# Minimum Cover Heights for Corrugated Plastic Pipe Under Vehicle Loading 

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#### Abstract

The minimum soil cover requirements are provided for corrugated plastic pipe (high density polyethylene) to safely withstand vehicular loading when the pipe is installed under roadways such as in culvert applications. Pipe diameters ranging from 12 to 36 in. and all pipe wall corrugations currently produced are also included. Design criteria are adopted from AASHTO specifications, and it is discussed that the allowable deflection criterion, 7.5 percent of the pipe diameter, controls the minimum soil cover requirement. It is also discussed that by increasing the corrugation's moment of inertia or improving the quality of the soil or both the minimum soil cover requirement can be reduced. Design solutions are obtained with aid of CANDE, the plane strain computer program. A new methodology is introduced to account for the three-dimensional effects of tire loads (H-trucks) in the context of a plane strain analysis. The design/analysis methodology is shown to compare favorably with field data for shallow buried plastic pipes with simulated $\mathrm{H}-20$ truck loadings. As a final result, design tables and guidelines are presented that specify the minimum required soil cover as a function of pipe diameter, H-truck loading, corrugation section properties, and soil type and percent compaction. Also, the results are extended to railroad loadings.


The objective is to establish minimum soil height requirements for high density polyethylene (HDPE) corrugated plastic pipe to safely withstand loadings from roadway vehicles (H-trucks). The final results are tabulated in easy-to-use charts and guidelines that give the minimum cover height as a function of pipe diameter and flexural stiffness, soil type and percent compaction, and H -truck loading.

## BACKGROUND

A previously completed companion study (1) provides maximum allowable fill heights for the same class of HDPE corrugated plastic pipes that are considered in this study for minimum cover. The major source of loading for deeply buried pipes is the gravity weight of soil as opposed to the additional soil stresses from vehicle surface loads that disperse rapidly with depth. The loads on the pipe for minimum cover primarily are due to the surface loading. A minimum amount of soil cover is needed to spread the surface loading and to create a more favorable soil pressure distribution around the pipe. With too little soil cover the pipe will experience high pressure concentrations at the crown and cause collapse.

Vehicular loadings, unlike well-defined gravity loads, vary

[^0]widely in load magnitude and distribution owing to the wide variety of vehicle types. Other difficulties associated with defining vehicular loading include impact, cyclic frequency, load shift, and wind. Also, construction equipment used during the placement of the pipe can cause greater loads on the pipe than the vehicular loads for which the pipe has been designed. Thus, the minimum cover requirement is a more challenging design problem than the maximum fill height.

Currently, the tentative guideline for minimum cover of plastic pipe, as suggested by the AASHTO Flexible Culvert Committee, is taken directly from the metal culvert industry, the American Iron and Steel Institute (AISI) (2). The AISI specification for corrugated metal culverts requires a minimum of 12 in . of soil cover for all pipe diameters up to 96 in . Paving material, if any, is not permitted to be included in the $12-\mathrm{in}$. minimum cover owing to the concern of construction loads prior to paving. This requirement is based on long-time observations by the corrugated steel pipe industry of structural performance under live loads.

Corrugated plastic pipes are considerably more flexible in ovaling deformation than are typical corrugated steel pipes of the same diameter. Consequently, it is natural to ask if the minimum 12-in. cover is adequate for plastic pipe, and, if not, what is the requirement and what does it depend on. Herein lies the motivation behind the stated objective.

## APPROACH AND SCOPE

The finite-element program CANDE (3), a proven methodology for soil-structure interaction analyses of buried conduits, is used with established design criteria to achieve the design objective, which are the minimum cover requirements for corrugated plastic pipe. Experimental data are used to verify the analytical assumptions.

The following step-by-step procedure outlines the approach and scope presented in this paper.

1. Establish H-truck loadings: Five loading cases are considered based on AASHTO truck definitions: H-10, H-15, H$20, \mathrm{H}-25$, and H-30. Conservative assumptions are employed to define contact area and pressure magnitude for each truck's tire footprint.
2. Identify plastic pipe properties: Six pipe sizes are considered: $12,15,18,24,30$, and 36 in . diameter pipe. Crosssectional properties are defined for each pipe size, and material properties for short-term loading are identified.
3. Introduce design/analysis methodology: The CANDE plane strain computer program is reviewed along with the soil modeling assumptions. A new technique for modeling the tire loads is presented and followed by the design criteria for plastic pipe.
4. Perform parametric studies: The influence of design variables (cross-section properties, quality of soil, and cover height) are examined in conjunction with the design criteria to establish the controlling criterion.
5. Compare analysis with experimental data: The design/ analysis procedure is verified with experimental field data, and conservatism is demonstrated.
6. Present final design results: Minimum cover height tables are given for each pipe size as a function of H -truck loading, pipe stiffness, and soil quality. Interpolation schemes and design examples are also given.

The final section, containing the design results, is selfcontained so the reader may make use of this section without referring to previous sections.

## H-TRUCK LOADINGS

## H-Truck Definition

The H-truck loading, as defined by AASHTO and presented in Figure 1 is designated by the symbol $H$-x where $x$ is one half of the total gross weight of the truck expressed in kips. The H-truck loading has two axles: 80 percent of the total gross weight is assigned to the rear axle and the remaining 20 percent is assigned to the front axle. Tires (single or dual) carry one-half the axle load. For example, the $\mathrm{H}-20$ truck has a total gross weight of 40 kips , a rear axie load of 32 kips , and a rear tire load of 16 kips .

The H-truck loading definition does not necessarily represent a real truck. Rather, it is a reference design vehicle developed by U.S. bridge engineers to serve as a worst case or umbrella loading for all vehicles whose actual load distributions (e.g., axial loads or spacing or both) are less severe to bridge design than the H -truck loading.

## Tire Load Distribution

The tire contact area on the roadway surface must be known in addition to the tire load to determine the minimim soil cover requirements for culverts. For any given tire loading (e.g., 16 kips for the rear tire of an $\mathrm{H}-20$ truck) the air pressure in the tire is a close approximation to the average contact pressure between the tire and roadway surface. Accordingly, the tire contact area (or tire footprint) may be computed by dividing the tire loading by the tire air pressure.

A high-pressure tire induces more structural distress in a shallow buried culvert than does an equally loaded lowpressure tire because the low-pressure tire distributes the load over a larger area. The tire air pressure of interstate trucks ranges from 65 to 100 psi. Because the AASHTO H-truck loading definition does not include specifications of tire air


FIGURE 1 H-truck loading and tire pressure distribution.

TABLE 1 H-TRUCK LOADING ON REAR TIRE

| Truck <br> Type | Gross Wt. <br> (kips) | Rear Tire Wt, <br> (kips) | Tire length <br> (inches) | Tire width <br> (inches) |
| :---: | :---: | :---: | :---: | :---: |
| H10 | 20 | 8 | 10 | 8 |
| H15 | 30 | 12 | 10 | 12 |
| H20 | 40 | 16 | 10 | 16 |
| H25 | 50 | 20 | 10 | 20 |
| H30 | 60 | 24 | 10 | 24 |

Tire (single or dual) pressure $=100$ psi.
pressure, conservative assumptions are presented next based on a tire pressure of 100 psi.

## Tire Loading Assumptions For Culvert Analysis

Table 1 supplies the five H-truck loadings as defined by AASHTO along with the assumed dimensions of a rectangularshaped footprint for the rear tire. In each case the tire pressure is taken as 100 psi , which is an upper-bound value for actual tire pressures. The footprint length, in the direction of travel, is taken as 10 in ., which is a nominal average of actual footprint lengths. With the tire pressure and footprint length so defined, the footprint width becomes a function of the H truck rear wheel loading and is easily determined by force
equilibrium. The implication is that as the H -truck series increases the additional load is accommodated by wider tires or the use of dual tires or both, thereby distributing the load along the rear axle. This method of distributing the rear wheel load presents a worse loading condition on a buried culvert than if the load were distributed in the direction of travel (e.g., increased footprint lengths or tandem axles or both).

No further load enhancements (wind, impact, load shift, etc.) appear justifiable in view of all the conservative assumptions employed in defining the tire loads and the pressure distributions. Thus, H-loading defined in Table 1 will constitute the net live load for subsequent design process.

## CORRUGATED PLASTIC PIPE PROPERTIES

## Section Properties

Corrugated plastic pipes are referenced by the inside diameter (also called the pipe size, e.g., 24 -inch pipe). Unlike the corrugated metal pipe industry, the manufacturers of corrugated plastic pipe do not employ a standardized set of corrugated shapes for each pipe diameter. Rather, a typical plastic pipe manufacturer makes only one corrugation size per pipe size. However, the corrugated shape made by one manufacturer and that of another differs somewhat in material thickness and in shape and height of the corrugation. As a consequence, the key sectional properties, cross-sectional area per unit length, and moment of inertia per unit length vary from manufacturer to manufacturer. This variation of section properties is accommodated in the design process.

In general, the robustness of a corrugated pipe can be assessed by the hoop stiffness, which is proportional to the corrugated section area, and by the flexural (ovaling) stiffness, which is proportional to the corrugation moment of inertia. The moment of inertia is the key section property that controls the minimum cover height for shallow buried pipes subject to vehicular loading because deflection by ovaling is almost always the controlling design criterion. Conversely, the cross-sectional area does not influence the minimum cover height as long as its value is greater than a certain minimum value that precludes thrust stress from controlling the design. The validity of those statements is amply demonstrated later in this study.

The following geometrical relationships, based on a previous survey study of corrugated section properties produced by five of the largest plastic pipe manufacturers (1), are noted for pipe sizes $12,15,18,24,30$, and 36 in.:

1. The average cross-sectional corrugated area $A$ is related to the inside pipe diameter $I D$ (inches) by the empirical expression

$$
\begin{equation*}
A=(I D+4.5) / 10 \quad \text { (in.2/in.) } \tag{1}
\end{equation*}
$$

2. The average corrugation height (i.e., one-half of the distance between outside and inside diameter) is related to $I D$ by the expression
$h=I D / 11$
3. The upper- and lower-bound moment of inertia that comfortably brackets all actual data is given by the dimensionally correct expressions
$I_{\text {max }}=A h^{2} / 5$
$I_{\text {min }}=A h^{2} / 10$
The moment of inertia will be treated as a design variable varying between the limits $I_{\text {min }}$ and $I_{\text {max }}$, and the crosssectional area and corrugation height will be assigned their average values.

## Pipe Material

Polyethylene exhibits significant creep behavior under longterm constant loading (4). Thus, the effective short-term modulus is considerably higher than the long-term modulus. Table 2 summarizes the AASHTO M294 specification and indicates that the recommended modulus for the short term is five times more than long term ( 50 years).

Strength behavior is not as well studied or understood as stiffness. The AASHTO specifications, as presented in Table 2 , are based on tensile stress-strain experiments, which exhibit nearly unlimited ductility without rupture. Those strength values are assumed to hold for compression and tension and are generally considered to be conservative.

Although the duration of the short-term loading period is not explicitly defined by AASHTO, the short-term plastic properties are considered appropriate for shallow buried pipe subject to vehicular loads. The validity of this assumption is demonstrated with experimental field data later in this study.

## METHOD OF ANALYSIS/DESIGN

## CANDE Analysis

CANDE, an acronym for culvert analysis and design, is a well-known and well-accepted finite-element computer program developed especially for the structural design and analysis of buried conduits $(3,5,6)$. Both the pipe and the surrounding soil envelope are incorporated into an incremental, static, plane strain formulation. The pipe is modeled with a connected sequence of beam-column elements, and the soil is modeled with continuum elements by using a revised Duncan hyperbolic soil model (5). The fundamental analysis assumptions are small deformation theory, linear elastic polyethylene properties (short term), and a bonded pipe-soil interface.

TABLE 2 POLYETHYLENE MATERIAL PROPERTIES

| Time Period <br> (rel) | Young's Modulus <br> (psi) | Design Strength <br> (psi) |
| :---: | :---: | :---: |
| Short term | 110,000 | 3,000 |
| Long term | 22,000 | 900 |

The gravity loading of the soil is applied in the first load step for the analysis of each pipe-soil system with a specified minimum cover. Next, the H-truck rear wheel loading, as defined in Table 1, is simulated by applying increments of pressure to the soil surface over a $10-\mathrm{in}$. segment (i.e., footprint length) centered directly above the pipe. Note only one rear wheel of the H-truck vehicle need be considered because the other wheels are too far away to add to the local deformation of the pipe under the wheel being considered. The method of analyzing the effects of various footprint widths (out-of-plane) is discussed next.

## H-Truck Load Representation

Because CANDE is a two-dimensional plane strain formulation, the footprint length $2 L$ in Figure 1 can be modeled exactly. However, plane strain analysis infers that the footprint width is infinitely deep, as is illustrated on the right side of Figure 1. To reasonably simulate a finite footprint width as pictured in the left side of Figure 1, the plane strain pressure $P_{s}$ should be appropriately reduced from that of the actual tire footprint pressure $P_{t}$, that is,
$P_{s}=r P_{r}$
where $r$ is a reduction factor (less than 1.0). This reduction is required because the soil stress associated with $P$, diminishes more rapidly with depth than does the soil stress associated with $P_{s}$ (i.e., two-dimensional load spreading versus onedimensional load spreading).

To compute the reduction factor, use is made of an exact elasticity solution for a homogenous half space (no pipe) loaded by the pressure $P_{\text {, }}$ acting on a rectangular footing with dimensions $2 L$ by $2 b$ (7). The solution for vertical soil stress as a function of depth $z$ beneath the center of pressure is given by

$$
\begin{align*}
S_{t}= & 2 P_{t}\{\arctan (B / Z R 3)+B Z[1 /(R 1 R 1 R 3) \\
& +1 /(R 2 R 2 R 3)]\} / \pi \tag{5}
\end{align*}
$$

where

$$
\begin{aligned}
B & =b / L \\
Z & =z / L \\
R 1 & =\sqrt{(1+Z Z)}, \\
R 2 & =\sqrt{(B B+Z Z)}, \\
R 3 & =\sqrt{(1+B B+Z Z)}, \text { and } \\
\pi & =3.14
\end{aligned}
$$

Similarly, the vertical soil stress for the pressure $P_{s}$ acting on an infinite strip of dimension $2 L$ (i.e., width $2 b$ is infinite) is given by
$S_{s}=2 P_{s}\{\arctan (1 / Z)+Z /(R 1 R 1)\} / \pi$
By equating $S_{t}=S_{s}$ from Equations 5 and 6 and solving for the reduction factor $\left(r=P_{s} / P_{t}\right)$,
$r=\frac{\arctan (B / Z R 3)+B Z /[1 /(R 1 R 1 R 3)+1 /(R 2 R 2 R 3)]}{\arctan (1 / Z)+Z /(R 1 R 1)}$

The reduction factor is a function of the footprint dimensions ( $2 b$ by $2 L$ ) and the depth at which the soil stress equality is desired. This depth, which is nondimensionally expressed as $Z=z / L$, is, for the moment, unspecified.

Table 3 supplies the reduction factors as a function of $Z$ for each of the H-truck footprint dimensions defined in Table 1. Note that the reduction factor decreases with depth and increases tire loading (footprint width).

A reasonable depth to establish "soil stress equivalence" is somewhere between the crown and springline elevation. For this study the depth is taken midway between the crown and springline elevations, which are based on comparisons with experimental data (shown later). Thus, the nondimensional depth $Z$ is taken as
$Z=[H+I D / 4] / L$
where $H$ is the soil cover height above crown and $L$ is onehalf the footprint length ( 5 in . for all H-Trucks).

To illustrate the use of Table 3 together with Equation 8, suppose a plane strain analysis (e.g., CANDE) is performed for a $24-\mathrm{in}$. pipe under 12 in . of soil cover and loaded by an H-20 truck tire ( 100 psi ). From Equation $8 Z=18 / 5=3.6$, and from Table $3 r=0.57$. Therefore, in accordance with Equation 4, the "equivalent pressure" to be used in plane strain analysis is $P_{s}=57 \mathrm{psi}$.

## Soil Model

All design cases are analyzed for two soil conditions generically called "fair" and "good" quality soil. Specifically, those two cases are represented by the Duncan soil models for silty clayey sand at 85 percent compaction (fair $=\mathrm{SC} 85$ ) and silty clayey sand at 100 percent compaction (good $=$ SC, 100). Table 4 supplies the Duncan model parameters for those two soil conditions. More general interpretations for those two "bracketing" cases are given in the last section, allowing the solutions to be interpolated over a range of soil types and percent compaction.

TABLE 3 REDUCTION FACTOR FOR STRIP PRESSURE

| Depth Ratio | H-Truck designation and ratio (b/L) |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Z $=2 / \mathrm{L}$ | H10 | H15 | H20 | H25 | H30 |  |
|  | $(0.8)$ | $(1.2)$ | $(1.6)$ | $(2.0)$ | $(2.4)$ |  |
| 1.2 | .72 | .86 | .93 | .96 | 98 |  |
| 1.8 | .56 | 73 | .84 | .90 | .94 |  |
| 2.4 | .45 | .62 | 74 | .82 | .88 |  |
| 3.0 | .37 | 52 | .65 | 74 | .81 |  |
| 3.6 | .32 | .45 | 57 | .67 | .74 |  |
| 4.2 | .28 | .40 | 51 | .60 | .68 |  |
| 4.8 | .44 | .35 | .46 | .55 | .62 |  |
| 5.4 | .22 | .32 | .41 | .50 | .57 |  |
| 6.0 | .20 | .29 | .38 | .46 | .53 |  |
| 6.8 | .18 | .27 | .35 | .42 | .49 |  |
| 7.2 | .16 | .24 | .32 | .39 | .46 |  |
| 7.8 | .15 | .23 | .30 | .36 | .43 |  |

TABLE 4 STANDARD HYPERBOLIC PARAMETER (7)

| $\begin{aligned} & \text { Soil } \\ & \text { Type } \end{aligned}$ | $\begin{gathered} \$ \\ (\mathrm{deg}) \end{gathered}$ | $\begin{gathered} d \phi \\ (\operatorname{deg}) \end{gathered}$ | $\begin{gathered} c \\ (\mathrm{psf}) \end{gathered}$ | K | I | Rf | Kb | m |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| (SC-85) | 330 | 0.0 | 200. | 100 | 0.6 | 0.7 | 50.0 | 0.5 |
| (SC-100) | 330 | 0.0 | 500 | 400. |  | 0.7 | 2000 | 0.5 |

TABLE 5 DESIGN CRITERIA FOR POLYETHYLENE PIPE

| Distress Measure | Allowatile Limit |
| :--- | :--- |
| (1) Thrust stress | $1 / 2$ Design strength* |
| (2) Flexural strain | 5.08 in outer fiber |
| (3) Relative deflection | 7.58 of ID (vertical) |
| (4) Buckling pressure | $1 / 2$ Critical pressure** |

* From Table 2, Design strength $=3000$ psi (short term).
** Critical buckiing pressure from Chelapati-Allgood (4).


## Design Criteria

The design criteria are a set of maximum allowable structural responses for which the pipe is considered structurally safe against various modes of distress. Table 5 explicitly lists the four design criteria where the measures of pipe distress are thrust stress, relative deflection, flexural strain, and buckling pressure. Those criteria satisfy the AASHTO requirements for Service Load Design and are regarded as reasonably conservative. As is indicated in the next section, the relative deflection criterion ( 7.5 percent of pipe diameter) controls the design for minimum cover height in all cases.

## ANALYTICAL RESULTS AND COMPARISONS

## Parametric Studies

A parametric study is presented to demonstrate how the predicted responses for the design criteria are influenced by the key system variables: corrugated section area, moment of inertia, soil quality, height of soil cover, and pavement overlay. Figure 2 illustrates a baseline system composed of a 24 in. plastic pipe with 12 in . of fair quality soil cover without a pavement overlay. Table 6 supplies the baseline values for each of the key variables along with two parametric variations per variable. CANDE solutions are obtained for each individual variation, inferring 10 separate solutions in addition to the baseline solution. Each CANDE solution is obtained by first applying the gravity loading followed by increments of live load pressure up to 120 psi .

Figure 3 presents the parametric influence of the corrugated section area where the analytical predictions for thrust stress, flexural strain, relative deflection, and buckling pressure are presented as a function of live load pressure. Those responses are given as ratios to the corresponding allowable design criterion previously defined in Table 5. For example, the deflection ratio is the predicted deflection divided by 7.5 percent of the diameter, the thrust ratio is the predicted thrust stress divided by one-half the yield stress, and so on. The allowable


FIGURE 2 Baseline problem for parametric study.

TABLE 6 KEY PARAMETER VALUES AND VARIATIONS

| Variable name | Baseline value | $\begin{aligned} & \text { Variation* } 1 \\ & \text { value } \end{aligned}$ | Variation*2 value |
| :---: | :---: | :---: | :---: |
| Section Area (in ${ }^{*}$ /in) | 030 | 0.25 | 0.35 |
| Mom Inertia (in $4 /$ in) | 0.18 | 0.12 | 024 |
| Cover Height (in) | 12. | 24. | 36. |
| Soil Quality | $\begin{aligned} & \text { Fair } \\ & \text { (SC 85) } \end{aligned}$ | Medium (SC 95) | Good (SC 100) |
| Payement Overlay | None | Asphalt ( 6 inches) | Concrete ( 6 inches) |

pressure loading has been reached when a response ratio reaches the value of 1.0 .

Figures 4-7 are presented in an identical format to Figure 3 and indicate the parametric influence of the remaining key variables supplied in Table 6. The following observations can be made from those figures:

1. Deflection is the controlling design criterion in all cases. That is, the deflection ratio reaches the value of 1.0 at a lower live load pressure than do the other corresponding response ratios (Figures 3-7).
2. The corrugated section area has negligible influence on the deflection, whereas increases in the moment of inertia help to reduce the deflection (Figures 3 and 4).
3. Improving the soil quality or increasing the cover height or both significantly reduces the deflection (Figures 5 and 6).
4. Paving material (asphalt or concrete) greatly reduces all structural distress including deflections (Figure 7). However, as is discussed earlier, it is not usually possible to take design advantage of the paving material because the pipe must support construction loads prior to placement of paving material.
5. The results in Figures 3-7 may be correlated to H-truck loading by computing the nondimensional reference depth given by Equation 8 and then referring to Table 3 to get the equivalent surface pressure. For example, the equivalent pressure for an H-20 truck is 57 psi for cover heights of 12 in .

SECTION AREA SERIES

| $0-0$ | $0.30 \mathrm{tn}^{2} \mathrm{~m}$ |
| :---: | :---: |
| $x \longrightarrow$ | 0.25 |
| $\triangle$ - | 0.35 |



FIGURE 3 Influence of corrugated section area on design criteria.

## Comparison with Experimental Data

Watkins and Reeve (8) in 1982 completed a comprehensive experimental test program to determine the live load deflection of plastic pipe as a function of soil cover and soil compaction. They investigated the response of a $24-\mathrm{in}$. corrugated plastic pipe subjected to an H-20 truck loading, simulated by a John Deere tractor ( 16 kips per wheel) as illustrated in Figure 8.

A sequence of tests was performed where the backfill soil, described as a sandy clayey silt, was compacted to densities ranging from 75 to 95 percent AASHTO standard. The soil cover height was varied for each soil density from 12 to 36 in., and the deflections were measured at 10 locations for each test. Statistical curves were derived to give deflections as a function of fill height at a confidence level of 95 percent (i.e., the curves are conservative because 95 percent of the deflection data falls below the curves). Figure 9, taken directly from Watkins and Reeve (8), presents two such curves for soil densities of 75 and 95 percent.

Also presented in Figure 9 are the CANDE deflection predictions for both fair and good quality soil. The predictions are based on the previously established methodology, that is, short-term polyethylene properties and $\mathbf{H}-20$ truck tire representation. The corrugated section properties, supplied in Figure 8 , are taken as reported by the pipe supplier (1).

The analytical predictions for fair soil and good quality soil track well, but conservatively, with the experimental curves for 75 and 95 percent soil density, respectively. Those results

MOMENT OF INERTIA SERIES



FIGURE 4 Influence of moment of inertia on design criteria.

## COVER HEIGHT SERIES



FIGURE 5 Influence of soil cover height on design criteria.


FIGURE 6 Influence of soil type on design criteria.

## PAVING SURFACE SERIES



FIGURE 7 Influence of pavement overlay on design criteria.


FIGURE 8 Watkins-Reeve experiment simulating H-20 truck.


FIGURE 9 Comparison of experimental data with CANDE.
lend credence to the foregoing methodology and the following design solutions for minimum cover.

## DESIGN RESULTS FOR MINIMUM COVER

## Minimum Cover Tables

Table 7 gives the computed minimum soil cover requirements for pipe diameters ranging from 12 to 36 in . as a function of H-truck loading. The cover depths are tabulated for two soil conditions, fair and good. For the fair soil condition the cover depths are given for the lower bound moment of inertia ( $I_{\text {min }}$ ) and the upper-bound moment of inertia $\left(I_{\max }\right)$, which brackets the range of corrugated cross sections produced by plastic pipe manufacturers. Those values are supplied in Table 8 as computed by Equations 3a and 3b. Design guidelines are given subsequently to determine the required soil cover height for intermediate values of the moment of inertia and various soil conditions.

Table 7 was developed by the following procedure. For each pipe diameter, four CANDE models were established on the basis of the four combinations arising from two soil conditions and two moments of inertia. Each CANDE model was solved for three different soil cover heights (12, 24, and 36 in .) with three increments of live load pressure ( 40,80 , and 120 psi ) applied to the surface of each cover height. The relative displacements predicted by CANDE were recorded in a $3 \times 3$ matrix for each model (i.e., relative displacements as a function of cover height and surface pressure). The pressure level corresponding to each of the five H -truck loads was determined by using this matrix as a data base in accordance with Table 3, and a special interpolation/extrapolation scheme was devised to determine the required cover height for which the predicted displacement would match the allowable displacement ( 7.5 percent of the diameter).

If the computed cover height requirement was less than 12 in., then the absolute minimum requirement of 12 in . was enforced. The absolute minimum requirement always governed for good soil so that cover height was 12 in . for any moment of inertia greater or equal to the lower bound, $I_{\text {min }}$. The other design criteria supplied in Table 5 were checked, but in all cases the deflection criterion or the $12-\mathrm{in}$. minimum requirement controlled.

It may be somewhat surprising to note that the larger diameter pipes generally required less cover depth than that of a smaller diameter pipe with the same loading. This is because pipe manufacturers make larger pipes more robust than smaller pipes, as demonstrated by the average flexibility factor listed in the last column of Table 8 (i.e., the flexibility factor decreases with increasing pipe diameter).

## Design Guidelines

A quick and conservative estimate of the minimum required soil cover can be read directly from Table 7 by assuming a pipe's corrugation provides only a minimum moment of inertia and the soil quality is only fair. Under those assumptions, for example, Table 7 indicates that an 18 -in. pipe for $\mathrm{H}-20$ loading requires 18 in . of soil cover.

If, however, the pipe's actual moment of inertia is known, say, $I^{*}$, or the actual quality of the soil is known (i.e., soil type and percent compaction), or both, then the minimum required soil cover, called $H^{*}$ can be accurately determined by the following interpolation scheme:
$H^{*}=H 1(1-q)(1-r)+H 2(q)(1-r)+12(r)$
where

$$
\begin{aligned}
H 1 & =\text { cover height for fair soil and } I_{\min } \text { (column } 1 \text { of Table } \\
& 7 \text { ), } \\
H 2= & \text { cover height for fair soil and } I_{\max } \text { (column } 2 \text { of Table } \\
& 7 \text { ), } \\
r= & \text { a ratio from } 0 \text { to } 1 \text { depending on soil quality (Table } \\
& 9), \text { and } \\
q= & \left(I^{*}-I_{\min }\right) /\left(I_{\max }-I_{\min }\right) \text { (a computed ratio using } \\
& \text { Table } 8) .
\end{aligned}
$$

The soil quality ratio $r$ was developed in a previous study (1) and is presented in Table 9 as a function of soil type and percent of standard compaction.

TABLE 7 MINIMUM COVER HEIGHT IN INCHES

| $\begin{array}{r} \text { ID } \\ (\mathrm{in}) \end{array}$ | H-truck$(\mathrm{H}-\mathrm{x})$ | Fair Soil |  | $\frac{\text { Good Soil }}{I \mathrm{~min}}$ |
| :---: | :---: | :---: | :---: | :---: |
|  |  | Imin | Imax |  |
| 12 | H-10 | 12 | 12 | 12 |
|  | H-15 | 16 | 12 | 12 |
|  | H-20 | 19 | 15 | 12 |
|  | H-2.5 | 21 | 17 | 12 |
|  | H-30 | 23 | 19 | 12 |
| 15 | H-10 | 12 | 12 | 12 |
|  | H-15 | 14 | 12 | 12 |
|  | H-20 | 18 | 14 | 12 |
|  | H-25 | 21 | 16 | 12 |
|  | H-30 | 23 | 18 | 12 |
| 18 | H-10 | 12 | 12 | 12 |
|  | H-15 | 14 | 12 | 12 |
|  | H-20 | 18 | 13 | 12 |
|  | H-25 | 20 | 16 | 12 |
|  | H-30 | 23 | 18 | 12 |
| 24 | H-10 | 12 | 12 | 12 |
|  | H-15 | 12 | 12 | 12 |
|  | H-20 | 15 | 12 | 12 |
|  | H-25 | 18 | 12 | 12 |
|  | H-30 | 20 | 14 | 12 |
| 30 | H-10 | 12 | 12 | 12 |
|  | H-15 | 12 | 12 | 12 |
|  | H-20 | 12 | 12 | 12 |
|  | H-25 | 15 | 12 | 12 |
|  | H-30 | 18 | 12 | 12 |
| 36 | H-10 | 12 | 12 | 12 |
|  | H-15 | 12 | 12 | 12 |
|  | H-20 | 12 | 12 | 12 |
|  | H-25 | 12 | 12 | 12 |
|  | H-30 | 15 | 12 | 12 |

TABLE 8 MAXIMUM AND MINIMUM MOMENT OF INERTIA AND FLEXIBILITY FACTOR

| $\begin{aligned} & \text { ID } \\ & \text { (in) } \end{aligned}$ | $\underset{\left(\operatorname{in}^{-} 4 / i n\right)}{ }$ | $\underset{\left(\min ^{-} 4 / \mathrm{in}\right)}{ }$ | $\begin{aligned} & D=I D+h \\ & (\text { in }) \end{aligned}$ | $\begin{gathered} \mathrm{FF}=\mathrm{D}^{\circ} 2 / \mathrm{EI} \text { avg } \\ (1 / n \mathrm{I} / \mathrm{in}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: |
| 12 | . 02 | 04 | 13.1 | . 052 |
| 15 | 04 | . 08 | 16.4 | . 041 |
| 18 | 06 | . 12 | 19.6 | 039 |
| 24 | . 15 | 30 | 262 | . 028 |
| 30 | . 26 | 52 | 32.7 | . 025 |
| 36 | . 44 | . 88 | 39.3 | . 021 |

As an example of the above, suppose an 18 -in. pipe has a moment of inertia, $I^{*}=0.08 \mathrm{in} . .^{4} / \mathrm{in}$, and that it is installed in a silty sand (SM) compacted to 85 percent standard density. The required minimum soil cover for an $\mathrm{H}-20$ loading is computed as follows. First, the moment of inertia ratio is computed with the aid of Table 8 as $q=(0.08-0.06) /(0.12-$ $0.06)=0.333$. Second, from Table 9 the soil quality ratio is found to be $r=0.5$, and from Table 7 the reference cover heights are found as $H 1=18 \mathrm{in}$. and $H 2=13 \mathrm{in}$. By using

TABLE 9 SOIL QUALITY RATIO FOR SOIL TYPES AND PERCENT COMPACTION

| Soil quality <br> ratio <br> $r$ | Granular <br> SM | Mixed | Cohesive |
| :---: | :---: | :---: | :---: |
| 0.0 (Fair) | 80 | SC | CL |
| 0.25 | 82 | 85 | 8 |
| 0.50 | 85 | 87 | 90 |
| 0.75 | 90 | 90 | 95 |
| 1.0 (Good) | 95 | 95 | 100 |

SM = Silty sand, well graded
SC = Silty clayey sand
$\mathrm{CL}=$ Clay (no organic)
those values in Equation 9 the required minimum soil cover is determined as $H^{*}=18(1-0.333)(1-0.5)+13(0.333)(1$ $-0.5)+12(0.5)=14.2 \mathrm{in}$. Thus, rounding to the nearest inch the required minimum soil cover is 14 in .

## Pavement Overlays

Demonstrated in a previous section was that pavements, asphalt or concrete, are extremely effective in reducing the live load distress on a shallow buried plastic pipe. Nonetheless, the pavement thickness is customarily not included as part of the minimum soil cover requirement because the pipe must be protected by a certain minimum soil cover to withstand the construction loads prior to the placement of the pavement. Thus, in keeping with the metal culvert industry (AISI), the general recommendation offered here is to assume that the thickness of the pavement overlay plays no role in the minimum soil cover requirement.

Conversely, special situations may exist where the engineer is confident that construction loads prior to the placement of pavement will be minimal. An example of such a special situation might be the case of installing a pipe under an existing pavement by tunneling, jacking, or trenching. In this and similar cases the inclusion of the pavement thickness into the required soil cover is justifiable.

## Minimum Soil Cover Under Railroads

The required minimum soil cover for plastic pipes under railroad tracks is the same as that required by an H-30 truck. This equivalence is based on standard railroad design practices (10).

The maximum allowable load for a statically loaded train wheel is 33 kips. By using an impact factor of 1.3 , the maximum dynamic load is 43 kips. Up to 60 percent of this dynamic load ( 26 kips ) is transmitted to the tie directly beneath the wheel, and the remainder of the load is transmitted by the rail to the neighboring ties, typically spaced at 21 in . on center. The 26 kip tie load is distributed to the ballast beneath the tie over a contact area of approximately $300 \mathrm{in} .^{2}$ [i.e., onethird of the tie length ( $1 / 3$ of 102 in .) times the tie width ( 9 in.)]. Thus, the local contact pressure of the tie on the ballast is 87 psi .

In comparison with the preceding, the 26 kip tie load is very nearly equal to the 24 kip rear tire load of the $\mathrm{H}-30$
truck. Also, the 87 -psi contact pressure of the tie is only slightly less than the 100 psi truck tire pressure, and the width of the tie is comparable to the tire footprint length. Thus, having demonstrated the equivalence between H-30 truck loading and railroad loading it is recommended that the soil cover height requirements for railroad loading follow the requirements for an $\mathrm{H}-30$ truck loading, as was previously presented. Ballast depth should not be included as part of the minimum soil cover requirement for the same reason pavements are usually excluded.

## CONCLUDING REMARKS

The minimum soil cover requirements presented here are applicable to all corrugated plastic pipe where material and cross-sectional properties conform to AASHTO specifications. Further, the backfill soil must be compacted to the design specification and be placed uniformly around the pipe without hard inclusions of soft voids in the soil envelope. Within those restrictions the minimum cover heights presented in Table 7 along with the design guidelines may be used with conservative confidence.

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