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 2400 kg/m³ and the approximate weight per linear meter of circular concrete pipe may be calculated by the following equation:

$$W_p = \frac{\pi}{4} (B_c^2 - D^2) 2400$$  \hspace{1cm} (1)

where:

- $W_p$ = weight of pipe in kg/m
- $B_c$ = outside pipe diameter, m
- $D$ = inside pipe diameter, m

For Tables I and II present average weight is kg/m. 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 1000 kg/m³ for normal ranges of ambient temperature. The average density of seawater is 1025 kg/m³. 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 meter of circular pipe can be calculated by the following equation:

$$W_w = \frac{\pi}{4} (B_c^2) 1000$$  \hspace{1cm} (2)

where:

- $W_w$ = weight of displaced water per m, kg,
- $B_c$ = outside pipe diameter, m.

The average weights of the volume of fresh water displaced per linear meter of 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:

$$w_i = w - w \left( \frac{SG}{1000} \right)$$  \hspace{1cm} (3)

which reduces to:

$$w_i = w - \left( \frac{W}{SG} \right)$$  \hspace{1cm} (4)

where:

- $w_i$ = average unit weight of inundated backfill, kg/m³.
- $w$ = average unit weight of surface dry backfill, kg/m³.
- $SG$ = 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 Bc^2 cubic meters per linear meter of pipe. The volume of backfill from the top of the pipe to the level of inundation equals HIBC cubic meters per linear meter of pipe. Therefore, the weight of inundated backfill per linear meter 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, kg/m.
- \( H_I \) = depth of inundated backfill above top of pipe, m.

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

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

where:

- \( W_D \) = weight of dry backfill directly over the pipe, kg/m.
- \( H \) = depth from top of pipe to surface of backfill, m.

Therefore, the total weight of backfill per linear meter 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, kg/m^3.

**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 than 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.

**PREVENTIVE PROCEDURES**

If the total weight of the pipe and backfill is not adequate to prevent flotation of the pipe, preventive nonflostation 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 2400 kg/m^3 in air, weighs only 1400 kg/m^3 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 kg/m.
2. Determine the buoyant upward force of the weight of the displaced water in kg/m 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 kg/m 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.

**Example 1**

Given:

A 1800 mm diameter, wall B, CSA A257.2 reinforced concrete pipe is to be installed in a trench in a sandy coastal area with 2.8 m 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 1760 kg/m^3 and a specific gravity of 2.65.
### Table 1 Dimensions and Approximate Weights of Nonreinforced Concrete Pipe

<table>
<thead>
<tr>
<th>Internal Diameter, mm</th>
<th>Wall A</th>
<th>Wall B</th>
<th>Wall C</th>
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<tr>
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</tr>
<tr>
<td>900</td>
<td>100</td>
<td>110</td>
<td>119</td>
</tr>
</tbody>
</table>

These tables are based on concrete weighing 2400 kg/m³ and will vary with heavier or lighter weight concrete.

Note: Pipe listed above the heavy black line will not float in sea water and need not be considered.

#### 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, \( W_p = +2606 \text{ kg/m} \) (downward force).

2. **Weight of displaced water**
   
   From Table 4, \( W_w = -3631 \text{ kg/m}^3 \) (upward force).

3. **Algebraic sum of Steps 1 and 2**
   
   \[
   W_p + W_w = +2606 + (-3631) = -1154 \text{ kg/m} \text{ (upward force)}. 
   \]

   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 1760 kg/m³ with a specific gravity of 2.65.

   From Equation 4, the unit weight of inundated backfill equals, \( w_i = 1760 \left( 1 - \frac{1}{2.65} \right) = 1095 \text{ kg/m}^3 \)
From Equation 5, the weight of inundated backfill equals, \( W_I = 1095 \left[ 0.1073 \times (2.15)^2 + (2.4 \times 2.15) \right] = +6292 \) kg/m (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 meter of pipe equals, \( W_B = +6292 + 0 = +6292 \) kg/m (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.

\[
W_B = \frac{+6292}{1.25} = +5033 \text{ kg (downward force)}
\]

6. Algebraic sum of Steps 3 and 5.
From Step 3, the resultant upward force is –1164 and from Step 5, the downward force is +6292, which produces a resultant downward force of +3878 kg/m.

**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 \( H_s \) by setting the algebraic sum of \( W_b \), 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:
HI = 0.38 m above the top of the pipe

Therefore, a minimum depth of 380 mm of inundated backfill above the top of the pipe is required to prevent flotation of the pipe.

Example 2

Given:

A 3600 mm diameter CSA A257.2 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 300 mm 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 1970 kg/m³ 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, \( W_p = +10.391 \text{ kg/m} \) (downward force).

2. Weight of displaced water.
   From Table 4, \( W_w = -14,509 \text{ kg/m} \) (upward force).

3. Algebraic sum of Steps 1 and 2.
   \( W_p + W_w = -4118 \text{ kg/m} \) (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 1970 kg/m³ with a specific gravity of 2.66.

   From Equation 4, the unit weight of inundated backfill equals, \( W_i = 4012 \text{ kg/m} \) (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 meter of pipe equals, \( W_B = +4012 + 0 = +4012 \text{ kg/m} \) (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.

   \[ W_{B,F.S.} = \frac{W_B}{1.15} = +3210 \text{ kg} \] (downward force)

6. Algebraic sum of Steps 3 and 5
   From Step 3, the resultant upward force is –4118 kg and from Step 5, the downward force is +3210 kg, which produces a resultant upward force of –907 kg per linear meter 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 –907 kg/m pipe as determined in Step 6 must equal the weight of the additional wall thickness \( (t_x) \) required, and may be expressed in the following quadratic equation:

   \[ \pi(B_c + t_x) \gamma_c + F_B = 0 \]

   where:
   \( t_x \) = additional wall thickness in feet.
   \( \gamma_c \) = density of submerged concrete, +1400 kg/m³.
   \( F_B \) = upward force in kg per linear meter of pipe.

   Substitution appropriate values in the above equation:

   \[ t_x = \frac{-4.298 \pm \sqrt{4.298^2 - 4(907)1400(3.14)}}{2} \]

   \[ t_x = +47.5 \text{ mm} \]
Since negative values have no significance, use $t_e = 47.5$ mm.

**Answer:**

Therefore, 47.5 mm of additional wall thickness are required to prevent flotation of the pipe in this installation.

**EXAMPLE 3**

**Given:**

The 3600 mm diameter pipe in Example 2 submerged in a fresh water lake with no backfill placed over it.

**Find:**

The dimensions per linear meter of a concrete anchor slab required to prevent flotation.

**Solution:**

1. Steps 1, 2, and 3 are the same as Example 2, leaving $-4118$ kg/m of pipe upward force. Since the resultant force is upward, proceed to Step 4.

2. Total weight of backfill.

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

3. Application of Factor of Safety.

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

4. Algebraic sum of Steps 3 and 5.

   From Step 3, the resultant upward force is $-4118$ kg/m of pipe. The pipe will float, therefore proceed to Step 7.

5. Analysis of method to prevent flotation.

   As stated, determine the required dimensions of a concrete anchor slab linear meter of pipe.

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

   $$ F_B = \gamma_c (bd \times 1) $$

   where:

   $F_B = $ The total negative (buoyant) force in kg.

   $b = $ Width of concrete slab, meters.

   $d = $ Depth of concrete slab, meters.

   $1 = $ One linear meter.

   $\gamma_c = $ Submerged weight of concrete per cubic meter.

   Substituting appropriate values in the above equation:

   $$ 1400 (bd \times 1) = 4118 \text{ kg} $$

   Since the outside diameter of the pipe, BC, is approximately 4.3 meters selecting this dimension for $b$, $d$ will then be:

   **Answer:**

   Therefore, a concrete anchor slab, 4.3 meters wide and 0.68 meters deep will prevent flotation of the pipe, assuming proper anchorage of the pipe to the slab.