# Quiz HD202

## Buried Flexible Steel Pipe

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# Problems

## Problem 1

True or false? Judge the following statements, regarding the AWWA's *M11 – Steel Pipe* manual of practice, ASCE's *Buried Flexible Steel Pipe* manual of practice, and *Pipelines for Water Conveyance and Drainage* manual of practice, also published by the ASCE.

If necessary, refer to the Iowa formula in the form shown below,

$$\Delta x = D_l \left( \frac{KWr^3}{EI + 0.061E'r^3} \right)$$

in which

$\Delta x$ → Horizontal deflection of pipe (in. or mm)
$D_l$ → Deflection lag factor (1.0 – 1.5)
$K$ → Bedding constant (= 0.1)
$W$ → Load per unit of pipe length (psi or kN/m)
$r$ → Radius (in. or mm)
$EI$ → Pipe wall stiffness

and

$E$ → Steel modulus of elasticity ($30\times10^6$ psi or $200\times10^6$ kPa)
$I$ → Transverse moment of inertia per unit length of individual pipe wall components = $t^3/12$, where $t$ is the thickness of the soil component in in. or mm
$E'$ → Modulus of soil reaction (psi or kPa)

**1.( )** One of the advantages of the Iowa formula is the inclusion of the *modulus of soil reaction*, *E'*, which is a measure of the stiffness of the embedment material that surrounds the pipe. It is a hybrid modulus that does away with the spring constant used in the original Iowa formula, and can be uniquely measured from a soil sample by means of a simple laboratory confined compression test.

**2.( )** To understand pipe-soil interaction, the Iowa formula can be rewritten for vertical ring deflection,

$$\delta(\%) = \frac{10P}{\Sigma\left(EI/r^3\right) + 0.06E'}$$

where $EI/r^3$ is the (sp)ring stiffness and $0.06E'$ is the soil stiffness, thus showing that both the steel and the soil play an important role in the stiffness of the system. If, however, the soil embedment is select and compact, the soil stiffness becomes relatively insignificant relative to the steel stiffness.

**3.( )** The widest cracks in a BFS pipe usually occur in the pipe's compressive zone, which, in the case of coatings, usually occurs at the springline.

**4.( )** According to AWWA standards, hoop stress may rise, within limits, above 50 percent of yield for transient loads. For steel pipe produced to meet AWWA standards, the increased hoop stress should be limited to 75 percent of the specified yield strength but should not exceed the mill test pressure.

**5.( )** If external pressure exceeds the factored allowable external pressure permitted by the method provided in AWWA Manual M11, the ring stiffness of the pipe must be increased. Although this is often accomplished by increasing the steel thickness in the pipe wall, a viable alternative is to use imported backfill rather than the native backfill in which the conduit is entrenched.

**6.( )** If the embedment about a buried pipe is densely compacted, vertical soil pressure at the top of the pipe is reduced by arching action of the soil over the pipe, like a masonry arch, that helps to support the load. Hence, soil arching provides an additional margin of safety. To be conservative, however, arching action is usually neglected in design procedures.

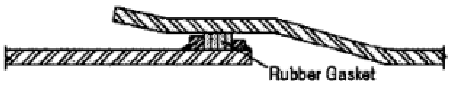
**7.( )** The lower part of a BFS pipe can be supported by flowable fill, which consists of a soil-cement grout that flows under the pipe and eventually becomes a uniform bedding. Despite being a convenient short-term solution, the material may be a nuisance for future excavation operations involving the pipe's site of installation.

**8.( )** Accurate results on a surge analysis in a BFS pipe depend on knowing the various hydraulic and physical characteristics of the system. The velocity of the pressure wave is a fundamental factor in any surge study, as the surge pressures are directly proportional to its value. This velocity depends on the pipe diameter, wall thickness, material of the pipe walls, and the density and compressibility of the fluid in the pipe. On the other hand, the pressure rise ensuing from, say, the sudden closure of a valve is generally not dependent on the length of the conduit.

**9.( )** If seismic waves move parallel to a buried pipe, pressure waves (*P* waves) cause longitudinal bending (undulations) that can cause leaks at bell-and-spigot joints by lever action. Shear waves (*S* waves) can cause leaks at joints by jamming and withdrawing adjoining pipes.

**10.( )** As is the case with other pipe materials, the Hazen-Williams formula is the most widely used equation for computing friction loss in steel pipelines. According to applicable manuals and standards, the Hazen-Williams *C* factor used in this equation is not constant, but rather taken as a function of diameter.

**11.( )** A number of commonly used joints are employed for steel pipe, including lap welded, butt strap, and rubber gasket joints. The figure below shows a rolled-groove rubber gasket joint.

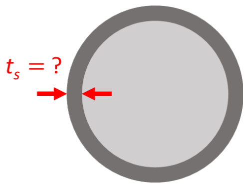



**12.( )** The allowable leakage rate for a steel pipeline depends on the type of joint used. A pipeline with welded joints, sleeve couplings, grooved-shouldered couplings, or flanged joints should have essentially no leakage, whereas some leakage, albeit quite small, is allowed for conduits with rubber gaskets joints.

## Problem 2A

What is the minimum required thickness, $t_s$, for a pipe to satisfy internal requirements and handling under the following conditions?

| | |
|---|---|
| Cylinder outer diameter | $D$ = 1250 mm |
| Working pressure | $p_w$ = 1000 kPa |
| Transient pressure | $p_t$ = 1600 kPa |
| Field test pressure | $p_f$ = 1350 kPa |
| Steel minimum yield stress | $\sigma_Y$ = 250 MPa |




**A)** $t_s$ = 3.67 mm

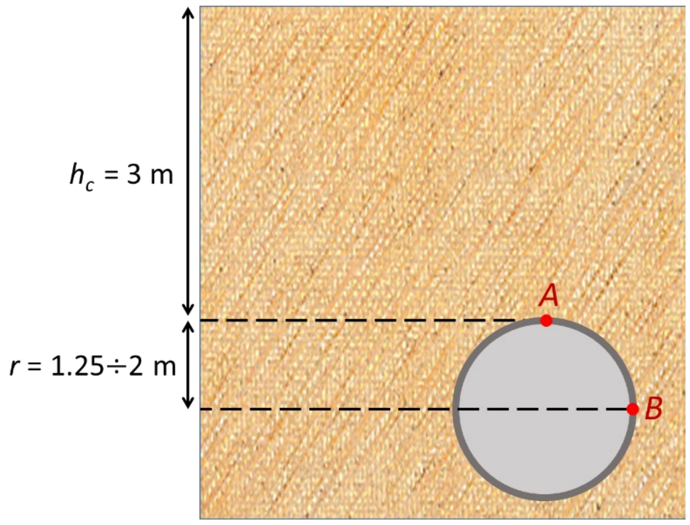
**B)** $t_s$ = 5.33 mm

**C)** $t_s$ = 7.00 mm

**D)** $t_s$ = 8.67 mm

## Problem 2B

Suppose that the pipe designed in Part A has the steel thickness specified therein and a 13-mm-thick cement mortar lining. The fill above and around the pipe is dry sand with dry unit weight $\gamma_d$ = 18.8 kN/m$^3$ and friction angle $\phi'$ = 33°. The soil compaction is 85% as per ASTM D698. There are no live loads to consider. The allowable deflection is 3%. Determine the vertical deflection at which slip occurs.




**A)** $d$ = 8.4%

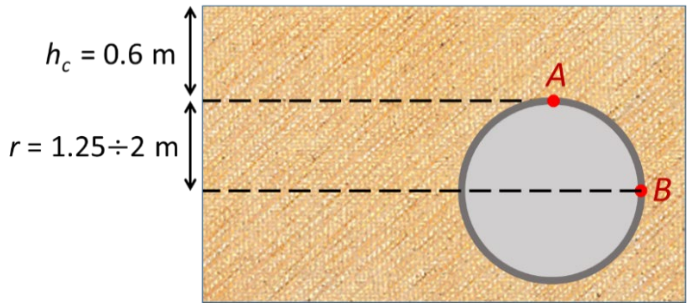
**B)** $d$ = 13.3%

**C)** $d$ = 18.4%

**D)** $d$ = 23.1%

## Problem 2C

Obtain the vacuum pressure that the pipe in the previous problem can withstand, then determine the factor of safety $FS$ $(= p_{\text{vacuum}}/p_{\text{atm}})$ against a full vacuum pressure. We now have a reduced soil cover, as the distance between the top of the pipe and the surface is only 0.6 m. The soil has the same properties as before. Use the steel thickness computed in Part A and 13 mm as the cement mortar lining thickness; the pipe deflection shall be the allowable value, namely $d$ = 0.03.Take $p_{atm}$ = 101.3 kPa as the atmospheric pressure, $E_s$ = 200,000 MPa and $E_c$ = 27,000 MPa for steel and mortar, respectively.




**A)** $FS$ = 2.0

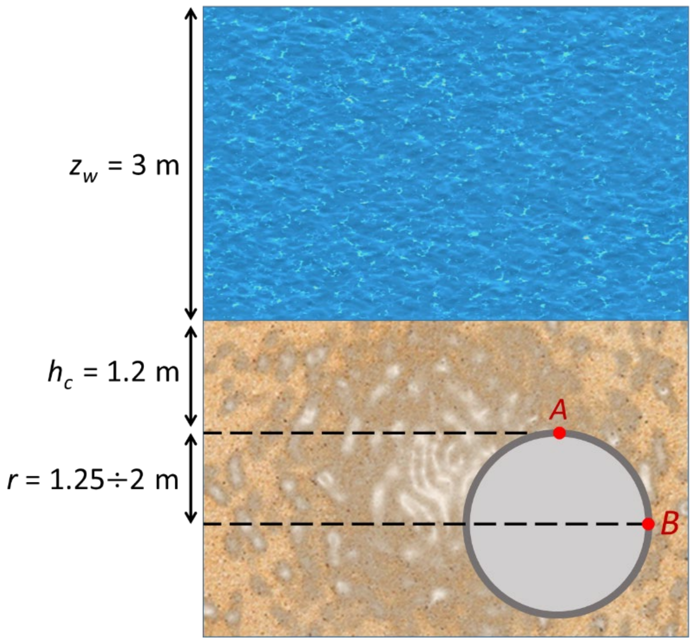
**B)** $FS$ = 2.9

**C)** $FS$ = 3.8

**D)** $FS$ = 4.7

## Problem 2D

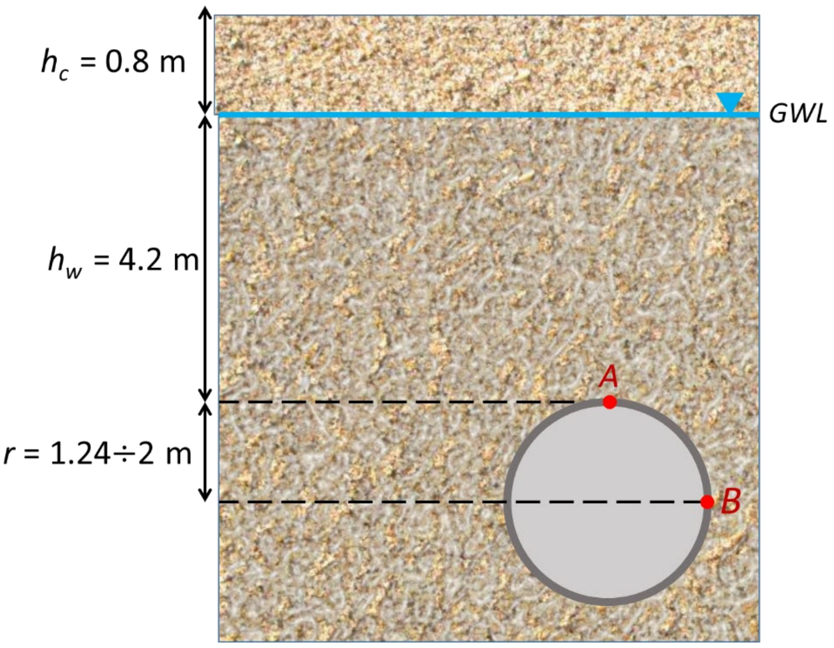
Suppose now that the pipe designed in Part A has a 3-m-tall water cover, in addition to 1.2 m of the same sand cover as before, which has a saturated unit weight $\gamma_{sat}$ = 20.8 kN/m$^3$. The pipe remains unchanged. Under these circumstances, determine the new vacuum pressure at which soil slip occurs, then establish the new factor of safety against a full vacuum pressure.




**A)** *FS* = 1.2
**B)** *FS* = 1.9
**C)** *FS* = 2.6
**D)** *FS* = 3.4

## Problem 3A

The figure shows a 1240 mm-outside diameter × 6 mm-wall pipe, full of water, buried in an embedment of silt and fine sand. The cover is 5 m. At certain times during the year, the water table rises to within 0.8 m below the ground surface. The dry unit weight of the soil is $\gamma_d$ = 15.7 kN/m$^3$, the saturated unit weight is $\gamma_{sat}$ = 19.6 kN/m$^3$, and the soil friction angle is $\phi'$ = 17°. The maximum vacuum pressure is 80 kPa. What is the elliptical ring deflection at which collapse occurs?




**A)** *d* = 0.03
**B)** *d* = 0.045
**C)** *d* = 0.06
**D)** *d* = 0.075

## Problem 3B

As a variation of the previous exercise, suppose the deflection is limited to 3.5%. What would then be the maximum vacuum or radial external pressure? Compute the factor of safety, taking $p_{atm}$ = 101.3 kPa as the atmospheric pressure.

**A)** *FS* = 1.2

**B)** *FS* = 2.0

**C)** *FS* = 2.8

**D)** *FS* = 3.6

# Solutions

## P.1 ■ Solution

**1. False.** The laboratory confined compression test is a uniaxial test typically used to predict the vertical compression of side fill, which in turn is useful for predicting ring deflection. While it is used to determine the soil secant modulus *E'* (which would be the equivalent of 'modulus of soil reaction'), it does not in any way provide a *unique* value for the soil, as the stress-strain relationship that it produces is highly nonlinear.

**2. False.** On the contrary, the fact that the soil is select and compact implies that it is the *soil*'s properties that govern the relative stiffness.

**3. False.** The widest cracks in a BFS pipe usually occur in the pipe's *tensile* zone. Indeed, the highest tensile stresses occur at the pipe's springline.

**4. True.** These quantities are prescribed in AWWA M11.

**5. True.** Use of a better-compacted soil is the best alternative to simply increasing the steel thickness of the pipe wall.

**6. True.** The extent to which a well-compacted soil embedment can aid in pipe resistance is remarkable. Pipes that have "cracked" or structurally failed in some other manner have been discovered to be still functional because the surrounding soil provided them with additional support. Nevertheless, engineers should not rely on such an additional protection to prevent the pipe from total collapse, but rather make use of a comprehensive pipe-soil interaction analysis.

**7. False.** On the contrary, flowable fill helps to protect the pipe in the event of future excavations, and is often a viable alternative to simply increasing the steel thickness when the ring stiffness is not strong enough.

**8. False.** Indeed, all the parameters mentioned, and velocity in particular, may be relevant to estimate the transient pressure in a BFS pipeline. For steel pipe conveying water, using metric units, the pressure rise *h* above normal can be estimated as

$$h = \frac{aV}{g} = \sqrt{\frac{0.319}{\frac{W}{g}\left(\frac{1}{k}+\frac{D}{Et}\right)}}\frac{V}{g}$$

where *a* is the wave velocity – equal to the term highlighted in blue – *W* is the specific weight of fluid, *g* is the acceleration of gravity, *k* is the bulk modulus of compressibility of the fluid, *D* is the inside diameter of the conduit, *E* is Young's modulus for the pipe wall material, *t* is the thickness of the conduit wall, and *V* is the velocity of flow. Note that in any way does the length of the pressure conduit appear in the equation. However, the length of the conduit becomes important when we want to establish the rate at which the pressure will rise and fall within the pipeline, which is generally based on the ratio $2L/a$.

**9. False.** The effects have been inverted: longitudinal bending is generally a consequence of shear waves, whereas jamming and withdrawing of adjoining pipes generally occurs due to pressure waves.

**10. True.** Indeed, according to the AWWA M11, the Hazen-Williams "*C*" in fact varies with nominal diameter, being such that

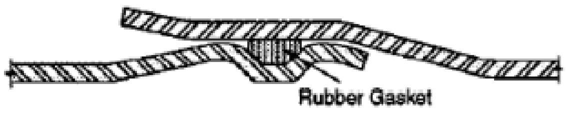
$$C = 130 + 0.0063D$$

where *D* is the nominal diameter in millimeters, or

$$C = 140 + 0.17D$$

where *D* is the nominal diameter in inches. (If, however, one considers long-term lining deterioration, slime build-up, and other conditions that may increase surface roughness, the use of a lower *C* is recommended; advisable formulas are $C = 130+0.0063D$ for nominal diameter given in millimeters, or $C = 130 + 0.1D$ for nominal diameter in inches).

**11. False.** The device shown is better classified as a rubber gasket joint. A "rolled-groove" rubber gasket joint would have one of the welded surfaces be embedded around the gasket and the other be positioned above it, as shown below.




**12. False.** Indeed, pipes with the mentioned structures should have no leakage, whereas a pipeline with rubber gaskets joints has an allowable leakage rate of 38 L /25.4 mm of diameter / 1.6 km of length / 24 h (or, equivalently, 10 gal. / in. of diameter / mi of length / 24 h).

## P.2 ■ Solution

**Part A:** The thickness *t is* based on the pipe's hoop stress,

$$t_s = \frac{pD}{2\sigma_p}$$

When designing the steel cylinder for the internal pressure, it is common to limit the allowable hoop tensile stress to a value equal to 50% of the specified minimum yield strength of the material. The pipe in question has 1250 mm outer diameter, working pressure $p_w$ = 1000 kPa, transient pressure $p_t$ = 1600 kPa, field test pressure $p_f$ = 1350 kPa, and steel minimum yield stress $\sigma_Y$ = 250 MPa. At first, the thickness is usually prescribed for the conduit's *working* pressure (which, as one would expect, can be also referred to as the *design* pressure). The allowable stress from internal pressure is taken as a half of the minimum yield stress, so that $\sigma_p = 0.5\times(250\times10^3) = 125\times10^3$ kPa. Thus, substituting $p = p_w$ = 1000 kPa and other pertaining variables in the formula for *t*, we obtain

$$t_s = \frac{p_w D}{2\sigma_p} = \frac{1000\times1250}{2\times\left(125\times10^3\right)} = 5.0\ \text{mm}$$

Finally, for field pressure conditions, the required thickness is

$$t_s = \frac{1350\times1250}{2\times\left(187.5\times10^3\right)} = 4.5\ \text{mm}$$

The minimum thickness for handling is determined by the ratio *D/t*, which is commonly taken as no more than 240.

$$\frac{D}{t_s} \le 240 \rightarrow t_s \ge \frac{D}{240} = 5.21\ \text{mm}$$

Therefore, we select a steel cylinder thickness equal to 5.33 mm nominal to satisfy internal pressure and handling requirements.

★ The correct answer is **B**.

**Part B:** The performance limit is for soil slip to occur at the springline. To assess the ring stability at the depth $h_c$ (distance from top-of-pipe to the soil cover surface), we proceed as follows. The top-of-pipe pressure *p* is

$$p = \gamma_d h_c = 18.8\times3 = 56.4\ \text{kPa}$$

At the springline (point B), the vertical stress is

$$\sigma_y = \gamma_d\left(h_c + D/2\right) = 18.8\times\left(3+1.25/2\right) = 68.2\ \text{kPa}$$

We also require the pressure coefficient *k*, which represents the ratio of maximum to minimum principal stresses on an infinitesimal cube of soil at soil slip; we obtain it via the equation

$$k = \frac{1+\sin\phi'}{1-\sin\phi'} = \frac{1+\sin 33^\circ}{1-\sin 33^\circ} = 3.39$$

in which $\phi'$ = 33° is the soil friction angle. At soil slip, the following relationship must hold,

$$p \times r_r = k \times \sigma_y$$

where $r_r$ is the ratio of vertical to horizontal radii of elliptical pipe, and is dependent on ring deflection $d$ as

$$r_r = \left(\frac{1+d}{1-d}\right)^3$$

We have $p$ = 56.4 kPa, $k$ = 3.39, and $\sigma_y$ = 68.2 kPa; therefore,

$$p \times r_r = k \times \sigma_y$$

$$\therefore 56.4 \times r_r = 3.39 \times 68.2$$

$$\therefore r_r = \frac{3.39 \times 68.2}{56.4} = 4.10$$

Then, returning to the equation for $r_r$, we can easily solve for $d$ using, for instance, Mathematica's *Solve* function,

$$\text{Solve}\left[4.10 == \left(\frac{1+d}{1-d}\right)^3, d\right]$$

which yields two meaningless imaginary solutions and $d \approx 0.231$. The deflection at soil slip is $d$ = 23.1%. (This is over seven times the specified allowable deflection to which the pipe is being maintained due to the cement mortar lining limit; hence, one can state that there will not be soil slip at the deflection limit.)

★ The correct answer is **D**.

**Part C:** The ratio $r_r$ at the allowable deflection ($d$ = 0.03) is $r_r$ = $[(1+d)/(1-d)]^3$= 1.20. The top of pipe pressure is now

$$p_A = \gamma_d h_c = 18.8 \times 0.6 = 11.3 \text{ kPa}$$

At the springline,

$$\sigma_y = \gamma_d\left(h_c + D/2\right) = 18.8 \times \left(0.6 + 1.25/2\right) = 23.0 \text{ kPa}$$

At soil slip, coefficient $k$ is such that

$$k = \frac{1+\sin 33^\circ}{1-\sin 33^\circ} = 3.39$$

The ring stiffness $\rho_s$ is obtained by adding the contributions of steel, cement mortar lining, and cement mortar coating, that is,

$$\rho_s = \sum\left(\frac{E}{(r/t)^3}\right)$$

In the above, $E$ is Young's modulus, taken as 200×10$^6$ kPa for steel and 27×10$^6$ kPa for mortar, $r$ = 1250/2 = 625 mm is the outer radius of the pipe, and $t$ is the thickness of each wall component; hence,

$$\rho_s = \frac{\left(200\times10^6\right)}{\left(625/5.33\right)^3} + \frac{\left(27\times10^6\right)}{\left(625/13\right)^3} = 124.0 + 243.0 = 367 \text{ kPa}$$

The vacuum pressure can be obtained by means of the equation

$$p_{\text{vac}}\left(r_r - 1\right) = k\sigma_y - \left(p_A - \rho_s d\right) r_r$$

where $p_{vac}$ is the vacuum pressure, $k$ = 3.39, $\sigma_y$ = 23.0 kPa, $p_A$ = 11.3 kPa, $d$ = 0.03 is the specified deflection, $r_r$ = 1.2, and $\rho_s$ = 367 kPa. Substituting each variable in the expression above, we get

$$p_{\text{vac}}(r_r - 1) = k\sigma_y - (p_A - \rho_s d) r_r \rightarrow p_{\text{vac}} = \frac{k\sigma_y - (p_A - \rho_s d) r_r}{r_r - 1}$$

$$\therefore p_{\text{vac}} = \frac{3.39 \times 23.0 - (11.3 - 367 \times 0.03) \times 1.2}{1.2 - 1} = 388.1 \text{ kPa}$$

This leads to a safety factor $FS = p_{vac}/p_{atm}$ = 388.1/101.3 = 3.8 against a 101.3-kPa full vacuum pressure. Critical vacuum pressure increases significantly by limiting ring deflection and by further compacting the embedment.

★ The correct answer is **C**.

**Part D:** Here, the worst case one can take into account is that of an empty pipe with the water table at flood level. The updated equation we need to model this problem is

$$p_{\text{vac}}(r_r - 1) = k\sigma_y + u_B - (p_A + \pi r \gamma_w / 2 - \rho_s d) r_r$$

In comparison to the equation employed in the previous part, here we have introduced terms $u_B$, which is the water pressure at the springline, and the product $\pi r \gamma_w/2$, which is the uplift buoyancy pressure of the empty pipe. The top-of-pipe pressure is

$$p_A = \gamma_{\text{sat}} h_c + \gamma_w z_w = 20.8 \times 1.2 + 9.8 \times 3 = 54.4 \text{kPa}$$

where we have used the saturated unit weight $\gamma_{\text{sat}}$ = 20.8 kN/m$^3$ and the unit weight of water $\gamma_w$ = 9.8 kN/m$^3$. Similarly, the water pressure at the springline is

$$u_B = (h_c + z_w + r)\gamma_{\text{w}} = (0.8 + 3 + 1.25/2) \times 9.8 = 47.3 \text{ kPa}$$

The vertical stress at the springline, $\sigma_y$, is

$$\sigma_y = p_A + r \times \gamma_{\text{sat}} - u_B = 54.4 + (1.25/2) \times 20.8 - 47.3 = 20.1 \text{ kPa}$$

At soil slip, $k = (1 + \sin 33^\circ)/(1 - \sin 33^\circ)$ = 3.39 as before; the ring stiffness also remains unchanged, $\rho_s$ = 367 kPa; the allowed deflection $d$ = 0.03, and the corresponding $r_r$ is 1.2. To compute the external pressure, we solve the expression we proposed for $p_{vac}$,

$$p_{\text{vac}}(r_r - 1) = k\sigma_y + u_B - (p_A + \pi r \gamma_w / 2 - \rho_s E) r_r$$

$$\therefore p_{\text{vac}} = \frac{k\sigma_y + u_B - (p_A + \pi r \gamma_w / 2 - \rho_s d) r_r}{(r_r - 1)}$$

$$\therefore p_{\text{vac}} = \frac{3.39 \times 20.1 + 47.3 - [54.4 + \pi \times (1.25/2) \times 9.8/2 - 367 \times 0.03] \times 1.2}{1.2 - 1} = 259.1 \text{ kPa}$$

The new factor of safety with respect to vacuum pressure is $FS$ = 259.1/101.3 = 2.6. Note that an increase in the water table above the pipe reduces the allowable vacuum pressure, and hence reduces the factor of safety against a full vacuum pressure.

★ The correct answer is **C**.

## P.3 ■ Solution

**Part A:** The equation used to investigate the stability of this pipe is

$$p_{\text{vac}}(r_r - 1) = k\sigma_y + u_B - (p_A - \rho_s d) r_r$$

We were given the outer diameter $D$ = 1240 mm and the wall thickness $t$ = 6 mm, and we know that the pipe is made of bare steel, i.e., there is no cement mortar lining or cement mortar coating. The fill height above the top of the pipe is 5 m of sandy silt. The top-of-pipe pressure, $p_A$, is

$$p_A = \gamma_d h_c + \gamma_{\text{sat}} h_w = 15.7 \times 0.8 + 19.6 \times 4.2 = 94.9 \text{ kPa}$$

At springline, in turn, the water pressure $u_B$ is

$$u_B = (h_w + r)\gamma_w = (4.2 + 1.24/2) \times 9.8 = 47.2 \text{ kPa}$$

and the vertical stress $\sigma_y$, in turn, is

$$\sigma_y = p_A + \gamma_{\text{sat}} r - u_B = 94.9 + 19.6 \times (1.24/2) - 47.2 = 59.9 \text{ kPa}$$

At soil slip, coefficient $k$ is

$$k = \frac{1 + \sin \phi'}{1 - \sin \phi'} = \frac{1 + \sin 17^\circ}{1 - \sin 17^\circ} = 1.83$$

The ring stiffness is given by $\Sigma(E/m^3)$, where $E$ is the modulus of elasticity of the material, $m = (r/t)$, and $\Sigma$ indicates a summation for the components of the pipe wall (steel, cement mortar lining, and cement mortar coating). Since the present case refers to a bare steel pipe, we have simply

$$\rho_s = \sum \left( \frac{E}{m^3} \right) = \left( \frac{E}{m^3} \right)_{\text{Steel}} + \underbrace{\left( \frac{E}{m^3} \right)_{\text{CML}}}_{=0} + \underbrace{\left( \frac{E}{m^3} \right)_{\text{CMC}}}_{=0}$$

$$\therefore \rho_s = \left( \frac{E}{m^3} \right)_{\text{Steel}} = \frac{E}{(r/t)^3} = \frac{200 \times 10^6}{(620/6)^3} = 181.3 \text{ kPa}$$

To obtain radius $r_r$, we must resort to two equations iteratively: first, for ellipses, we have the ratio of axes

$$r_r = \frac{r_y}{r_x} = \left( \frac{1+d}{1-d} \right)^3 \quad \text{(I)}$$

where $d$ is the deflection, and the equation for $p_{vac}$, without the uplift component, is

$$p_{\text{vac}}(r_r - 1) = k\sigma_y + u_B - (p_A - \rho_s d) r_r$$

This can be easily solved for $r_r$,

$$r_r = \frac{(k\sigma_y + u_B + p_{\text{vac}})}{(p_{\text{vac}} + p_A - \rho_s d)} \quad \text{(II)}$$

Let us begin by assuming a deflection of 4% ($d$ = 0.04). In the first equation, we have

$$r_r = \left( \frac{1 + 0.04}{1 - 0.04} \right)^3 = 1.27$$

Then, substituting the same assumed deflection and other data in the second equation, it follows that

$$r_r = \left( \frac{k\sigma_y + u_B + p_{\text{vac}}}{p_{\text{vac}} + p_A - \rho_s d} \right) = \left( \frac{1.83 \times 59.9 + 47.2 + 80}{80 + 94.9 - 181.3 \times 0.04} \right) = 1.41$$

The two values do not coincide, and another value of $d$ is in order. Calculations can be automated in Mathematica by creating two lists, one for each equation, then using the *Table* function to obtain a series of evaluations for increasing values of $d$, which goes from 0.01 (1% deformation) to 0.10 (10% deformation) in 0.1% increments; we then use *Transpose* to couple the results of the two equations for a given deflection, and, for brevity, we add *SetPrecision* to adjust the precision of the numbers to 3. The appropriate command is

$$r_r = \text{SetPrecision}\left[\text{Transpose@}\left\{ \begin{array}{c} \text{Table}\left[\left(\frac{1+d}{1-d}\right)^3, \{d, 0.01, 0.1, 0.01\}\right], \\ \text{Table}\left[\frac{1.83 * 59.9 + 47.2 + 80}{80 + 94.9 - 181.3 * d}, \{d, 0.01, 0.1, 0.01\}\right] \end{array} \right\}, 3\right]$$

Selected values of the table thus obtained are shown below.

| Deflection (%) | $r_r$ from equation (I) | $r_r$ from equation (II) |
|---|---|---|
| 1 | 1.06 | 1.37 |
| 2 | 1.13 | 1.38 |
| 3 | 1.20 | 1.40 |
| 4 | 1.27 | 1.41 |
| 5 | 1.35 | 1.43 |
| 6 | 1.43 | 1.44 |
| 7 | 1.52 | 1.46 |
| 8 | 1.31 | 1.39 |
| 9 | 1.35 | 1.39 |
| 10 | 1.39 | 1.39 |

The deflection for which $r_r$ is closest in both equations is highlighted above. That is, the critical elliptical ring deflection at soil slip is taken as 6%. Further refinement would reveal that $d$ = 6.2% is a more precise answer. This is greater than the 2 to 5% deflections employed in BFS pipe practice, and hence suggests that a redesign is advised.

★ The correct answer is **C**.

**Part B:** Using the equation for $r_r$, we have

$$r_r = \left(\frac{1+d}{1-d}\right)^3 = \left(\frac{1+0.035}{1-0.035}\right)^3 = 1.23$$

Then, the vacuum pressure can be determined with the relationship

$$p_{\text{vac}} = \frac{k\overline{\sigma}_y + u_B - (p_A - \rho_s d)r_r}{(r_r - 1)}$$

As before, we have $k$ = 1.83, springline stress $\sigma_y$ = 59.9 kPa, water pressure at springline $u_B$ = 47.2 kPa, top-of-pipe pressure $p_A$ = 94.9 kPa, ring stiffness $\rho_s$ = $E/m^3$ = $E/(r/t)^3$ = 181.3 kPa, and $r_r$ = 1.23 as we have just established; substituting these quantities in the expression for $p_{vac}$, it follows that

$$p_{\text{vac}} = \frac{1.83 \times 59.9 + 47.2 - (94.9 - 181.3 \times 0.035) \times 1.23}{1.23 - 1} = 208.2\ \text{kPa}$$

Contrasting this with an atmospheric pressure of 101.3 kPa, we obtain a safety factor $FS$ such that

$$FS = \frac{208.2}{101.3} = 2.0$$

Thus, at the 3.5% deflection limit, the safety factor is 2.0.

★ The correct answer is **B**.

## Answer Summary

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# References


- AMERICAN WATER WORKS ASSOCIATION. (2004). *Steel Pipe – A Guide for Design and Installation*. 4th edition. Denver: AWWA.
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