Buoyancy
& Pipe Flotation

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Buoyancy & Pipe Flotation

- Why is this a timely topic?
- What is buoyancy?
- TWO methods to account for this our designs
- Factors of Safety
- Where the rubber meets the road...example problems!

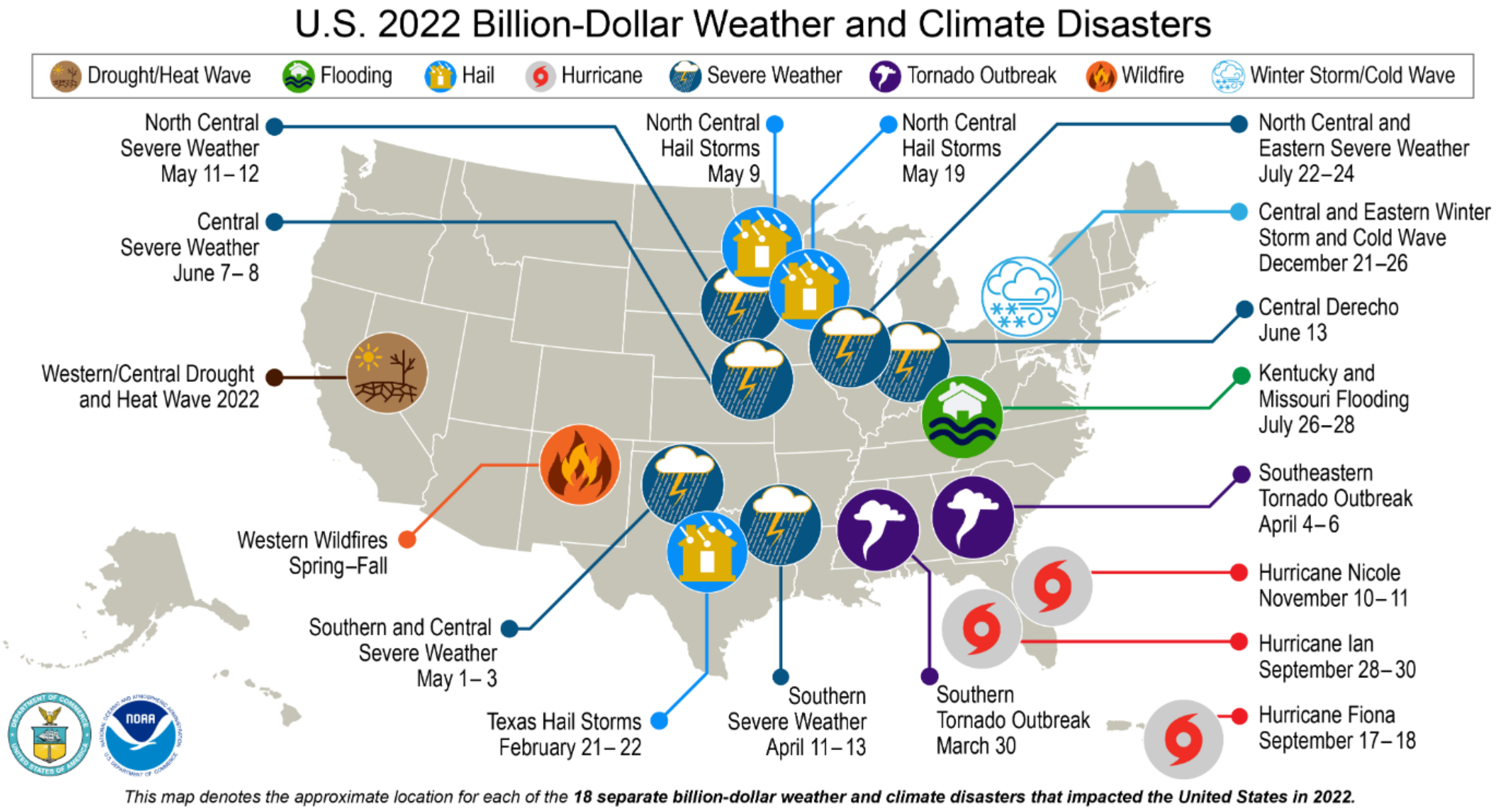

CAUTION

FLOODING IMPACTS

OUT OF SIGHT, OUT OF MIND

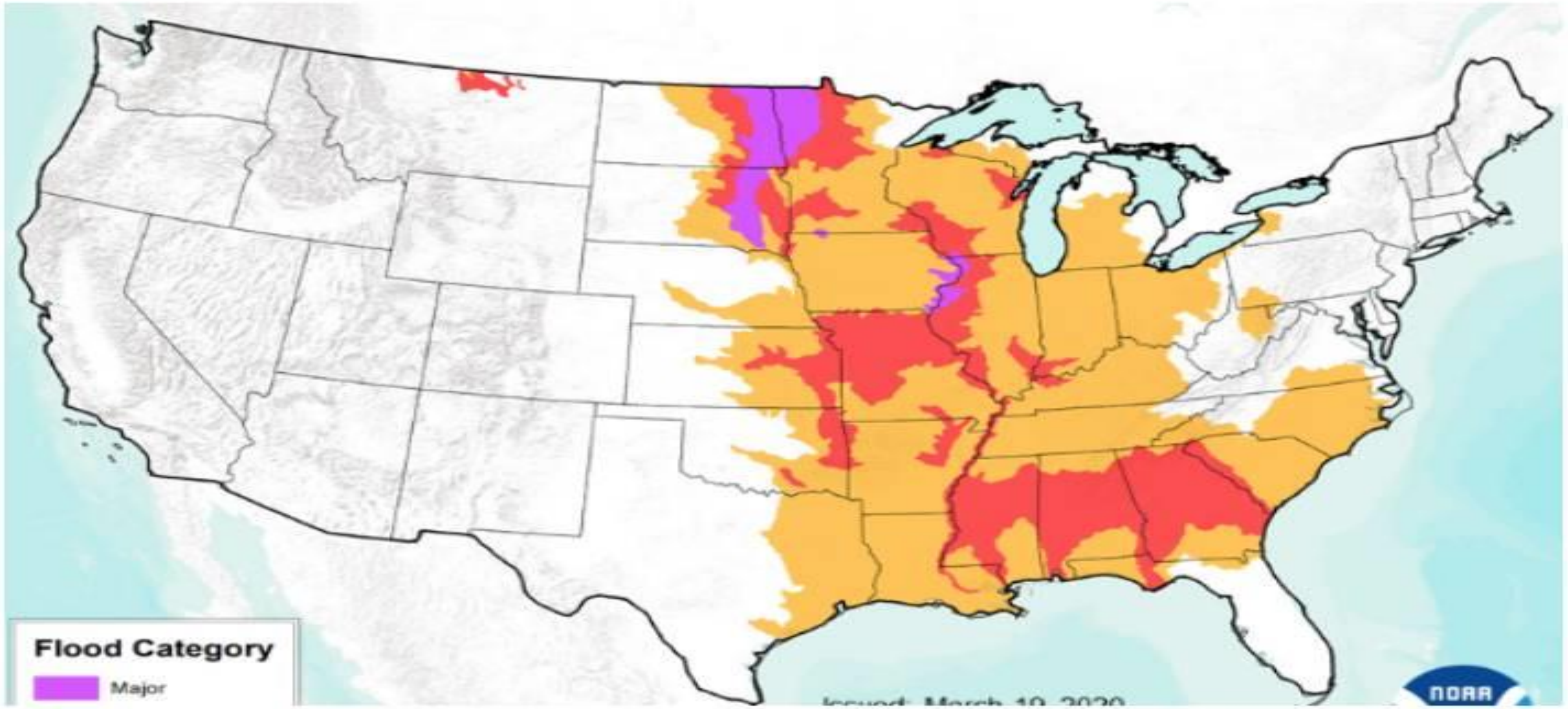
Changing Weather Patterns

Costly Disasters



Changing Weather Patterns

Prolonged Flooding



Buoyancy

GAMES | BROWSE THESAURUS | WORD OF THE DAY | WORDS AT PLAY

Merriam-Webster SINCE 1828

buoyancy

Dictionary | Thesaurus

Save Word

buoy·an·cy | \ ˈbȯi-ən(t)-sē, ˈbü-yən(t)- \

Definition of *buoyancy*

1 **a** **:** the tendency of a body to float or to rise when submerged in a fluid

// testing an object's *buoyancy*

b *chemistry* **:** the power of a fluid to exert an upward force on a body placed in it

// the *buoyancy* of water

also **:** the upward force exerted

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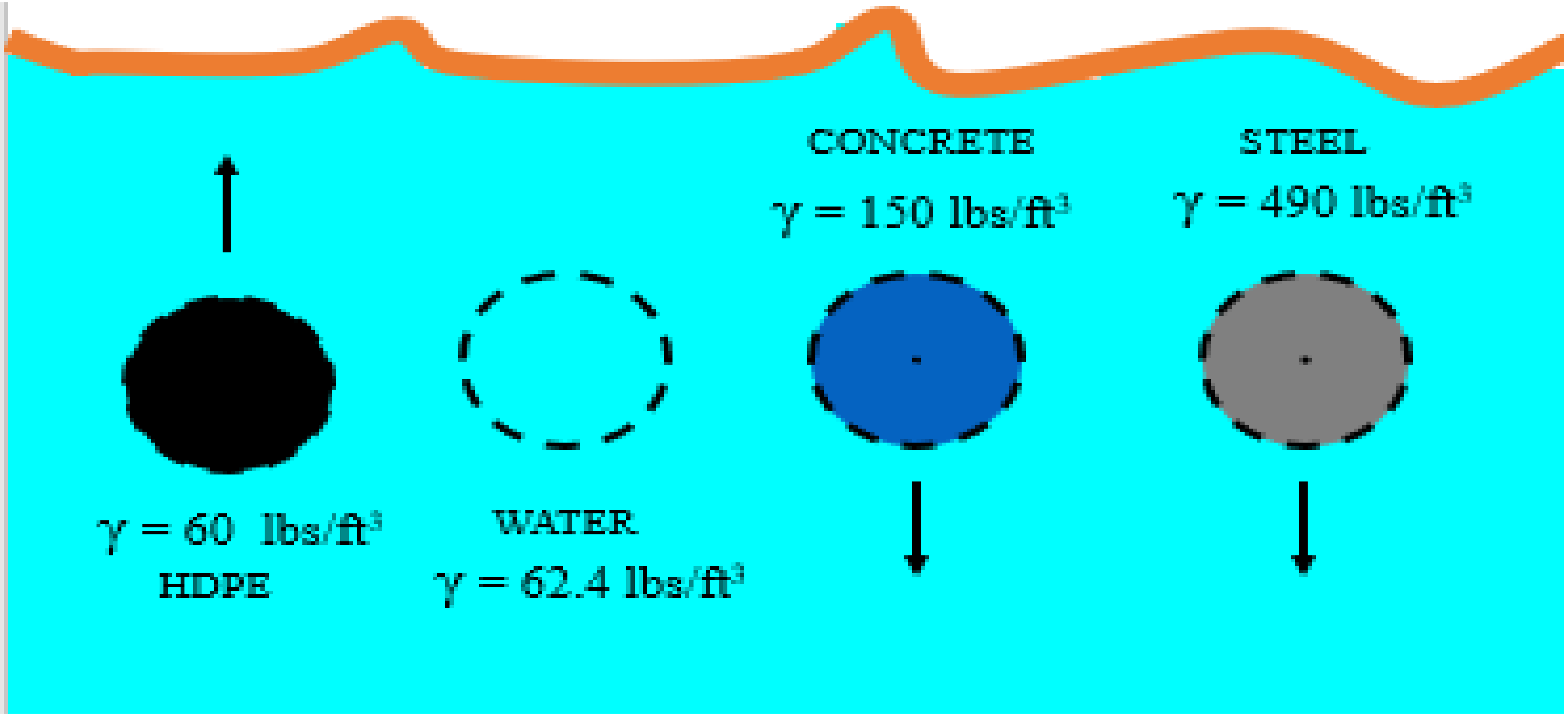
Buoyancy

Relative Pipe Weights

HDPE – Concrete - Steel



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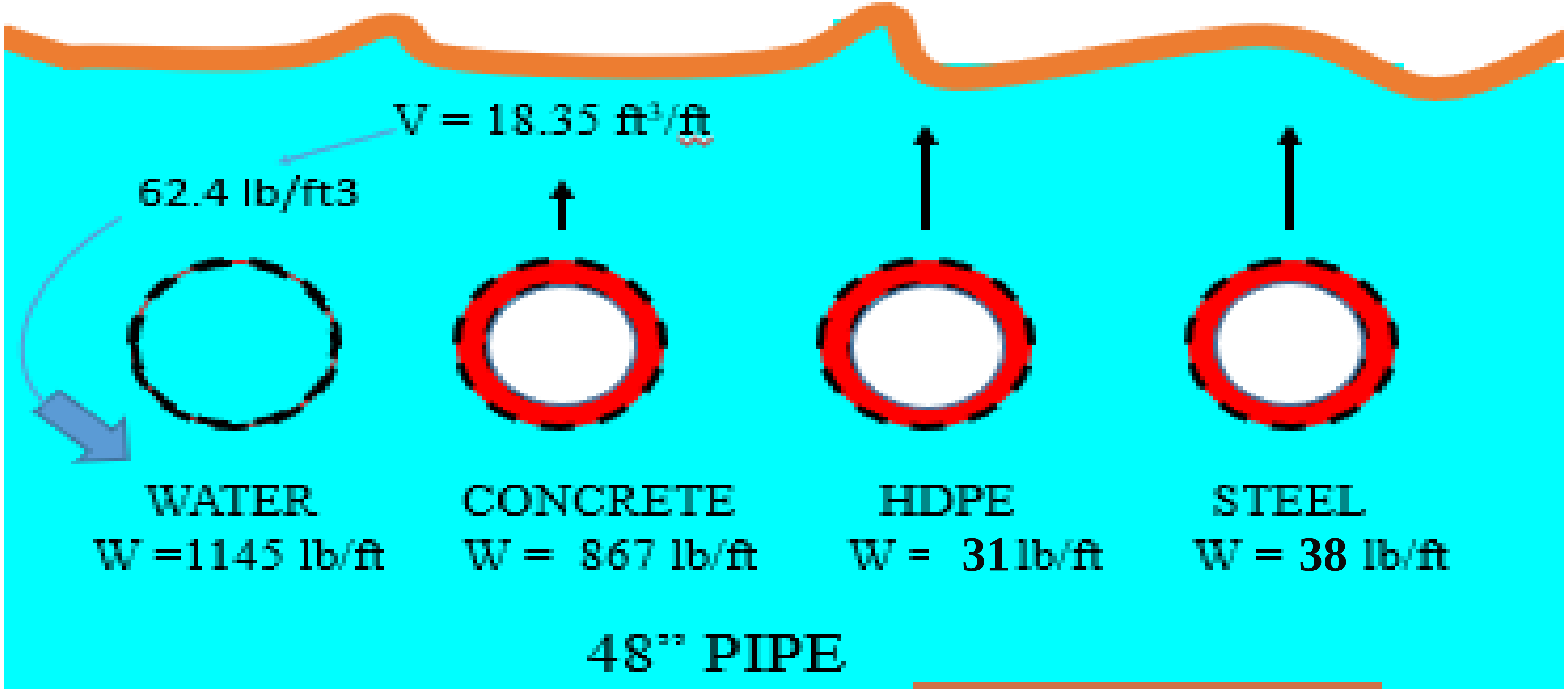
EVEREST
UNIVERSITY OF NEVADA, RENO
AQUATONE
QUINTESSENCE

Pipe Weights

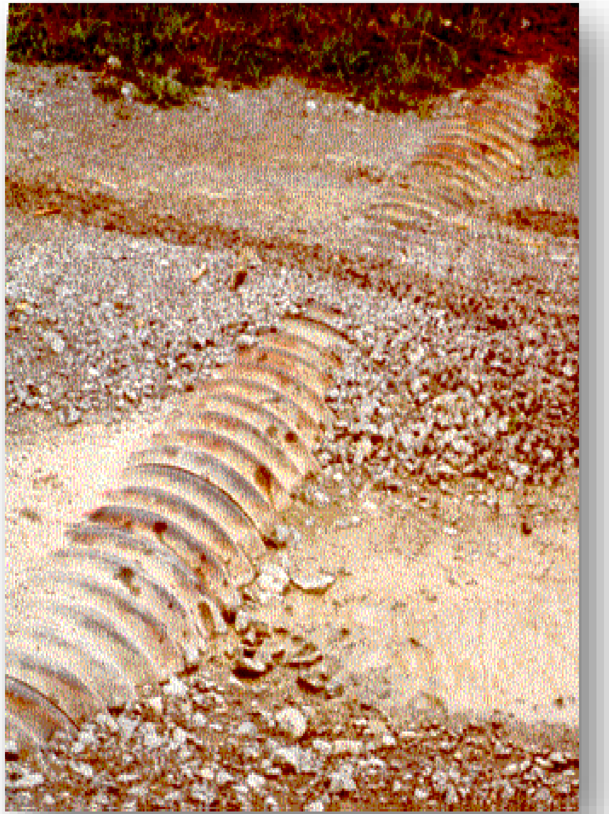
Why does this matter?



Buried Pipe

When to be concerned?

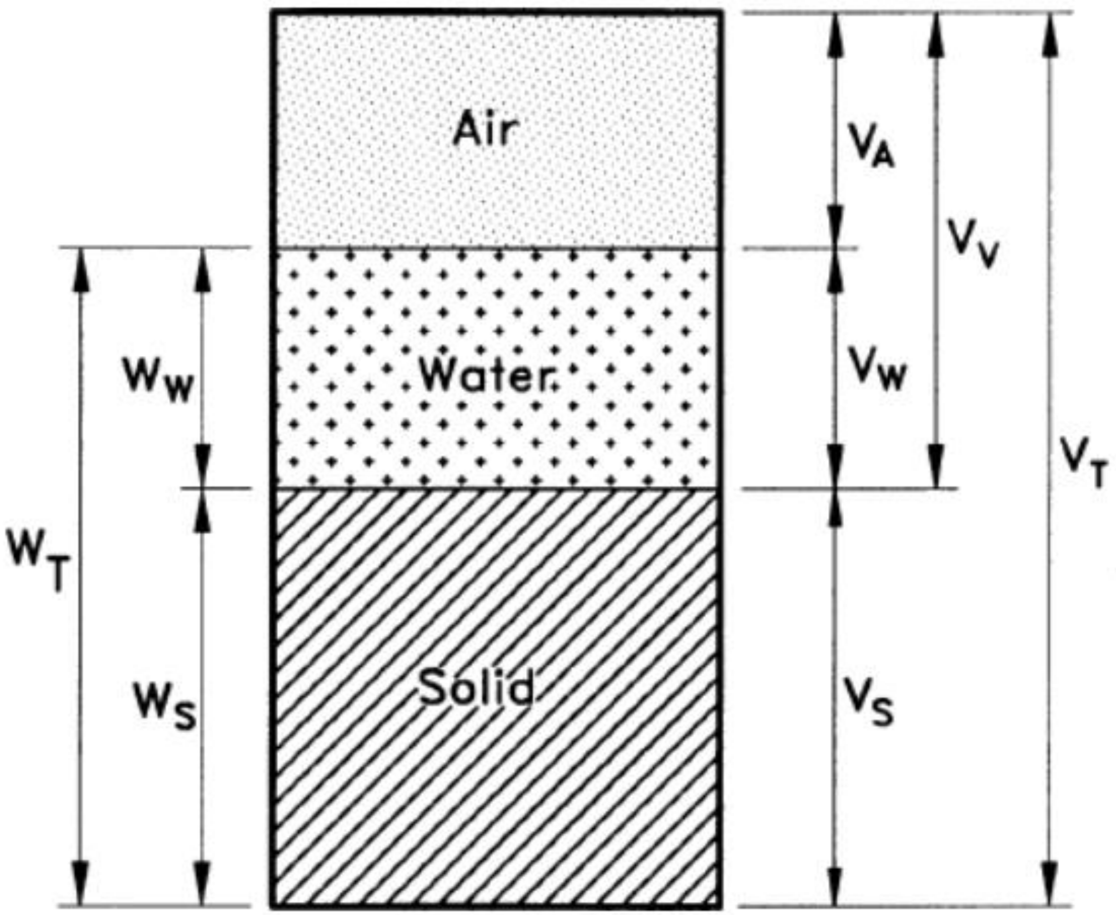




$\gamma_t = 120 \text{ lbs/ft}^3$

Pipe Weight + Soil Resistance – Buoyancy Force $\geq$ 0.0

Microstructure of Soil



Buoyant Weight of Soil

$$\gamma_b = \gamma_t - \gamma_w$$

γ_t = saturated unit weight of soil (pcf)

γ_w = unit weight of water (pcf)

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Calculations

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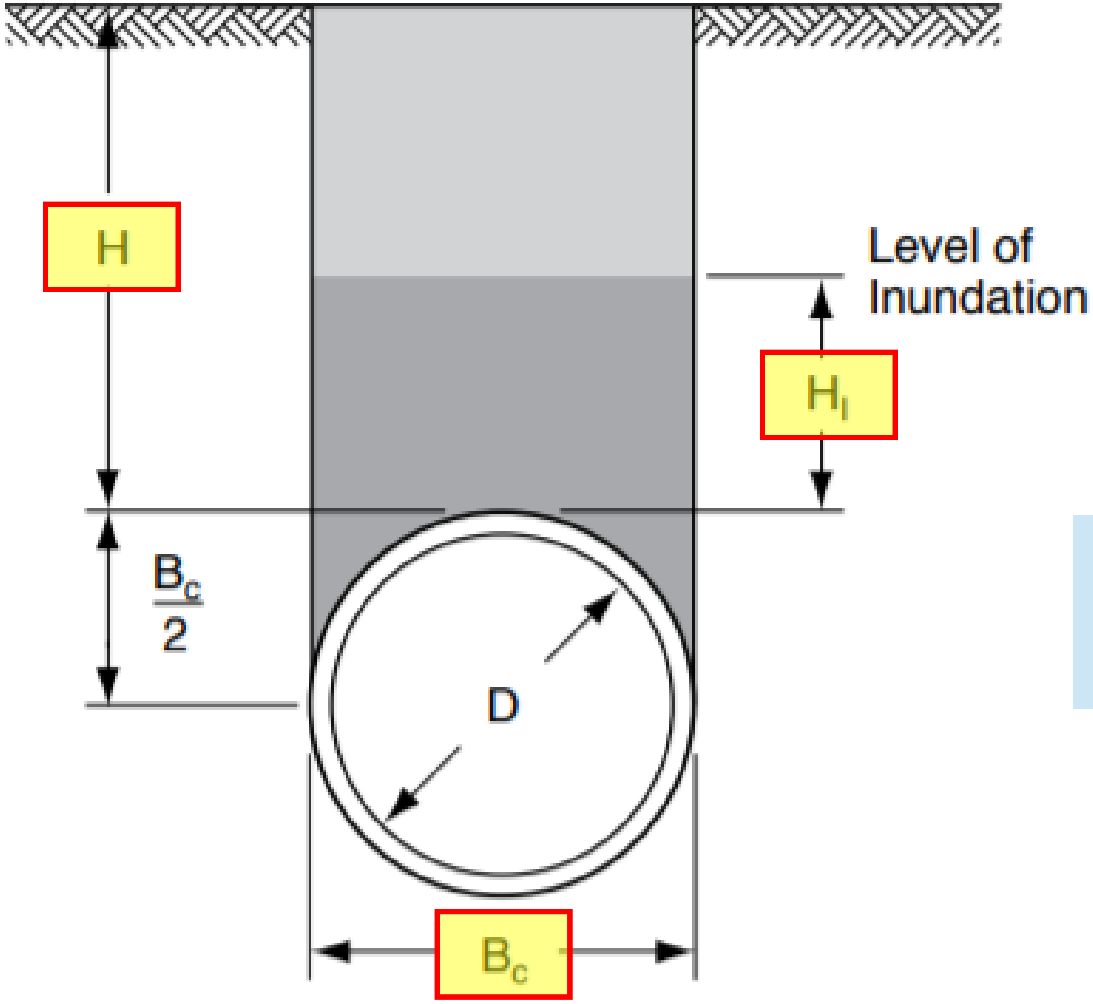
Required Information

What do we need to know?



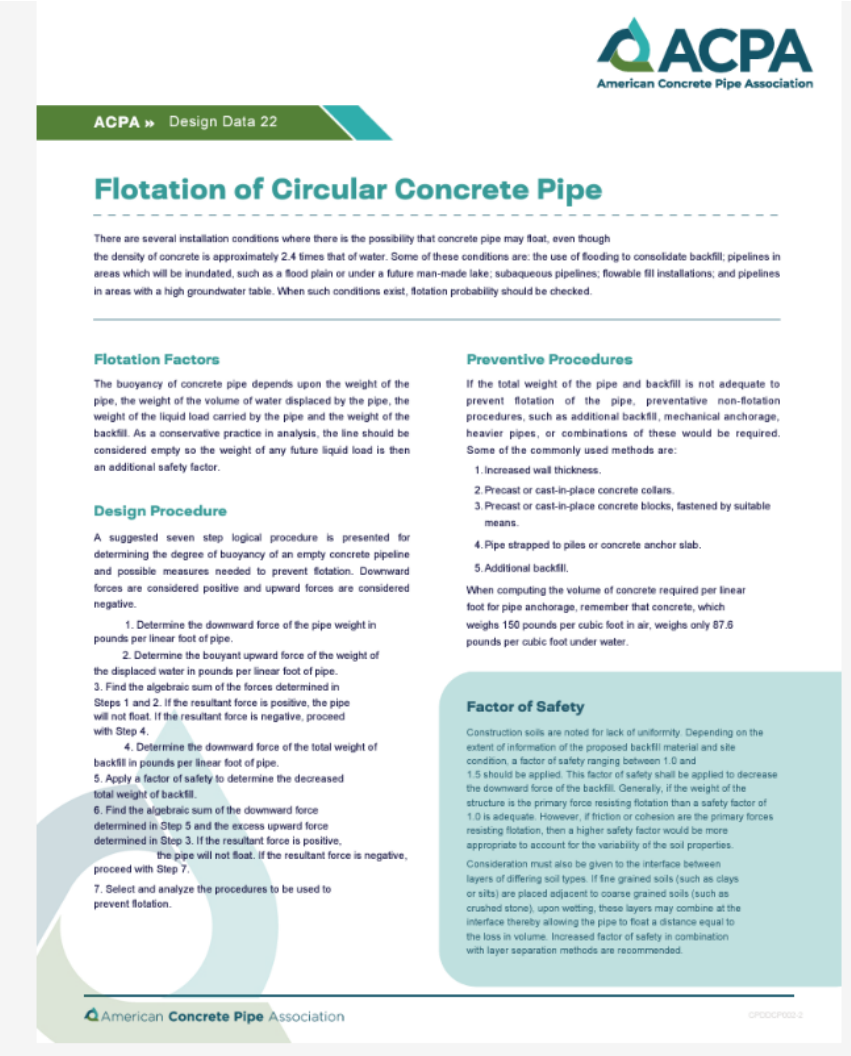
γ_t = Saturated unit weight of soil (pcf)

Design Data 22

ACPA Document

www.concretepipe.org

- Resources
- Design
- Design Data



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ACPA » Design Data 22

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.

Design Procedure

A suggested seven step logical procedure is presented for determining the degree of buoyancy of an 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 of pipe.
2. Determine the bouyant 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.

Preventive Procedures

If the total weight of the pipe and backfill is not adequate to prevent flotation of the pipe, preventative non-flotation 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.

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.

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.

Watkins Moser Method

Calculating Soil Resistance

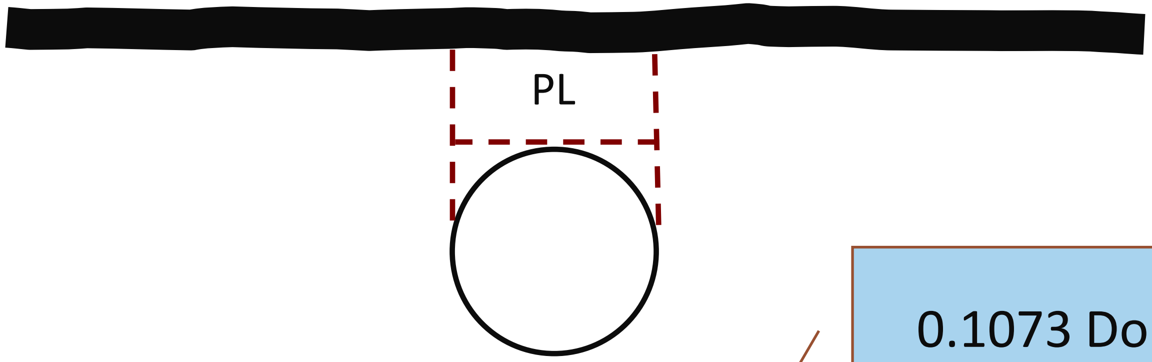
Design Data 22

$\gamma_b = \gamma_t - \gamma_w$

R_s = Soil Resistance

W_s = Weight of Soil

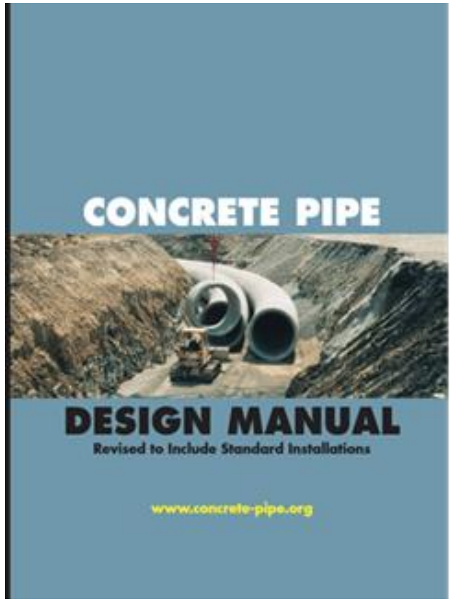
PL = Prism Load



0.1073 Do

$$R_s = W_s = PL = \gamma_b \left[H + \frac{D_o\,(4 - \pi)}{8} \right] D_o$$

Equation 4.2 – Concrete Pipe Design Manual



Calculating Soil Resistance

Watkins–Moser Method

$\gamma_b = \gamma_t - \gamma_w$

R_s = Soil Resistance

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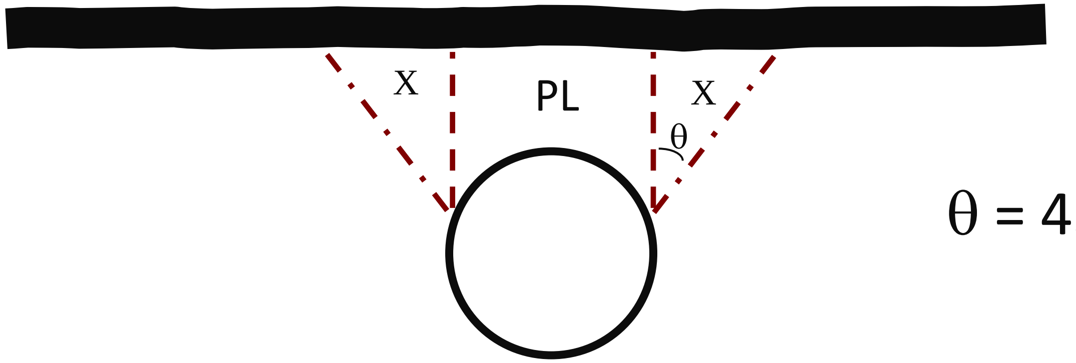


$\theta = 45 - \phi/2$

$$R_s = PL + 2X$$

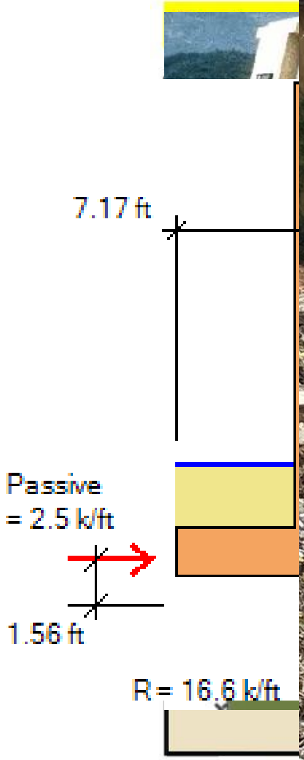
$$2X = [(H + D_o/2)^2 \tan(45 - \phi/2)]\gamma_b$$

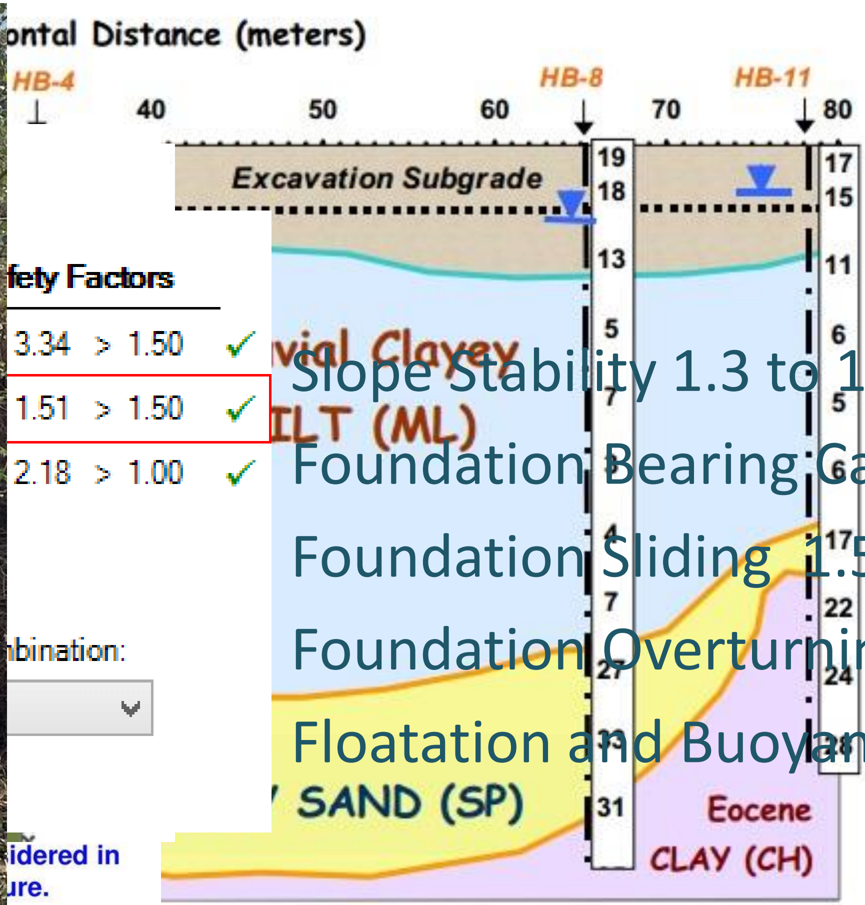
ϕ = internal angle of friction

Factors of Safety

Factors of Safety

Geotechnical Eng. – LRFD Bridge Structures





- Slope Stability 1.3 to 1.5
- Foundation Bearing Capacity 2 to 3
- Foundation Sliding 1.5+
- Foundation Overturning 2.0+
- Floatation and Buoyancy ???

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Factors of Safety

Factors of Safety

Example Problems

Process:

Calculate Buoyant Force

Calculate Soil Resistance

Solve for the Net Force

Example Problem

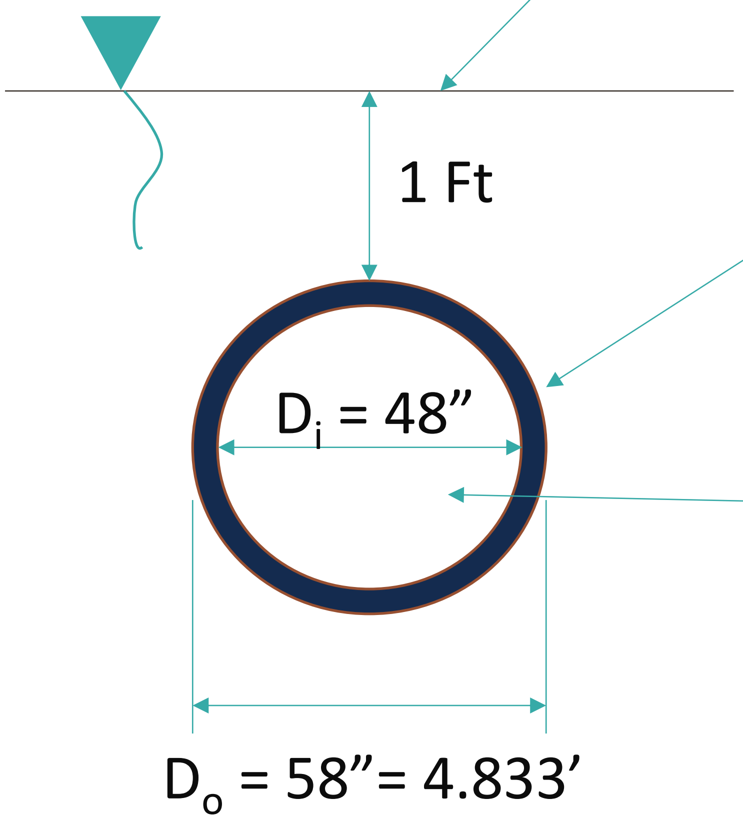
Reinforced Concrete Pipe

Given:

γ_t = 120 pcf

γ_w = 62.4 pcf

ϕ = 30 deg



RC Pipe Weight

W_p = 867 lbs/ft

Weight of Water Displaced

$W_w = \pi\,(d_o/2)^2\,\gamma_w$

$W_w = \pi\,(4.833/2)^2 \times 62.4$

W_w = 1,145 lbs/ft

BF = - 278 lbs/ft

Example Problem

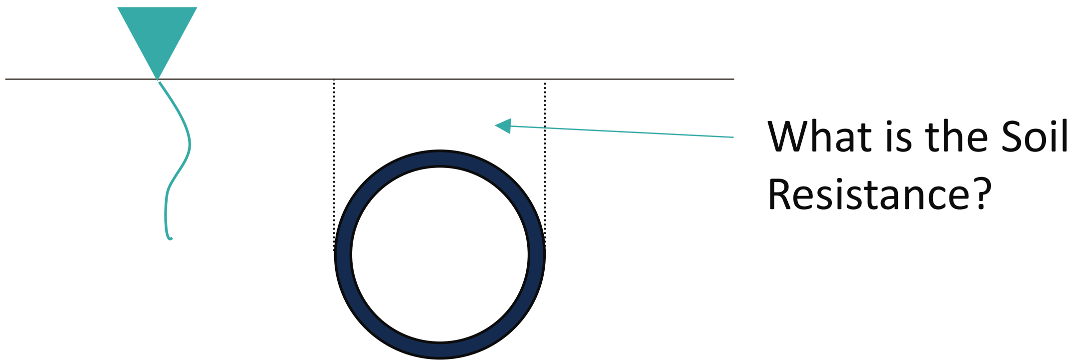
Calculate soil resistance (Rs) – ACPA Method

$\gamma_b = \gamma_t - \gamma_w$

R_s = Soil Resistance

W_s = Weight of Soil

PL = Prism Load



$$R_s = W_s = PL = \gamma_b \left[H + \frac{D_o (4 - \pi)}{8} \right] D_o \qquad \text{(eq. 4.2)}$$

$$R_s = (120 - 62.4) \left[1 + \frac{4.833\,(4 - \pi)}{8} \right] 4.833$$

R_s = 423 lbs/ft

Example Problem

Calculate soil resistance (Rs) – Watkins-Moser Method

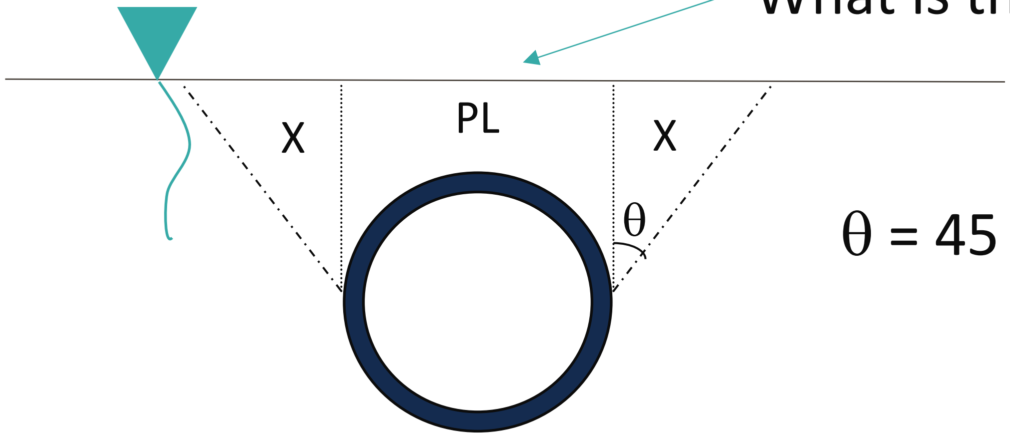
Given:

γ_t = 120 pcf

γ_w = 62.4 pcf

ϕ = 30 deg

What is the Soil Resistance?



$\theta = 45 - \phi/2$

$$R_s = PL + 2X$$

$$2X = [(H + D_o/2)^2 \tan(45 - \phi/2)]\ \gamma_b$$

$$2X = [(1 + 4.833/2)^2 \tan(45 - 30/2)]\ (120\text{-}62.4)$$

$$2X = 388 \text{ lbs/ft}$$

R_s = 423 + 388 = 811 lbs/ft

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Example Problem

Calculate Net Force

ACPA Method

Net force = BF + (R_s / FS)

= (-278) + (423/1.25) = 60 lbs/ft

Watkins/Moser Method

Net force = BF + (R_s / FS)

= (-278) + (811/2.0) = 128 lbs

Both Methods Show That The Pipe Will Not Float.

Example Problem

Results – Reinforced Concrete Pipe

RCP Results

Method	Buoyancy Force, BF (lbs/ft)	Soil Resistance R_s (lbs/ft)	Factor of Safety, FS	Net Force (lbs/ft)
ACPA	-278	423	1.25	60
W/M	-278	811	2.0	128

Example Problem

Calculate the buoyant force (BF) – CMP & HDPE

γ_t = 120 pcf
γ_w = 62.4 pcf
ϕ = 30 deg

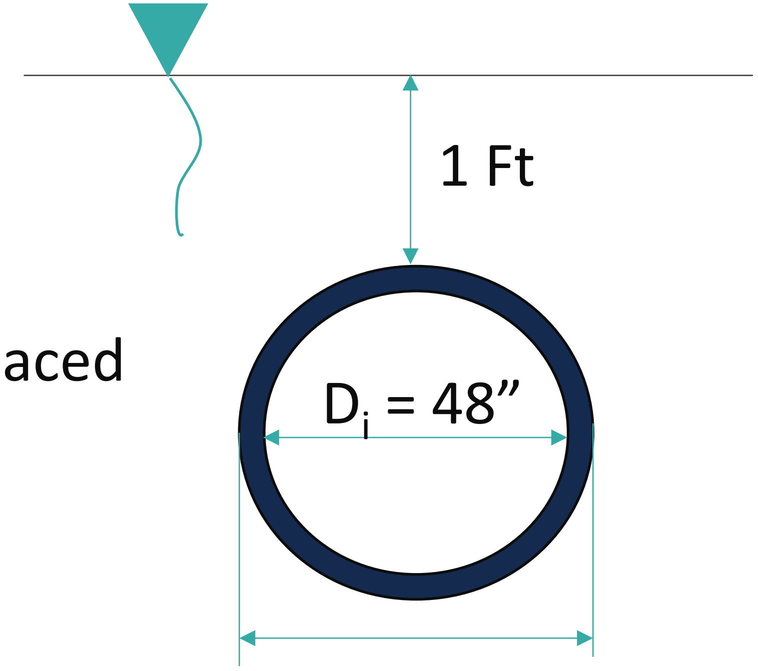
CMP Pipe Weight
W_p = 38 lb/ft

Weight of Water Displaced
$W_w = \pi (d_o/2)^2 \gamma_w$
W_w = 957 lbs/ft

BF = - 919 lbs/ft

R_s = 375 lbs/ft - ACPA

R_s = 717 lbs/ft – W/M



CMP - D_o = 53”= 4.42’
HDPE - D_o = 54”= 4.50’

HDPE Pipe Weight
W_p = 31 lb/ft

Weight of Water Displaced
$W_w = \pi (d_o/2)^2 \gamma_w$
W_w = 992 lbs/ft

BF = - 961 lbs/ft

R_s = 383 lbs/ft - ACPA

R_s = 734 lbs/ft – W/M

Example Problem

Comparison – Different Pipe Materials

Comparison – ACPA Method

48" Pipe Type	Buoyancy Force, BF (lbs/ft)	Soil Resistance R_s (lbs/ft)	Factor of Safety, FS	Net Force (lbs/ft)
CMP	-919	375	1.25	-619
HDPE	-961	383	1.25	-654
RCP	-278	423	1.25	60

Example Problem

Comparison – Different Pipe Materials

How Much Fill For a 48 Inch Pipe?

	Pipe Type		
Method	RCP	CMP	HDPE
ACPA	9”	49”	50”
M/W	6”	34”	36”

*For plastic pipe, a good rule of thumb is fill height equal to pipe diameter.

Example Standards

How is Floatation Addressed?

Designation: D2321 – 20

ASTM D2321 – Section 7.6 Minimum Cover

Size	Class I	Class II, III, IV	Hydrohammer
12"	24"	36"	48"
18"	24"	36"	48"
24"	[illegible]	[illegible]	48"
30"	[illegible]	[illegible]	[illegible]
36"	[illegible]	[illegible]	48"
42"	42"	42"	48"
48"	48"	48"	48"
54"	54"	54"	48"
60"	60"	60"	48"

7.6 *Minimum Cover*—To preclude damage to the pipe and disturbance to pipe embedment, a minimum depth of backfill above the pipe should be maintained before allowing vehicles or heavy construction equipment to traverse the pipe trench. The minimum depth of cover should be established by the engineer based on an evaluation of specific project conditions.' In the absence of an engineering evaluation, the following minimum cover requirements should be used. For embedment materials installed in accordance with Table 3, provide cover (that is, depth of backfill above top of pipe) of at least 24 in. (0.6 m) or one pipe diameter (whichever is larger) for Class I embedment, and a cover of at least 36 in. (0.9 m) or one pipe diameter (whichever is larger) for Class II, III, and IV …

Example

Reinforced Concrete Can Float

Resist the Float

Minimum Cover for Concrete Pipe* – ACPA Method

Pipe Size	Min. Fill	Pipe Size	Min. Fill	Pipe Size	Min. Fill
21”	1”	42”	7”	78”	18”
24”	2”	48”	9”	84”	21”
27”	2”	54”	10”	90”	23”
30”	3”	60”	13”	96”	24”
33”	4”	66”	15”	102”	27”
36”	5”	72”	17”	108”	29”

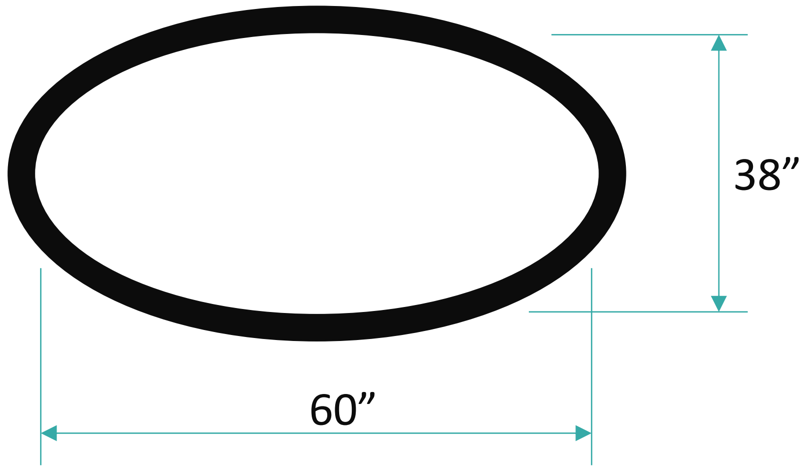
*Assumes the groundwater table is at the surface.
F.S = 1.25

Example Problem

Horizontal Elliptical Pipe – 48” Equivalent (38” x 60”)

Illustration 5.3 Dimensions and Approximate Weights of Elliptical Concrete Pipe

ASTM C 507-Reinforced Concrete Elliptical Culvert, Storm Drain and Sewer Pipe					
Equivalent Round Size, inches	**Minor Axis, inches**	**Major Axis, inches**	**Minimum Wall Thickness, inches**	**Water-Way Area, square feet**	**Approximate Weight, pounds per foot**
18	14	23	2 3/4	1.8	195
24	19	30	3 1/4	3.3	300
27	22	34	3 1/2	4.1	365
30	24	38	3 3/4	5.1	430
33	27	42	3 3/4	6.3	475
36	29	45	4 1/2	7.4	625
39	32	49	4 3/4	8.8	720
42	34	53	5	10.2	815
48	38	60	5 1/2	12.9	1000
54	43	68	6	16.6	1235
60	48	76	6 1/2	20.5	1475
66	53	83	7	24.8	1745
72	58	91	7 1/2	29.5	2040



Example Problem

Horizontal Elliptical Pipe – 48” Equivalent (38” x 60”)

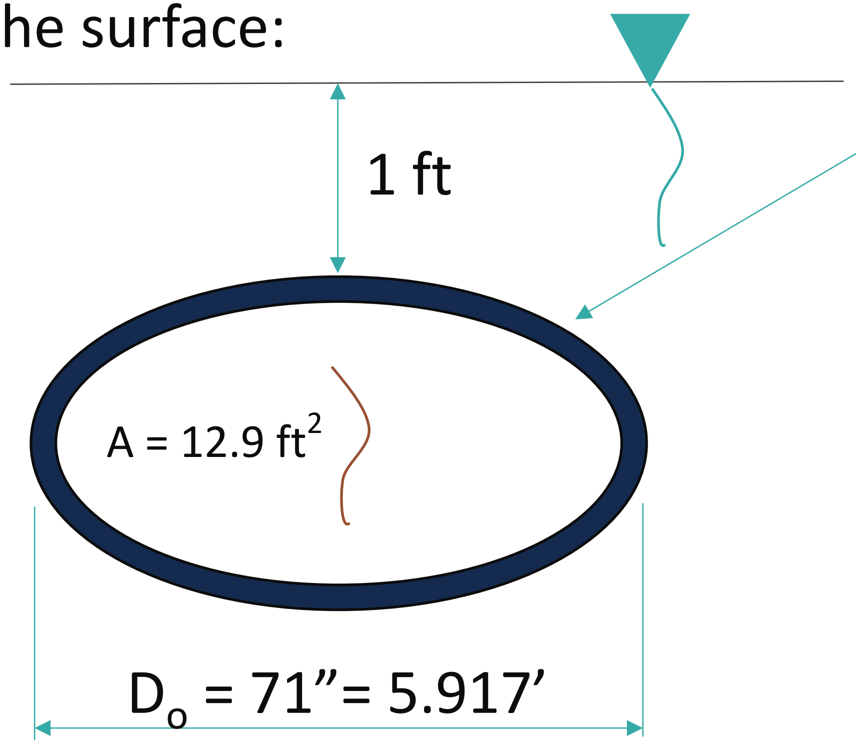
Given:

Ground water level at the surface:

γ_t = 120 pcf

γ_w = 62.4 pcf

ϕ = 30 deg



RC Pipe Weight

W_p = 1000 lb/ft

Area of Water Displaced

A = 19.64 ft^2

Weight of Water Displaced

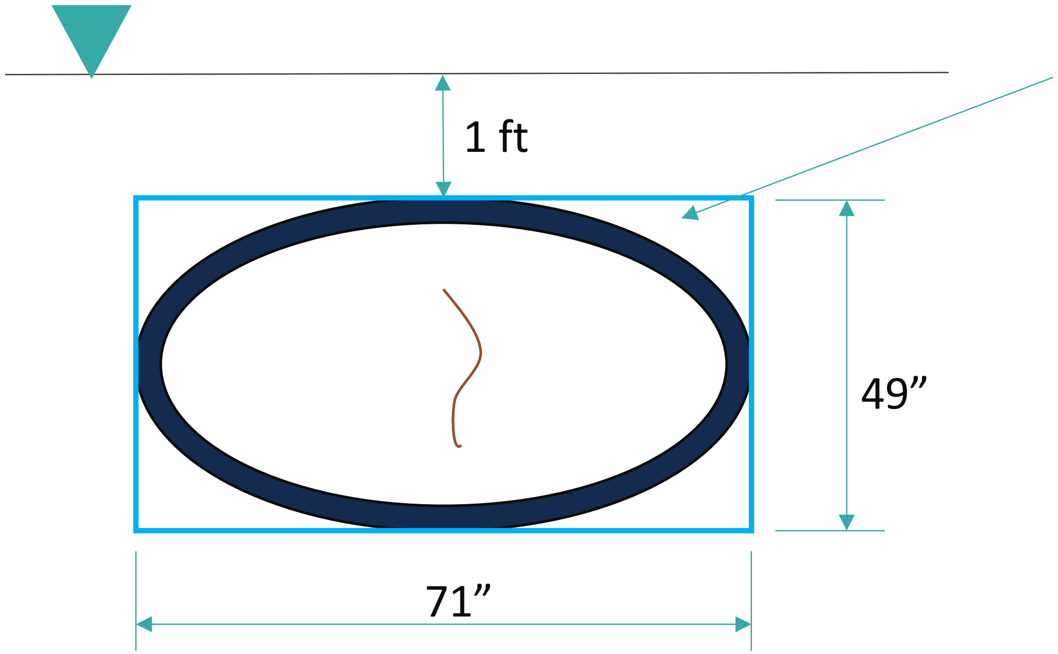
W_w = 1,226 lbs/ft

BF = - 226 lbs/ft

Example Problem

Horizontal Elliptical Pipe – 48" Equivalent (38" x 60")

Rise = 38"
Span = 60"
Wall = 5.5"



What is the Soil Resistance from the Upper Haunches?

Total Rectangle Area
$(49 \times 71)/144 = 24.16 \text{ ft}^2$

Pipe Area
$A = 19.64 \text{ ft}^2$

Upper Haunch Area
$A = (24.16 - 19.64)/2 = 2.26 \text{ ft}^2$

Upper Haunch Soil Resistance
$R_s = 2.26 \times (120-62.4) = 130 \text{ lbs/ft}$

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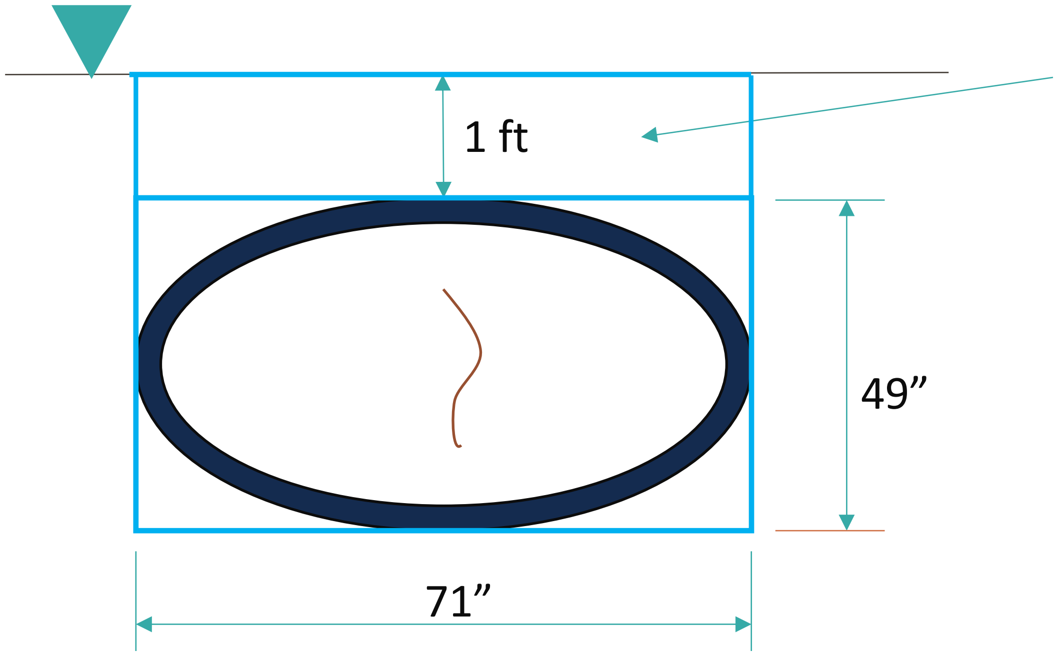
Example Problem

Horizontal Elliptical Pipe – 48” Equivalent (38” x 60”)

Rise = 38”
Span = 60”
Wall = 5.5”



What is the Soil Resistance from the Soil Prism Above the Crown?

Upper Rectangle Area
(12 x 71)/144 = 5.92 ft^2

Upper Rectangle Soil Resistance
R_s = 5.92 x (120-62.4) = 341 lbs/ft

Total Soil Resistance
Rs = Upper Haunch + Rectangular Soil Prism
R_s = 130 + 341 = **471 lbs/ft**

Example Problem

Comparison – Different Pipe Shapes – 48”

Shape	Buoyancy Force, BF (lbs/ft)	Soil Resistance R_s (lbs/ft)	Factor of Safety, FS	Net Force (lbs/ft)
Elliptical	-226	471	1.25	150
Circular	-278	423	1.25	60


PLAN
YES
NO
BOSS
TOP
MORE?

Example Problem

HDPE Pipe when Water Table Not at the Surface

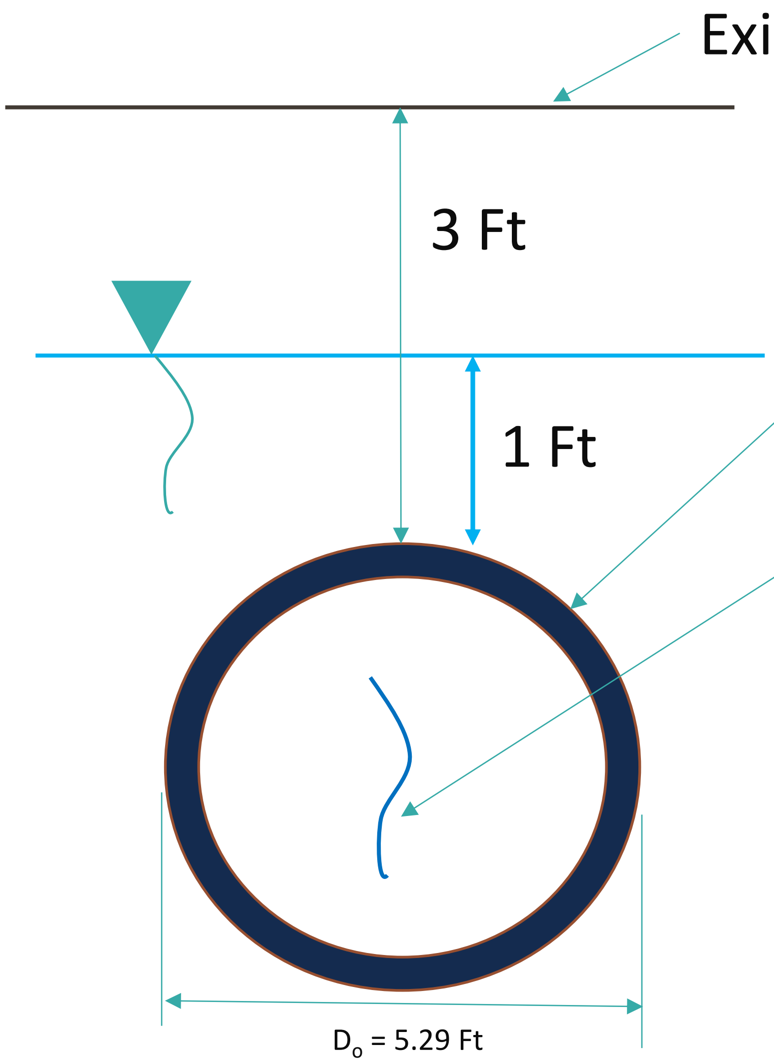
Given:

60” HDPE

γ_t = 130 pcf

γ_d = 110 pcf

γ_w = 62.4 pcf



60” HDPE Pipe Weight

W_p = 45 lbs/ft

Weight of Water Displaced

$W_w = \pi\,(d_o/2)^2\,\gamma_w$

W_w = 1373 lbs/ft

BF = - 1328 lbs/ft

Example Problem

HDPE Pipe when Water Table Not at the Surface

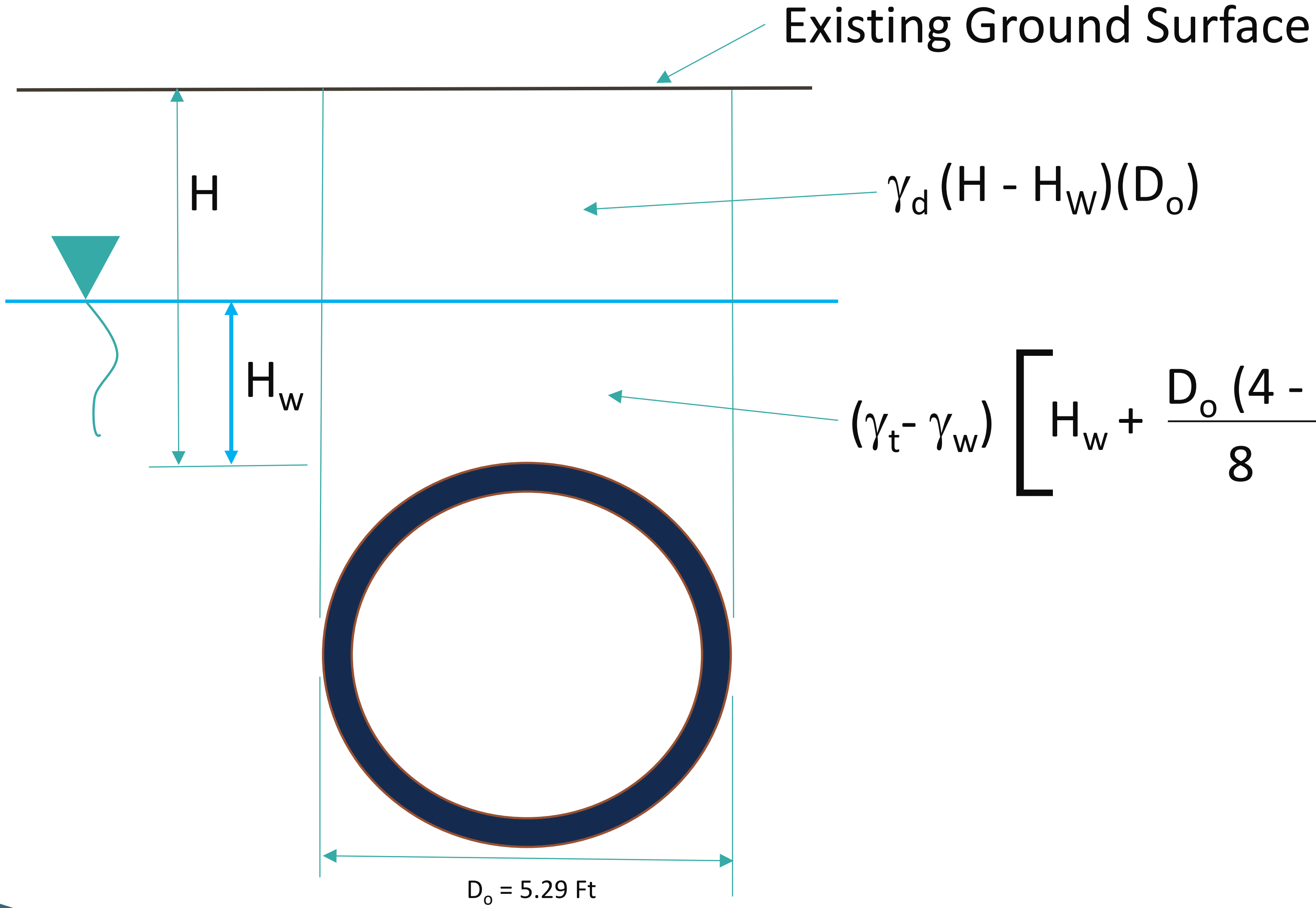
Given:

60” HDPE

γ_t = 130 pcf

γ_d = 110 pcf

γ_w = 62.4 pcf



$$\gamma_d (H - H_w)(D_o)$$

$$(\gamma_t - \gamma_w)\left[H_w + \frac{D_o(4 - \pi)}{8}\right] D_o$$

Example Problem

HDPE Pipe when Water Table Not at the Surface

Calculation of Soil Resistance

$$R_s = (\gamma_t - \gamma_w)\left[H_w + \frac{D_o(4 - \pi)}{8}\right]D_o + \gamma_d(H - H_W)(D_o)$$

$$R_s = (130 - 62.4)\left[1.0 + \frac{5.29(4 - \pi)}{8}\right]5.29 + 110(3\text{-}1.0)(5.29)$$

$$R_s = 561 + 1163$$

R_s = 1724 lbs/ft

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Example Problem

HDPE Pipe when Water Table Not at the Surface

60” HDPE Results – 3 Ft. Cover

Water Over Pipe (ft.)	Buoyancy Force, BF (lbs/ft)	Soil Resistance R_s (lbs/ft)	Factor of Safety, FS	Net Force (lbs/ft)
1.0	-1328	1724	1.25	51

Example Problem

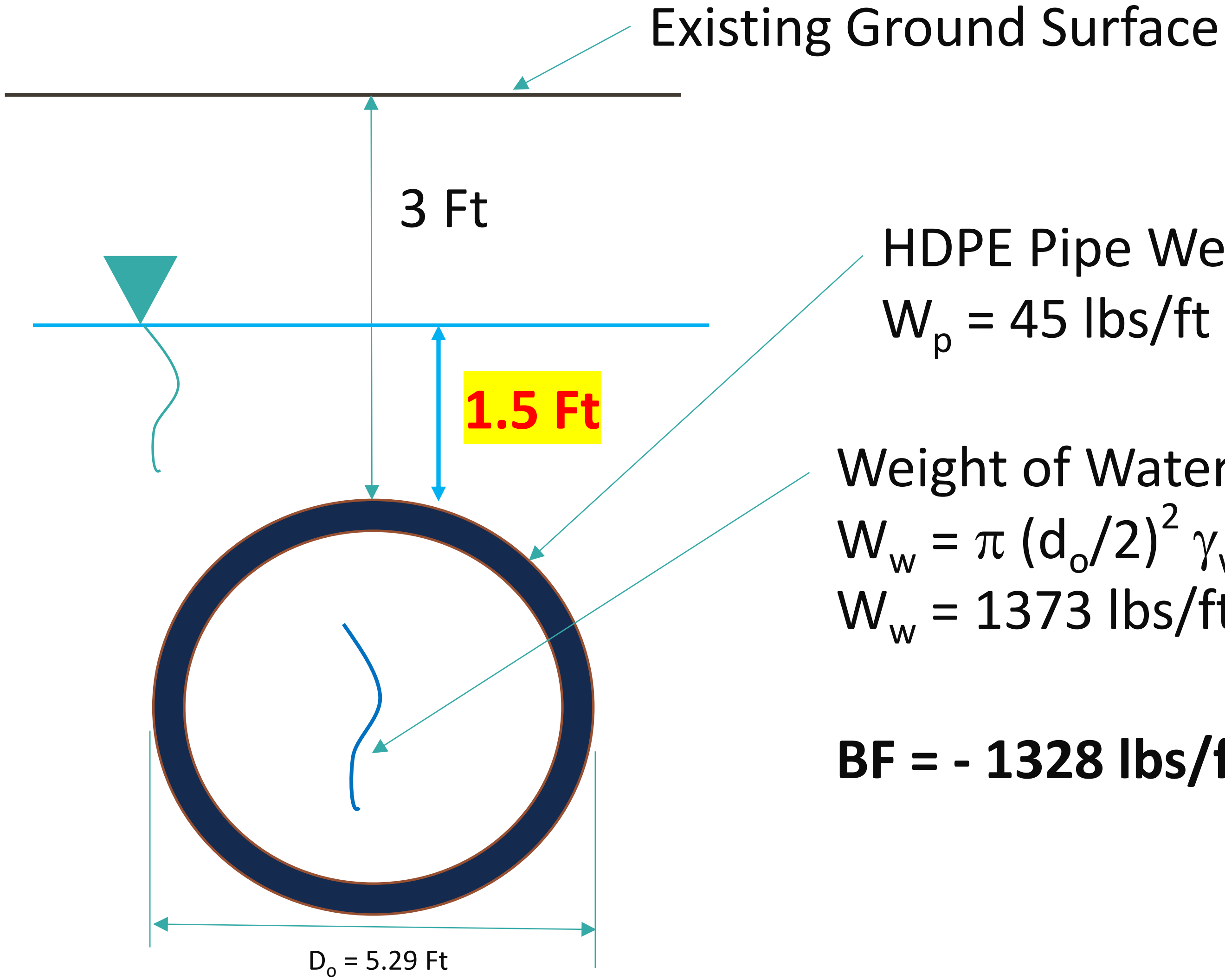
HDPE Pipe when Water Table Not at the Surface

Given:

γ_t = 130 pcf

γ_d = 110 pcf

γ_w = 62.4 pcf



HDPE Pipe Weight

W_p = 45 lbs/ft

Weight of Water Displaced

$W_w = \pi\, (d_o/2)^2\, \gamma_w$

W_w = 1373 lbs/ft

BF = - 1328 lbs/ft

Example Problem

HDPE Pipe when Water Table Not at the Surface

Calculation of Soil Resistance

$$R_s = (\gamma_t - \gamma_w)\left[H_w + \frac{D_o(4-\pi)}{8}\right]D_o + \gamma_d (H - H_W)(D_o)$$

$$R_s = (130 - 62.4)\left[\mathbf{1.5} + \frac{5.29\,(4-\pi)}{8}\right]5.29 + 110\,(3-\mathbf{1.5})(5.29)$$

$$R_s = 739 + 873$$

$$\mathbf{R_s = 1612\ lbs/ft}$$

Example Problem

HDPE Pipe when Water Table Not at the Surface

60” HDPE Results – 3 Ft. Cover

Water Over Pipe (ft.)	Buoyancy Force, BF (lbs/ft)	Soil Resistance R_s (lbs/ft)	Factor of Safety, FS	Net Force (lbs/ft)
1.0	-1328	1724	1.25	51
1.5	-1328	1612	1.25	-38

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Example Problem

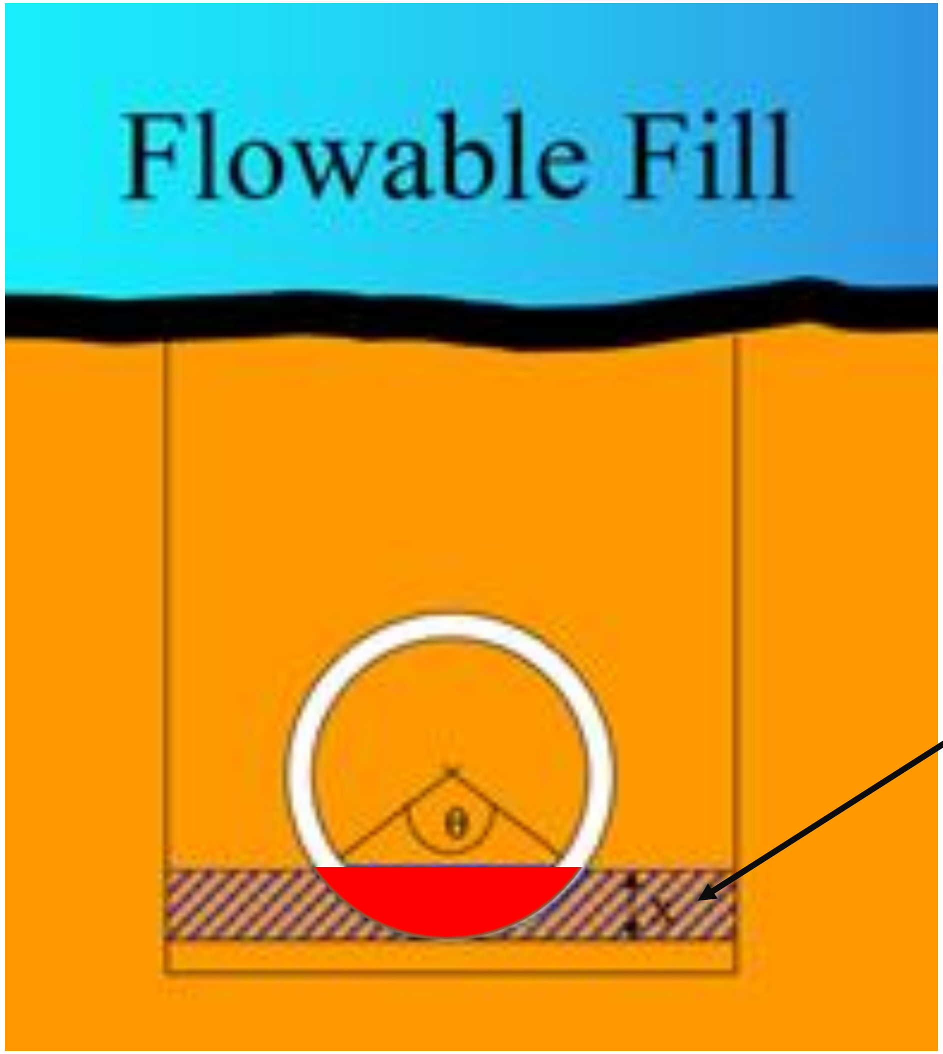
Flowable Fill

When is the pipe subject to floatation?

γ_{ff} = 130 pcf

Area of Segment of Circle

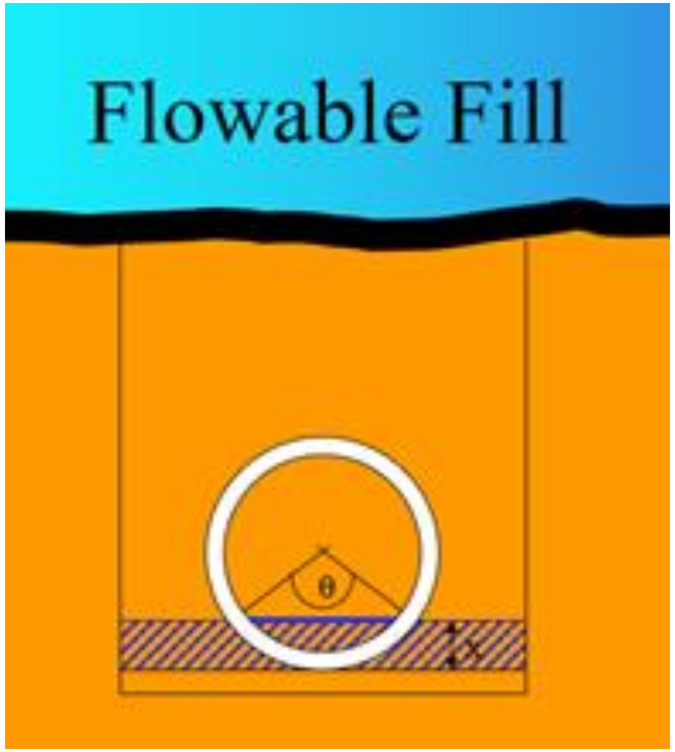
Calculate Weight of Displaced Fill



X = Depth of Fill

Example Problem

Flowable Fill – Controlled Low Strength Material - CLSM

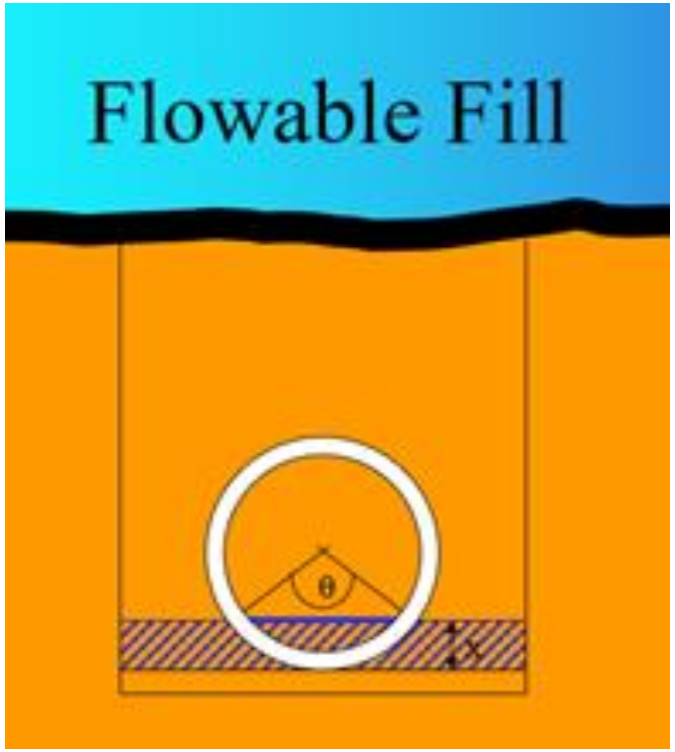


HDPE Pipe

Pipe Size	Pipe OD (ft)	Weight of Pipe	Density of CLSM	Height of CLSM	Area of Segment	Wt of CLSM Displaced	Weight of Pipe	Bouyant Force	% of Do
12	1.21	3.2	130	2	13.75	-12.41	3.2	-9.21	13.80%
15	1.50	4.6	130	2	15.46	-13.95	4.6	-9.35	11.11%
18	1.83	6.4	130	2	17.20	-15.52	6.4	-9.12	9.09%
24	2.33	11	130	2	19.51	-17.61	11	-6.61	7.15%
30	3.00	15.4	130	2	22.25	-20.08	15.4	-4.68	5.56%
36	3.50	19.8	130	3	43.92	-39.65	19.8	-19.85	7.14%
42	4.00	26.4	130	3	47.09	-42.51	26.4	-16.11	6.25%
48	4.50	31.3	130	3	50.05	-45.19	31.3	-13.89	5.56%
60	5.58	45.2	130	3	55.94	-50.50	45.2	-5.30	4.48%

Example Problem

Flowable Fill – Controlled Low Strength Material - CLSM



Reinforced Concrete Pipe									
Pipe Size	**Pipe OD (ft)**	**Weight of Pipe**	**Density of CLSM**	**Height of CLSM**	**Area of Segment**	**Wt of CLSM Displaced**	**Weight of Pipe**	**Bouyant Force**	**% of Do**
12	1.33	93	130	9	116.47	-105.14	93	-12.14	56.26%
15	1.63	127	130	10	154.20	-139.21	127	-12.21	51.28%
18	1.92	168	130	11	196.24	-177.16	168	-9.16	47.83%
24	2.50	264	130	13	293.61	-265.06	264	-1.06	43.33%
30	3.08	384	130	16	445.38	-402.08	384	-18.08	43.24%
36	3.67	524	130	18	585.24	-528.34	524	-4.34	40.91%
42	4.25	686	130	21	793.10	-716.00	686	-30.00	41.18%
48	4.83	867	130	23	975.53	-880.69	867	-13.69	39.66%
60	6.00	1295	130	28	1464.52	-1322.14	1295	-27.14	38.89%

Culverts

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March 20, 2020

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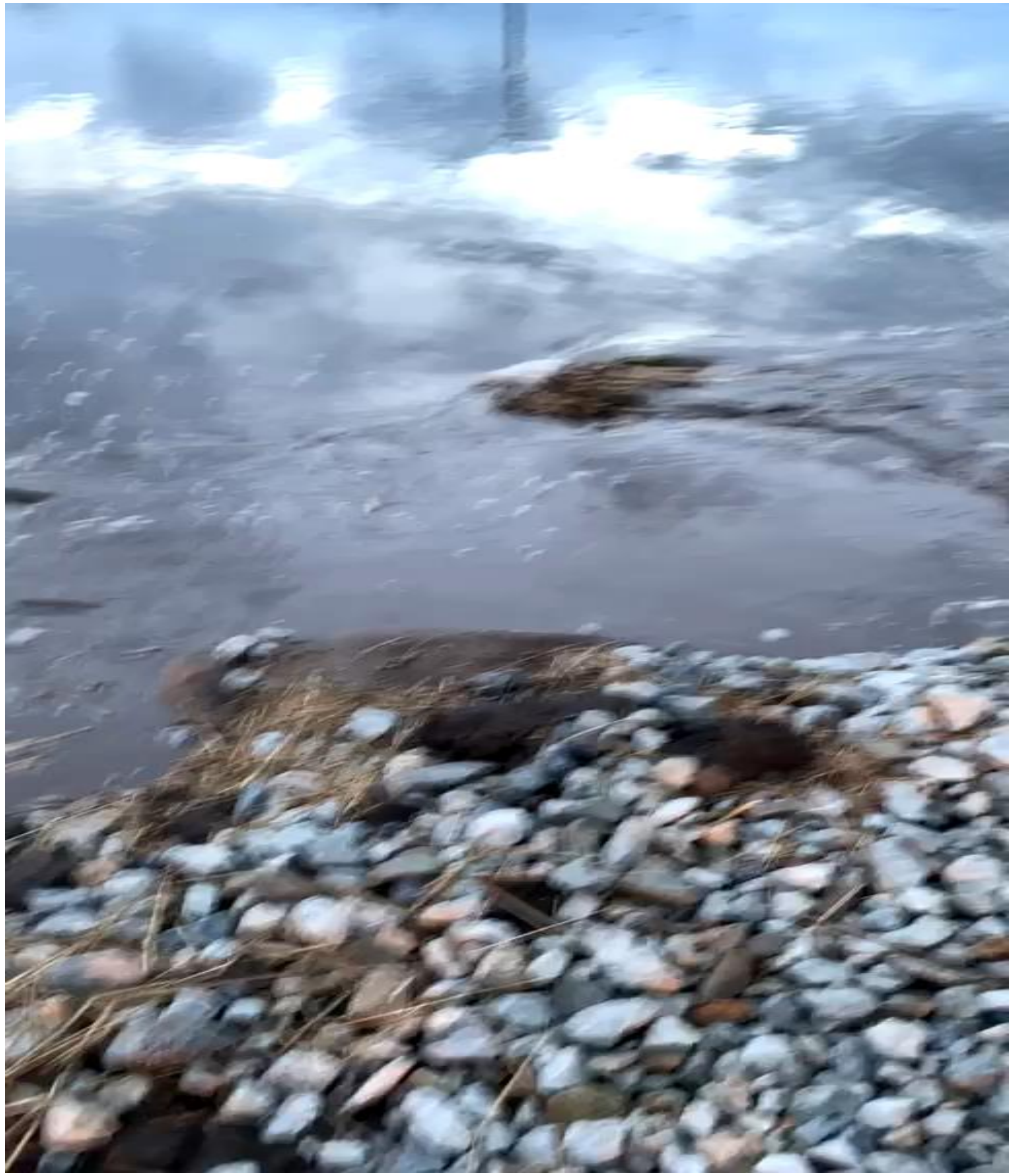

Culverts

The Pyramids of Egypt

HOW WERE THEY REALLY BUILT?

Buoyancy & Pipe Flotation

ACPA

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