress σ is the sum of ring compression stress and ring deflection stress, that is,

$$\sigma = Pr/A + 3Ecd/[r(1 - 2d)] \quad (5)$$

where

- σ = circumferential compression stress,
 Pr/A = ring compression stress,
 $3Ecd/[r(1-2d)]$ = ring deflection stress as the circular ring deforms into an ellipse,
 E = modulus of elasticity,
 r = mean radius of the pipe,
 A = area of cross section of pipe wall per unit length of pipe,
 P = vertical soil pressure at the level of the top of the pipe,
 c = distance from neutral surface of the corrugation cross section to the inside corrugation crest, and
 d = ring deflection.

If ring deflection is controlled so that $d = 0$, then stress σ is simply ring compression stress. However, the contribution of ring deflection toward dimpling is usually significant.

Ring deflection is determined by pipe stiffness and compaction of the backfill. However, the effect of pipe stiffness is negligible if the backfill is dense and if ring deflection does not include initial ring deflection due to soil compaction. Such ring deflection becomes

$$d = \epsilon \quad (6)$$

where

- $d = \Delta/D$ = ring deflection excluding ring deflection due to soil compaction;
 Δ = decrease in vertical diameter due to vertical soil pressure P ;
 D = initial, vertical, mean diameter with dense backfill already in place about the pipe;
 ϵ = soil compression, i.e., vertical soil strain due to load P ;
 P = vertical soil pressure at the level of the top of the pipe;
 $P = P_d + P_l$;
 $P_d = \gamma H$ = dead weight of soil cover;
 $P_l = f(W)$ = vertical live-load soil pressure on the pipe due to surface load W , usually calculated by Boussinesq formula;
 H = height of soil cover over the pipe;
 γ = unit weight of the soil cover; and
 W = surface live load crossing over pipe.

Because maximum soil cover H is usually more than 8 ft, the live-load pressure due to an HS-20 dual-wheel load is less than $P_l = 100 \text{ lb/ft}^2$, and so can be neglected. If live-load pressure is included, it is not treated as an approaching load. P_l is simply added to P_d . If a vertical load-deflection (P versus ϵ) diagram is available for the compacted backfill, then at the anticipated vertical soil pressure P the corresponding soil strain ϵ can be read directly. From Equation 6, the approximate ring deflection $d = \epsilon$ can be predicted. Figures 7 and 8 show typical plots of high soil cover tests performed at

Utah State University on CPEP. The plot relates ring deflection d to vertical soil pressure P in granular backfill compacted to 85 percent standard Proctor density (AASHTO Specification T-99). The most important observation is that the pipe-soil conduit is stable up to a vertical soil pressure of $P = 7.5 \text{ kips/ft}^2$. At this pressure, the ring deflection is roughly $d = 13$ percent. Figure 8 shows the relationship of ring deflection to soil pressure in loose backfill at 75 percent density for which the pipe-soil conduit is stable up to soil pressure of $P = 4 \text{ kips/ft}^2$. Equation 5 is of the form $\sigma = Pr/A + Kcd/[r(1-2d)]$, where K includes modulus of elasticity E and a number of minor variables. From Figures 7 and 8 assuming the same σ at dimpling in each, $K = 0.329 \text{ ksi}$, and apparent yield point stress is $\sigma = 3.57 \text{ ksi}$. Substituting these values into Equation 5 and solving for P ,

$$P = A\{3.57 - [0.239cd/[r(1-2d)]]\} / r$$

For 18-in. CPEP, this equation reduces to

$$P = [10.1 - 15d/(1-2d)] \text{ksf}$$

The following is a table of values for 18-in. CPEP.

d (%)	P (ksf)	H (ft)	H/sf (ft)
0	10.1	84.4	33.8
5	9.3	77.2	30.9
10	8.2	68.5	27.4
15	6.9	57.4	23.0
20	5.1	42.5	17.0
25	2.6	21.7	8.7

The values for H are based on unit weight of soil of 120 lb/ft^3 . The allowable values of H/sf are based on a safety factor of $sf = 2.5$. Figure 9 is a plot of P as a function of d from the table. The safety factor of $sf = 2.5$ is higher than necessary if the backfill is good granular soil. On the other hand, if the backfill is marginal, or if the pipe is installed carelessly, a generous safety factor may be justified because of the high cost of repair or replacement.

The use of quick-load strength rather than 50-year strength is appropriate for design. If polyethylene is held under constant deformation, such as the ring deformation of a pipe buried in select pipe zone backfill under a high soil cover, stresses in the polyethylene relax. The highest stresses are the initial stresses generated at the time of installation.

Example: Maximum Soil Cover

What is the maximum height of soil cover H allowed for 18-in. CPEP pipe if the backfill is to be granular soil at 90 percent standard density? Figure 10 is a hypothetical graph of a laboratory compression test on the granular backfill. The answer to the question is simply the point of intersection of the graph of Figure 9 and the 90 percent graph of Figure 10. This is easily done by inspection or by plotting Figure 9 on Figure 10. $P = 9.7 \text{ kips/ft}^2$. If the soil unit weight is 120

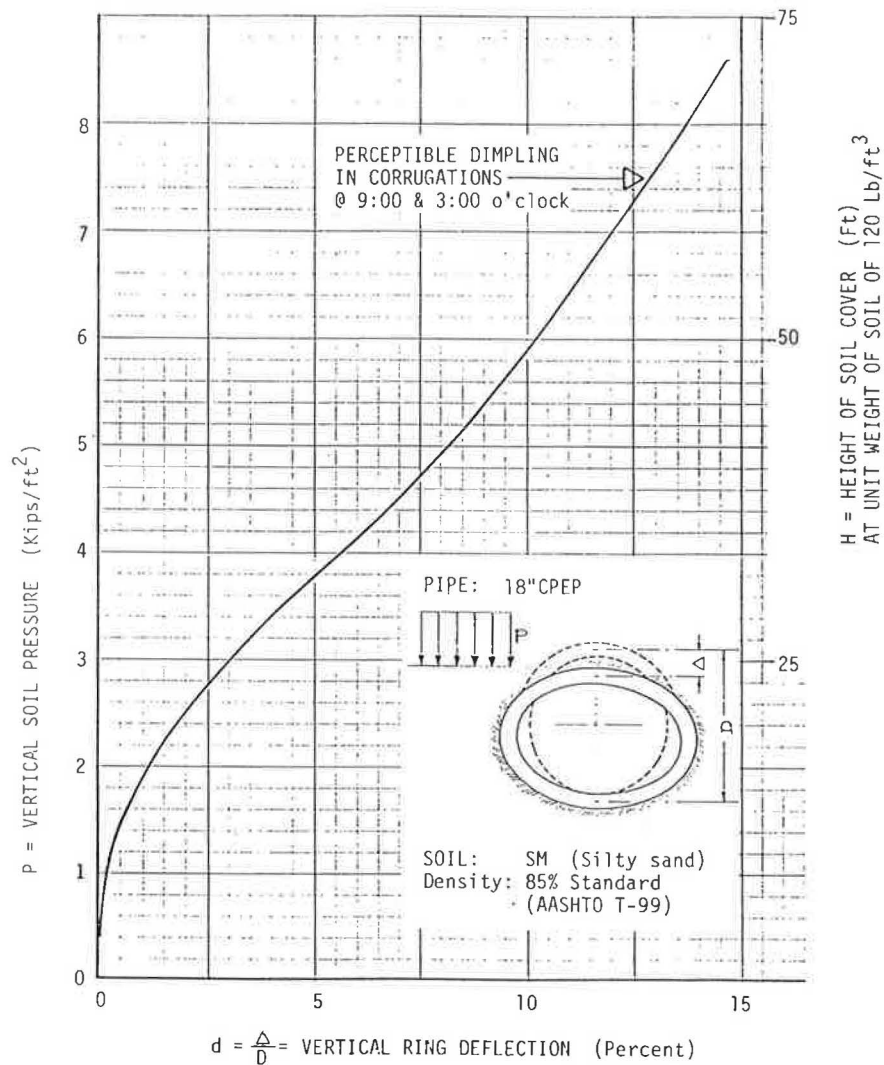


FIGURE 7 Typical load-deflection diagram for 18-in. CPEP buried under high soil cover H . (Vertical soil pressure P is a function of H).

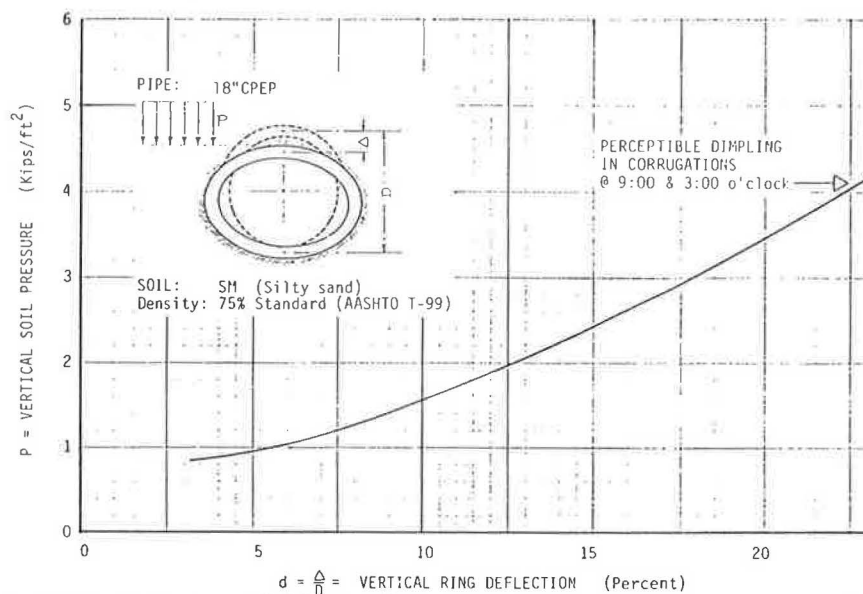


FIGURE 8 Typical load-deflection diagram from a test on 18-in. CPEP under high soil cover where load is the calculated vertical soil pressure P at the top of the pipe, but where the backfill is uncompacted.

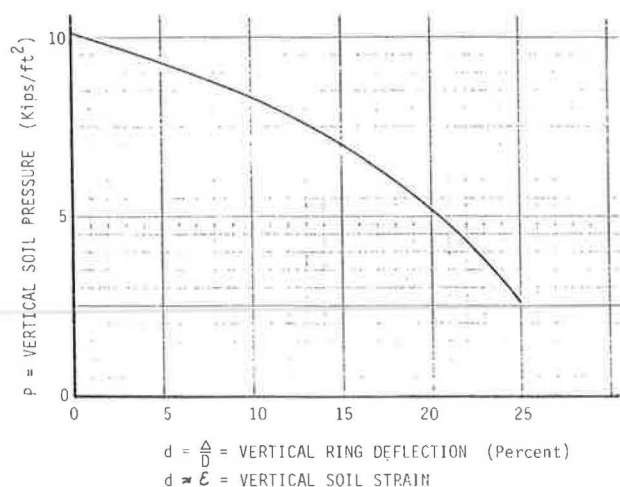


FIGURE 9 Vertical pressure at performance limit (dimpling at 9 and 3 o'clock) as a function of ring deflection for 18-in. CPEP.

lb/ft^3 , then at dimpling, the maximum height of soil cover is $H = 81$ ft. If a safety factor of 2.5 is called for, $H/sf = 32$ ft of allowable soil cover.

It is clear that the best control of the pipe-soil conduit under maximum soil cover is control of the backfill. Specifications should establish minimum values for compacted density and should assure competent granular material.

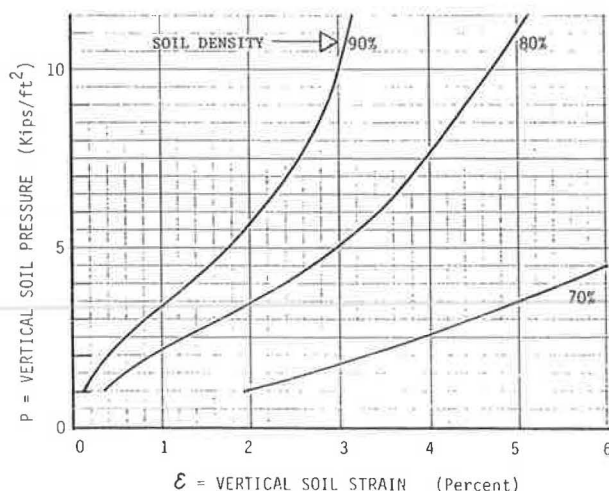


FIGURE 10 Hypothetical graphs of vertical soil stress as a function of vertical soil strain for granular soil from compression tests in the laboratory.

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