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/m^3 and the approximate weight per linear meter of circular concrete pipe may be calculated by the following equation:

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

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/m^3 for normal ranges of ambient temperature. The average density of seawater is 1025 kg/m^3. 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:

$$W_w = \frac{\pi}{4} (B_c^2) \, 1000 \qquad (2)$$

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:

$$w_I = w - \left[\frac{w}{(SG \times 1000)} \times 1000 \right] \qquad (3)$$

which reduces to:

$$w_I = w - \left[\frac{W}{SG} \right] \text{ or } W \left(1 - \frac{1}{SG} \right) \qquad (4)$$

where:

w_I = average unit weight of inundated backfill, kg/m^3.
w = average unit weight of surface dry backfill, kg/m^3.
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 meters per linear meter of pipe. The volume of backfill from the top of the pipe to the level of inundation equals $H_I B_C$ 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:

$$W_I = w_I\,(0.1073\,B_c^2 + H_I B_c) \qquad (5)$$

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:

$$W_D = w\,(H - H_I)\,B_c \qquad (6)$$

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:

$$W_B = W_I + W_D \qquad (7)$$

where:

W_B = total weight of backfill directly over the pipe, kg/m³.

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 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 2400 kg/m³ in air, weighs only 1400 kg/m³ 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/m³ and a specific gravity of 2.65.

Figure 1 Backfill Volumes Over Pipe

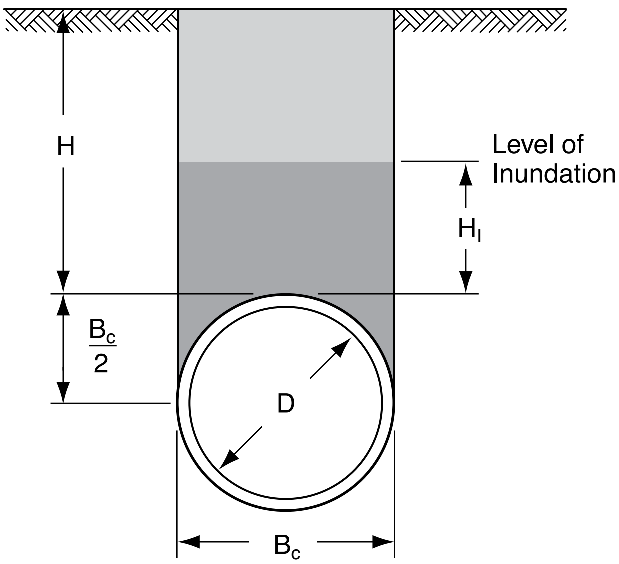

Table 1 Dimensions and Approximate Weights of Nonreinforced Concrete Pipe

CSA A257.1 - Nonreinforced Sewer, and Culvert Pipe, Bell and Spigot Joint

	Class 1			Class 2			Class 3		
Internal Diameter, mm	Min. Wall Thickness, mm	B_C, mm	Average Weight, kg/m	Min. Wall Thickness, mm	B_C, mm	Average Weight, kg/m	Min. Wall Thickness, mm	B_C, mm	Average Weight, kg/m
100	16	132	14	19	138	17	19	138	17
150	16	182	20	19	188	24	22	194	29
200	19	238	31	22	244	37	29	258	50
225	19	263	35	22	269	41	29	283	56
250	22	294	45	25	300	52	32	314	68
300	25	350	61	35	370	88	44	388	114
375	32	439	98	41	457	129	47	469	150
450	38	526	140	50	550	188	57	564	218
525	44	613	189	57	639	250	69	663	309
600	54	708	266	75	750	382	94	788	492
675	82	839	468	100	875	584	100	875	584
750	88	926	556	107	964	691	107	964	691
825	94	1013	651	113	1051	799	113	1051	799
900	100	1100	754	119	1138	914	119	1138	914

These tables are based on concrete weighing 2400 kg/m^3 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 kg/m (downward force).

Table 2 Dimensions and Approximate Weights of Circular Concrete Pipe

CSA A257.2 - Reinforced Concrete Culvert, Storm Drain and Sewer Pipe

	Wall A			Wall B			Wall C		
Internal Diameter, mm	Min. Wall Thickness, mm	B_C, mm	Average Weight, kg/m	Min. Wall Thickness, mm	B_C, mm	Average Weight, kg/m	Min. Wall Thickness, mm	B_C, mm	Average Weight, kg/m
300	44	388	114	50	400	132	0	0	0
375	47	469	150	57	489	186	0	0	0
450	50	550	188	63	576	244	0	0	0
525	57	639	250	69	663	309	0	0	0
600	63	726	315	75	750	382	0	0	0
675	66	807	369	82	839	468	0	0	0
750	69	888	426	88	926	556	0	0	0
825	72	969	487	94	1013	651	0	0	0
900	75	1050	551	100	1100	754	119	914	914
975	83	1141	662	108	1191	882	127	1055	1055
1050	88	1226	755	113	1276	991	132	1176	1176
1200	100	1400	980	125	1450	1249	144	1459	1459
1350	113	1576	1246	138	1626	1548	157	1784	1784
1500	125	1750	1532	150	1800	1866	169	2127	2127
1650	138	1926	1860	163	1976	2228	182	2514	2514
1800	150	2100	2205	175	2150	2606	194	2917	2917
1950	163	2276	2597	188	2326	3031	207	3367	3367
2100	175	2450	3002	200	2500	3468	219	3829	3829
2250	188	2626	3456	213	2676	3956	232	4342	4342
2400	200	2800	3921	225	2850	4453	244	4864	4864
2550	213	2976	4437	238	3026	5003	257	5439	5439
2700	225	3150	4962	250	3200	5561	269	6022	6022
2850	241	3332	5617	267	3384	6275	286	6762	6762
3000	254	3508	6232	279	3558	6898	298	7410	7410
3150	267	3684	6879	292	3734	7578	311	8116	8116
3300	279	3858	7529	305	3910	8290	324	8853	8853
3450	292	4034	8238	318	4086	9034	337	9622	9622
3600	305	4210	8980	330	4260	9778	349	10391	10391

These tables are based on concrete weighing 2400 kg/m^3 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.

2. Weight of displaced water.
   From Table 4. W_W = - 3631 kg/m^3 (upward force).

3. Algebraic sum of Steps 1 and 2.
   $W_P + W_W$ = + 2606 + (-3631) = -1154 kg/m (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/m^3 with a specific gravity of 2.65.

   From Equation 4, the unit weight of inundated backfill equals, $w_I = 1760\left(1 - \frac{1}{2.65}\right) = 1095$ kg/m^3

Table 3 Approximate Weight of Water Displaced by Circular Nonreinforced Concrete Pipe						
CSA A257.1 - Nonreinforced Concrete Pipe, Bell and Spigot Joint						
Internal Diameter, mm	Weight of Water Displaced, m/kg					
	Class 1		Class 2		Class 3	
	Min. Wall Thick-ness, mm	Water Displaced	Min. Wall Thick-ness, mm	Water Displaced	Min. Wall Thick-ness, mm	Water Displaced
100	16	14	19	15	19	15
150	16	26	19	28	22	30
200	19	44	22	47	29	52
225	19	54	22	57	29	63
250	22	68	25	71	32	77
300	25	96	35	108	44	118
375	32	151	41	164	47	173
450	38	217	50	238	57	250
525	44	295	57	321	69	345
600	54	394	75	442	94	488
675	82	553	100	601	100	601
750	88	673	107	730	107	730
825	94	806	113	868	113	868
900	100	950	119	1017	119	1017

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

From Equation 5, the weight of inundated backfill equals, $W_I = 1095 [0.1073 (2.15)^2 + (2.4 \times 2.15)] = +$ 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.

$$\frac{W_B}{F.S.} = \frac{+6292}{1.25} = +5033 \text{ kg (downward force)}$$

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.

Table 4 Dimensions and Approximate Weight of Reinforced Circular Concrete Pipe			
CSA A257.2 - Reinforced Concrete Pipe, Bell & Spigot Joint			
Internal Diameter, Inches	Weight of Water Displaced, Pounds Per Linear Foot		
	Wall A	Wall B	Wall C
12	82	87	-
15	119	130	-
18	164	181	-
21	222	239	-
24	287	306	339
27	355	381	418
30	429	465	505
33	511	560	600
36	600	660	704
42	816	885	940
48	1069	1143	1206
54	1351	1440	1504
60	1666	1764	1842
66	2020	2122	2207
72	2401	2519	2605
78	2786	2944	3043
84	3271	3401	3508
90	3752	3899	4005
96	4266	4423	4545
102	4823	4980	5109
108	5403	5580	5706
114	6017	6203	6341
120	6674	6863	7008
126	7354	7556	7709
132	8067	8282	8443
138	8826	9042	9210
144	9906	9836	10,010
150	10,418	10,662	10,844
156	11,278	11,523	11,711
162	12,157	12,416	12,612
168	13,069	13,343	13,546
174	14,031	14,303	14,513
180	15,009	15,296	15,513

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

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:

$$\frac{1095\,(0.496 + H_I \times 2.15)}{1.25}\ 1154$$

$$\frac{1095\,(0.1073\,(2.15)^2 + H_I \times 2.15)}{1.25} + (-1154) - 0$$

H_I = 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/m 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 kg/m (downward force).

2. Weight of displaced water.
   From Table 4, W_W = -14,509 kg/m (upward force).

3. Algebraic sum of Steps 1 and 2.
   $W_P + W_W$ = -4118 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/m^3 with a specific gravity of 2.66.

   From Equation 4, the unit weight of inundated backfill equals, $W_I = 1970\,(1 - \frac{1}{2.65}) + 1226$ kg/m^3

   From Equation 5, the weight of inundated backfill equals, W_I = 4012 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 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.

   $$\frac{W_B}{F.S.} = \frac{+4012}{1.15} = +3210 \text{ kg (downward force)}$$

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 (tx) required, and may be expressed in the following quadratic equation:

   $\pi\,(B_c + t_x)\,t_x \gamma_c + F_B = 0$, or solving for t_x

   $$t_x = \frac{-B_c \pm \sqrt{B_c^2 - \frac{4F_B}{\gamma_c \pi}}}{2}$$

   where:
   t_x = additional wall thickness in feet.
   γc = density of submerged concrete, +1400 kg/m^3.
   F_B = upward force in kg per linear meter of pipe.

   Substitution appropriate values in the above equation:

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

   t_x = +47.5 mm

Since negative values have no significance, use t_x = 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.

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 –4118 kg/m 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 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:

   $F_B = \gamma_c \text{ (bd x1)}$

   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.
   γ_C = Submerged weight of concrete per cubic meter.

   Substituting appropriate values in the above equation:

   1400 (bd x 1) = 4118 kg
   and b x d x 1 ft. = 2.94 m^3

   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.