Flotation of Circular Concrete Pipe

There are several installation conditions where there is the possibility that concrete pipe may float even though the density of concrete is approximately 2.4 times that of water. Some of these conditions are: the use of flooding to consolidate backfill; pipelines in areas which will be inundated, such as, a flood plain or under a future man-made lake; subaqueous pipelines; flowable fill installations; and pipelines in areas with a high groundwater table. When such conditions exist, flotation probability should be checked.

FLOTATION FACTORS

The buoyancy of concrete pipe depends upon the weight of the pipe, the weight of the volume of water displaced by the pipe, the weight of the liquid load carried by the pipe and the weight of the backfill. As a conservative practice in analysis, the line should be considered empty so the weight of any future liquid load is then an additional safety factor.

Pipe Weights

The average density of concrete is 150 pounds per cubic foot and the approximate weight per linear foot of circular concrete pipe may be calculated by the following equation:

\[ W_p = \frac{1}{4} (B_c^2 - D^2) 150 \]  

where

- \( W_p \) = weight of pipe in pounds per linear foot.
- \( B_c \) = outside pipe diameter, feet.
- \( D \) = inside pipe diameter, feet.

Average weights in pounds per linear foot for ASTM C14 Nonreinforced Concrete Sewer, Storm Drain and Culvert Pipe and ASTM C76 Reinforced Concrete Culvert, Storm Drain and Sewer Pipe are given in Tables I and II. Most pipe manufacturers publish data that tabulates product dimensions and weight. The data from these publications should be used when available.

Water Density

The density of fresh water is 62.4 pounds per cubic foot for normal ranges of ambient temperature. The average density of seawater is 64.0 pounds per cubic foot. In this Design Data, only fresh water is considered, but local conditions should be investigated when seeking solutions for specific projects.

Displaced Water Weight

When water is displaced a buoyant or upward force exists, and, if the buoyant force is greater than the weight of the object displacing the water, flotation will occur. The weight of fresh water displaced per linear foot of circular pipe can be calculated by the following equation:

\[ W_w = \frac{1}{4} (B_c^2) 62.4 \]  

where

- \( W_w \) = weight of displaced water per linear foot, pounds.
- \( B_c \) = outside pipe diameter, feet.

The average weights of the volume of fresh water displaced per linear foot of C14 and C76 pipe are presented in Tables 3 and 4.

Backfill Weight

The weight of the backfill directly over the pipe assists in holding the pipe down. The unit weight of compacted backfill material varies with specific gravity, the grain size, and the degree of compaction. For preliminary computations, however, average values for surface dry density and specific gravity of backfill materials are of sufficient accuracy.

The unit weight of inundated backfill is equal to the surface dry density of the backfill minus the weight of water displaced by the solid particles and can be calculated as followed:

\[ w_I = w - w_w = w - \left( \frac{1}{SG} \times 62.4 \right) \times 62.4 \]  

which reduces to:

\[ w_I = w \left( \frac{W}{SG} \right) \text{ or } W \left( 1 - \frac{1}{SG} \right) \]  

where;

- \( w_i \) = average unit weight of inundated backfill, pounds per cubic foot.
- \( w \) = average unit weight of surface dry backfill, pounds per cubic foot.
SG  =  specific gravity of backfill.

Figure 1 illustrates the backfill over the pipe and the different volumes to be considered. The volume of backfill over the haunches from the springline to the top of the pipe is equal to 0.1073 $B_c^2$ cubic feet per linear foot of pipe. The volume of backfill from the top of the pipe to the level of inundation equals $HIBC$ cubic feet per linear foot of pipe. Therefore, the weight of inundated backfill per linear foot of pipe acting downward on the pipe can be calculated as follows:

\[
W_I = w_I (0.1073 B_c^2 + HIBC)
\]  

where;

- $W_I$ = weight of inundated backfill directly over the pipe, pounds per linear foot.
- $H_I$ = depth of inundated backfill above top of pipe, feet.

The weight of dry backfill above the water level, if any, per linear foot of pipe acting downward on the pipe can be calculated as follows:

\[
W_D = w (H - H_I) B_c
\]

where;

- $W_D$ = weight of dry backfill directly over the pipe, pounds per linear foot.
- $H$ = depth from top of pipe to surface of backfill, feet.

Therefore, the total weight of backfill per linear foot of pipe acting downward on the pipe is the algebraic sum of Equations 5 and 6 as follows:

\[
W_B = W_I + W_D
\]

where;

- $W_B$ = total weight of backfill directly over the pipe, pounds per cubic ft.

**FACTOR OF SAFETY**

Construction soils are noted for lack of uniformity. Depending on the extent of information of the proposed backfill material and site condition, a factor of safety ranging between 1.0 and 1.5 should be applied. This factor of safety shall be applied to decrease the downward force of the backfill. Generally, if the weight of the structure is the primary force resisting flotation then a safety factor of 1.0 is adequate. However, if friction or cohesion are the primary forces resisting flotation, then a higher safety factor would be more appropriate to account for the variability of the soil properties.

Consideration must also be given to the interface between layers of differing soil types. If fine grained soils (such as clays or silts) are placed adjacent to coarse grained soils (such as crushed stone), upon wetting, these layers may combine at the interface thereby allowing the pipe to float a distance equal to the loss in volume. Increased factor of safety in combination with layer separation methods are recommended.

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**PREVENTIVE PROCEDURES**

If the total weight of the pipe and backfill is not adequate to prevent flotation of the pipe, preventive nonflotation procedures, such as additional backfill, mechanical anchorage, heavier pipes, or combinations of these would be required. Some of the commonly used methods are:

1. Increased wall thickness.
2. Precast or cast-in-place concrete collars.
3. Precast or cast-in-place concrete blocks, fastened by suitable means.
4. Pipe strapped to piles or concrete anchor slab.
5. Additional backfill.

When computing the volume of concrete required per linear foot for pipe anchorage, remember that concrete which weighs 150 pounds per cubic foot in air, weighs only 87.6 pounds per cubic foot under water.

**DESIGN PROCEDURE**

A suggested seven step logical procedure is presented for determining the degree of buoyancy of empty concrete pipeline and possible measures needed to prevent flotation. Downward forces are considered positive and upward forces are considered negative.

1. Determine the downward force of the pipe weight in pounds per linear foot.
2. Determine the buoyant upward force of the weight of the displaced water in pounds per linear foot of pipe.
3. Find the algebraic sum of the forces determined in Steps 1 and 2. If the resultant force is positive, the pipe will not float. If the resultant force is negative proceed with Step 4.
4. Determine the downward force of the total weight of backfill in pounds per linear foot of pipe.
5. Apply a factor of safety to determine the decreased total weight of backfill.
6. Find the algebraic sum of the downward force determined in Step 5 and the excess upward force determined in Step 3. If the resultant force is positive, the pipe will not float. If the resultant force is negative, proceed with Step 7.

7. Select and analyze the procedures to be used to prevent flotation.

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### Example 1

**Given:**

A 72-inch diameter, wall B, ASTM C76 reinforced concrete pipe is to be installed in a trench in a sandy coastal area with 8 feet of backfill over the top of the pipe. Since the groundwater table is near...
the ground surface in this area and the natural soil is basically sand, flooding of the backfill for consolidation is permitted. The sandy soil is assumed to have a surface dry density of 110 pounds per cubic foot and a specific gravity of 2.65.

Find:

If the pipe would float under conditions of complete backfill, determine the procedures necessary to prevent flotation and what height of backfill is necessary to prevent flotation.

Solution:

1. Weight of pipe

   From Table 2, WP = +1811 pounds per linear foot (downward force).

2. Weight of displaced water.

   From Table 4, WW = -2519 pounds per linear foot of pipe (upward force).

3. Algebraic sum of Steps 1 and 2.

   WP + WW = +1811 + (-2519) = -708 pounds per linear foot of pipe (upward force).

   The resultant force is upward, therefore proceed to Step 4.

4. Total weight of backfill.

   **Weight of inundated backfill**

   Given the compacted surface dry density of sand is 110 pounds per cubic foot with a specific gravity of 2.65.

   From Equation 4, the unit weight of inundated backfill equals, \( w_I = 110 \left(1 - \frac{1}{2.65}\right) = 68 \) pounds per cubic foot.

   From Equation 5, the weight of inundated backfill equals, \( W_I = 68 \left[0.1073 (7.17)^2 + (8 \times 7.17)\right] = +4276 \) pounds per linear foot of pipe (downward force).
Weight of dry backfill:
Since the groundwater table was assumed to be at the ground surface, there would be no additional downward force.

Total weight of backfill:
From Equation 7, the total weight of backfill per linear foot of pipe equals, \( W_B = +4267 + 0 = +4276 \) pounds per linear foot of pipe (downward force).

5. Application of Factor of Safety.
Since no precise information is available on the density and the specific gravity of the sandy backfill, a Factor of Safety of 1.25 will be used to reduce the assumed total weight of the backfill.

\[
\frac{W_B}{\text{F.S.}} = \frac{+4276}{1.25} = +3421 \text{ pounds (downward force)}
\]

6. Algebraic sum of Steps 3 and 5.
From Step 3, the resultant upward force is –708 and from Step 5, the downward force is + 3421, which produces a resultant downward force of + 2713 pounds per linear foot of pipe.

Answer:
Therefore, the pipe will not float when backfill is completed, additional procedures described in Step 7 are not required. However, to find the required depth of inundated backfill necessary to prevent flotation during construction use Equation 5. Solve for \( H_I \) by setting the algebraic sum of \( W_I \), the weight of inundated backfill over the pipe, decreased by the factor of safety, and the resultant upward force determined in Step 2 equal to zero, as follows:

\[
68 \{0.1073 (7.17)^2 + (H_I \times 7.17)\} + (-708) = 0
\]

\( H_I = 1.05 \text{ ft. above the top of the pipe} \)

Therefore, a minimum depth of 1 foot 1-inch of inundated backfill above the top of the pipe is required to prevent flotation of the pipe.

Example 2

Given:
A 144-inch diameter ASTM C76 reinforced concrete pipe is to be installed as an outfall line for a wastewater treatment plant. The line is to be installed underneath the flood plain of the stream and will have only one foot of cover over the top of the pipe for a portion of its length. It will have a flap gate at the discharge end to prevent flood water and debris from entering the pipe. Soil tests have determined that the average surface dry density of the in-place clay backfill is 123 pounds per cubic foot with specific gravity of 2.66.

Find:
If the pipe will float and if required, the volume of concrete per linear foot of pipe expressed as additional wall thickness necessary to prevent flotation.

Solution:
1. Weight of pipe.
   From Table 2, \( W_P = +6126 \) pounds per linear foot (downward force).

2. Weight of displaced water.
   From Table 4, \( W_W = -9606 \) pounds per linear foot of pipe (upward force).

3. Algebraic sum of Steps 1 and 2.
   \( W_P + W_W = +6126 + (-9606) = -3480 \) pounds per linear foot of pipe (negative, upward force).

   The resultant force is upward, therefore, proceed to Step 4.

4. Total weight of backfill.
   Weight of inundated backfill:
   Given, the average surface dry density of the clay backfill is 123 pounds per cubic foot with a specific gravity of 2.66
   From Equation 4, the unit weight of inundated backfill equals, \( W_I = 123 (1 - \frac{1}{2.66}) + 77 \) pounds per cubic foot
   From Equation 5, the weight of inundated backfill equals, \( W_I = 77 [0.1073 (14)^2 + (1 \times 14)] = +2697 \) pounds per linear foot of pipe (downward force).

   Weight of dry backfill:
   Since the site is a floodplain, the backfill is considered completely inundated, therefore there is no additional downward force.

Total weight of backfill:
From Equation 7, the total weight of backfill per linear foot of pipe equals, \( W_B = +2697 + 0 = +2697 \) pounds per linear foot of pipe (downward force).

5. Application of Factor of Safety.
Since the soils information is based on tests, a Factor of Safety of 1.15 will be used to decrease the downward force of the inundated backfill.

\[
\frac{W_B}{\text{F.S.}} = \frac{+2697}{1.15} = +2345 \text{ pounds (downward force)}
\]
6. Algebraic sum of Steps 3 and 5
   From Step 3, the resultant upward force is \(-3480\) pounds and from Step 5, the downward force is \(+2345\) pounds, which produces a resultant upward force of \(-1135\) pounds per linear foot of pipe. The pipe will float, therefore proceed to Step 7.

7. Analysis of method to prevent flotation.
   As given, the method will be to increase the wall thickness of the pipe. The algebraic sum of the unbalanced upward force of \(-1135\) pounds per linear foot of pipe as determined in Step 6 must equal the weight of the additional wall thickness \((tx)\) required, and may be expressed in the following quadratic equation:

   \[
   (B_c + tx)x + F_B = 0, \text{ or solving for } tx
   \]

   \[\begin{align*}
   tx &= \frac{-B_c \sqrt{B_c^2 - 4FB}}{2} \\
   &\text{where;}
   \\
   tx &= \text{additional wall thickness in feet.} \\
   \gamma_c &= \text{density of submerged concrete, } +87.6 \text{ pounds per cubic foot.} \\
   F_B &= \text{upward force in pounds per linear foot of pipe.}
   \end{align*}\]

   Substitution appropriate values in the above equation:

   \[tx = \frac{-14 + \sqrt{(14)^2 - 4(-1135)}}{2} = +0.29 \text{ feet}\]

   Since negative values have no significance, use \(tx = 0.29\) feet or 3.5 inches.

   **Answer:**
   Therefore, 3.5 inches of additional wall thickness are required to prevent flotation of the pipe in this installation.

**EXAMPLE 3**

Given:
   The 144-inch diameter pipe in Example 2 submerged in a fresh water lake with no backfill placed over it.

Find:
   The dimensions per linear foot of a concrete anchor slab required to prevent flotation.

Solution:
1. Steps 1, 2, and 3 are the same as Example 2, leaving \(-3480\) pounds per linear foot of pipe upward force.
   Since the resultant force is upward, proceed to Step 4.

4. Total weight of backfill.
   Since the pipe is submerged with no backfill placed over it, there is no additional downward force.

5. Application of Factor of Safety.
   Since this pipe is submerged in water only, a Factor of Safety of 1.0 is used.

6. Algebraic sum of Steps 3 and 5.
   From Step 3, the resultant upward force is \(-3480\) pounds per linear foot of pipe. The pipe will float, therefore proceed to Step 7.

7. Analysis of method to prevent flotation.
   As stated, determine the required dimensions of a concrete anchor slab linear foot of pipe.

   To prevent flotation, the algebraic sum of the submerged weight of the anchor slab per linear foot and, the resultant upward force per linear foot must equal zero, and may be expressed in equation form as follows:

   \[F_B = \gamma_c (bd x 1)\]

   where;
   \[F_B = \text{The total negative (buoyant) force in pounds.} \\
   b = \text{Width of concrete slab, feet.} \\
   d = \text{Depth of concrete slab, feet.} \\
   1 = \text{One linear foot.} \\
   \gamma_c = \text{Submerged weight of concrete per cubic foot.}\]

   Substituting appropriate values in the above equation:

   \[87.6 (bd x 1) = 3480\]
   \[\text{and } b x d x 1 \text{ ft.} = 39.37 \text{ ft.}^3\]

   Since the outside diameter of the pipe, \(B_c\), is approximately 14 ft. selecting this dimension for \(b, d\) will then be:

   \[d = \frac{39.37}{14} = 2.84 \text{ ft.}\]

   **Answer:**
   Therefore, a concrete anchor slab, 14 feet wide and 2.84 feet deep will prevent flotation of the pipe, assuming proper anchorage of the pipe to the slab.