Steel Pipe Installation in Poor Soil Conditions: A Determination of Optimum Trench Width

Robert J. Card, P.E., M.ASCE[1]; and Brent Keil, P.E., M.ASCE[2]

[1]Lockwood, Andrews & Newnam, Inc., Miami, FL. E-mail: RJCard@lan-inc.com
[2]Northwest Pipe Company, Vancouver, WA. E-mail: BKEIL@nwpipe.com

Abstract

A common and practical rule of thumb for trench widths when installing steel pipe is to keep the trench as narrow as possible and still allow for the needed compaction equipment to consolidate the embedment around the pipe, particularly in the haunch area. Pipe deflection is caused by the soil and live loads above the pipe and it is resisted by the support of the side fill soil next to the pipe. In poor native soil conditions there is sometimes a concern about enough soil support in the trench wall to prevent over-deflection of the pipe. Some design engineers in these cases have looked for guidance on how to properly analyze the pipe soil interaction and develop a procedure that keeps the pipe within the recommended deflection limits. Methods sometimes used include making the trench substantially wider, developing a ratio of the apparent side fill stiffness to the apparent embedment soil stiffness or even encasing the pipe. This paper will review poor trench wall conditions and provide a practical, analytical method for analyzing these conditions based on soil mechanics and the pipe soil interaction. Prevention of over-deflection of the steel pipe and other adverse conditions that poor trench wall soils can create will be discussed and evaluated. This paper will offer the design engineer tools to develop adequate trench widths in poor soils.

The "Problem"

Often pipelines must cross areas with very poor native soils. New Orleans comes to mind, along with the photo (Fig. 1) below from Green Bay, Wisconsin.

Figure 1 – Poor Soil Conditions

Dr. Reynold Watkins, respected Emeritus Professor at Utah State University, has often used the technical soil term “mud” to describe such soils, which brings up a question in many designers mind; what is the proper trench width to use when installing steel pipe in such soils? This paper will explore many differing published papers on the subject with the intent of providing proper guidance to designers.

Typically keeping the flexible steel pipe nearly round (with less than 5% out-of-roundness [ellipse]) once the entire earth load is placed over the pipe, before pressurization of the pipeline, is the primary goal. However, it is easy to calculate the corrective effect of re-rounding of the pipe after pressurization (ASCE 2012). Moreover, this phenomenon can be witnessed by touring a steel pipe production facility and observing the shop hydrotest of the steel cylinder. As the steel pipe section is filled with water, the shape goes from circular to an oval. But, once internal pressure is introduced in the steel pipe (now oval section), the cylinder “pops” back to the initial round shape. Over time the embedment around the pipe will migrate to take up the new shape and fill in the void between the deflected ellipse shape and the re-rounded shape. See Figure 2.

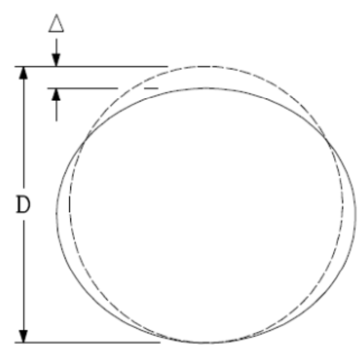

Figure 2 – Pipe Shapes, Round and Ellipse

History of Deflection Analysis

The history of deflection analysis can be traced back to the origins of the development of loads on pipe. In 1913, Anson Marston published his first treatise on earth loads on rigid pipe (Marston 1913). See Equation 1.

Eq. 1: $W = CwB^2$

Where:

C = Load coefficient for ditch conduits
w = unit weight of backfill
B = width of trench

It is important to recognize that the term, “B”, is the overall width of trench at the top of the pipe. Therefore, as the trench width increases, the earth load increases.

Rigid pipe is not meant to deflect, but there were flexible drainage pipe being utilized by the late-1920's, which lead to a subsequent publication (Marston 1930). This publication modified the original earth load formula with a new formula to be utilized with flexible conduits. See Equation 2.

Eq. 2: $$W_c = HwB_c$$

Where:
H = height of soil above the pipe
w = unit weight of backfill
Bc = pipe outside diameter

However, now the term B_c is the outside diameter of the pipe and the width of trench does not influence the load on the pipe. With these two papers, there was now a method in which to calculation loads on both rigid and flexible pipe.

A procedure was then needed to determine the resistance to these loads. The procedure for flexible pipe was a bit more difficult to derive as it became apparent to Dr. Marston and his student, Dr. Spangler, (in the 1930's) that flexible pipe would crush under loads if not for the additional support of the earth surrounding the pipe. In 1937 Dr. Spangler presented his findings in a paper to the Seventeenth Annual Meeting of the Highway Research Board in Washington D.C. which lead to his publication on flexible pipe in 1941 (Spangler 1941). This design procedure became known as the "Iowa Formula"; however, one of the early manufacturers of flexible pipe, ARMCO, soon found the formula to be unreliable as their field measurements did not match the theoretical calculations, hence they suspended use of the formula.

Reynold K. Watkins, a doctoral student of Dr. Spangler, discovered the error in the original Iowa Formula and published a doctoral dissertation on the subject in the Proceedings, Highway Research 47 (Watkins 1958). This became known as the "Modified Iowa Formula". To quickly sum up the basic difference between the two, Dr. Spangler had originally thought that *e*, the modulus of passive resistance, was a function of soil alone, but, Dr. Watkins determined that the modulus of passive resistance was a hybrid function, that of the soil along with the radius of the pipe. The product *e***r* was shown to be constant (rather than *e* alone). Subsequently this constant was renamed as E', the Modulus of Soil Reaction.

The Modified Iowa Formula is as shown below in Equation 3:

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

With flexible pipe, the pipe stiffness term, EI, is typically quite low, often less than 10%. It is low enough that some designers choose to conservatively ignore the pipe stiffness when designing the load resistance. Therefore, it is easy to see that the most important term in the formula for resisting the load is the Modulus of soil reaction. The Modulus of Soil Reaction is a passive resistance in the horizontal direction. As the flexible pipe deflects (goes out-of-round from the vertical earth load) into the surrounding embedment support, the passive nature of the soil support is activated thereby limiting the deflection. Therefore, the E' term is of the utmost importance in flexible pipe design. Many designers to this day still utilize the Modified Iowa Formula to predict the horizontal deflection of unpressurized flexible pipe.

Since the Modified Iowa Equation was first published, many studies have been undertaken to determine the value of E’ for embedment materials. Most studies are based on back calculating E’, knowing all the other terms. However, these researchers and their published papers have provided a very large scatter for E’ values based on similar installations. Attempts to derive a clear reproducible soil test to generate E’ have been unsuccessful. All of this has led to much confusion over the E’ term.

Amster Howard, formally with the United States Bureau of Reclamation (USBR), has studied E’ and the design of flexible pipe extensively, leading to many papers and theories on the subject (Howard 1968 - present). In much of his work, he has back calculated the E’ value when knowing the vertical deflection of the pipe (a slight change from the classic theory developed by Spangler and Watkins that utilized the horizontal deflection). This led to a USBR published equation that they utilized with flexible pipe in the 1990’s. However, this equation has not had wide spread use throughout the industry by flexible pipe designers. Further work by Mr. Howard led to yet another term, combined E’, that is, combining the E’ of the native soil with the pipe embedment soil. Some pipe designers have used this newly created term, but, it must be remembered that the original definition of E’ was that of a hybrid function, which included the pipe radius and the embedment. Native soil outside the trench area of influence does not match this classic definition of the original use of the E’ term. E’ values for native soil are also less defined than embedment material because the trench wall soil has settled to a point of equilibrium, embedment soils where E’ values have been generated from soils that have been mechanically placed and compacted, but will undergo further consolidation and change as they find their equilibrium.

Basically, since the early 1960’s Dr. Watkins has regretted “inventing” the E’ term for horizontal passive support because of the misuse of it in the Modified Iowa Formula. Many engineers, incorrectly, use the Modified Iowa Formula to actually design pipe wall thicknesses by rearranging the terms when in fact, it was only developed to conservatively predict horizontal pipe deflection. This lead to the most recent work on flexible pipe deflection, a collection of the life work of Dr. Watkins, published in the ASCE Manual of Practice Number 119 (ASCE 2009). In this MOP a verifiable (by laboratory testing of soil samples) soil stiffness, E’, can now be determined. However, this new E’ is a “vertical” or “secant” soil stiffness, based on the aforementioned laboratory measured soil stress-strain tests and should not be confused with the classic, hybrid, E’. See Figure 3. Using verifiable soil properties, flexible steel pipe can now be properly analyzed for a variety of loading conditions, soil types, trench widths, etc.

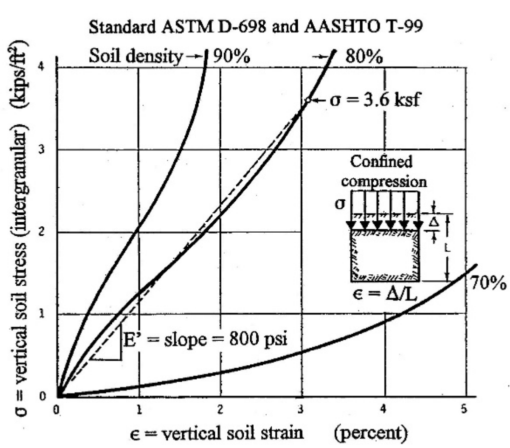

Figure 3 – Vertical or Secant E’

Loads above Buried Pipe

Buried pipe has soil load above it, causing the pipe to deflect out-of-round. Figure 4 below depicts the earth load due to soil acting at the top of the pipe.

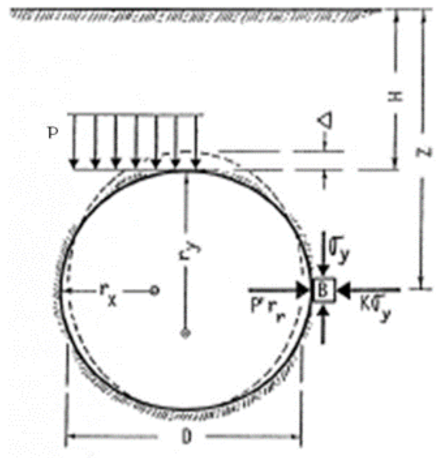

Figure 4 – Earth Load

Earth loads are calculated using the Spangler-Watkins modified Marston load as shown in Equation 4:

Eq. 4: $P = H\gamma D$

Where:

H = height of soil above the pipe
γ = unit weight of backfill
D = pipe outside diameter

Equation 4 is sometimes called the "prism" load, it is simply the theoretical weight of the prism of soil above the pipe. Care should be taken when calculating the earth load as the water table is often above the top of the pipe, making the soil unit weight, γ, different between the "dry" and saturated or "wet" soils.

Live loads occur when any moving vehicle passes over a buried pipe. Common live loads are truck loadings per AASHTO. A simplified graphic of a wheel live load is found in Figure 5 below.

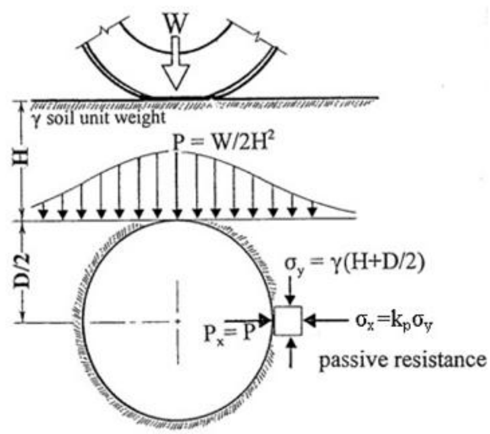

Figure 5 – Live Load

To make calculations easier, and a bit more conservative, the live load is simply as shown by Equation 5:

Eq. 5: $$P = \frac{W}{(2H^2)}$$

Where:
W = wheel load
H = height of load above the pipe

Vehicular live loads typically dissipate out once the height of fill above the pipe equals 8 feet. Over 8 feet of fill all traffic live loads are considered insignificant.

This leads us to the next load; uniform external pressure around the pipe due to a high water table or even a vacuum inside the pipe. See Figure 6. However, uniform external pressure and vacuum are not loads that cause the pipe to go out-of-round but rather are considered buckling loads. Embedment around the pipe also assists in resisting buckling loads much the same as it does in assisting to arrest pipe deflection.

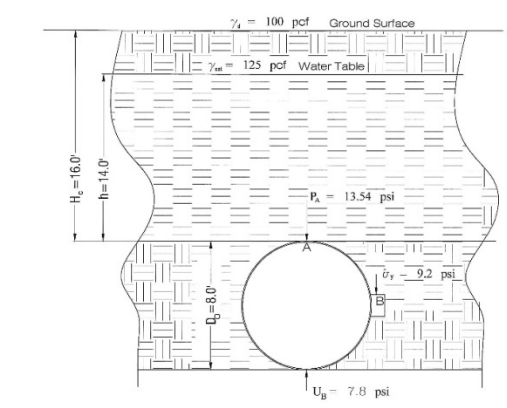

Figure 6 – Uniform External Pressure

Embedment

The embedment material used to surround the pipe forms a soil conduit with the pipe being the liner, forming a pipe/soil system. The embedment holds the pipe shape, supports nearly all the load and is the structural component of the conduit for resisting external loads. Knowing the embedment material properties is an important part of any pipe installation.

In most installations using the excavated trench material as embedment is most economical. Regardless of the material source, knowing properties of the embedment will assist in determining if an embedment will be adequate for the conditions.

Soils can be classified by the Unified Soil Classification system, Table 1, which is found in ASTM D2487 (ASTM 2011). This system can be used to categorize some of the soil mechanical properties and a general determination of certain properties can be achieved. Soils are broken down into particle sizes and categorized by clays, silts, sands, gravels and larger sizes of cobble and boulders.

Unified Soil Classification (USC) System (from ASTM D 2487)

Major Divisions				Typical Names
Course-Grained Soils More than 50% retained on the 0.075 mm (No. 200) sieve	**Gravels** 50% or more of course fraction retained on the 4.75 mm (No. 4) sieve	Clean Gravels	GW	Well-graded gravels and gravel-sand mixtures, little or no fines
			GP	Poorly graded gravels and gravel-sand mixtures, little or no fines
		Gravels with Fines	GM	Silty gravels, gravel-sand-silt mixtures
			GC	Clayey gravels, gravel-sand-clay mixtures
	Sands 50% or more of course fraction passes the 4.75 (No. 4) sieve	Clean Sands	SW	Well-graded sands and gravelly sands, little or no fines
			SP	Poorly graded sands and gravelly sands, little or no fines
		Sands with Fines	SM	Silty sands, sand-silt mixtures
			SC	Clayey sands, sand-clay mixtures
Fine-Grained Soils More than 50% passes the 0.075 mm (No. 200) sieve	**Silts and Clays** Liquid Limit 50% or less		ML	Inorganic silts, very fine sands, rock four, silty or clayey fine sands
			CL	Inorganic clays of low to medium plasticity, gravelly/sandy/silty/lean clays
			OL	Organic silts and organic silty clays of low plasticity
	Silts and Clays Liquid Limit greater than 50%		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts
			CH	Inorganic clays or high plasticity, fat clays
			OH	Organic clays of medium to high plasticity
Highly Organic Soils			PT	Peat, muck, and other highly organic soils

Table 1 – Unified Soil Classification System

Cobbles and boulders are not used in embedment around the pipe due to the potential damage they can cause. Organic soils (OL, OH, PT) should never be used for bedding and embedment as they offer very poor to no support to the pipe (rigid or flexible) in resisting loads. Expansive clays and organic soils are not desirable for embedment materials, but inorganic clays and silts can be used for embedment materials when installed properly.

In the embedment, the soil is confined. The strength for granular soils is provided by the soil friction angle, **φ**. The friction angle can be defined in a simplified way as the maximum angle of repose of a soil slope, see Figure 7. Sands and gravels shown above in Table 1 are common pipe embedment material used to support the load over the pipe. Clean gravels can be considered "select", clean sands are "good". Saturated clays and some silts are considered "poor" and highly organic soils (PT) are considered "mud".

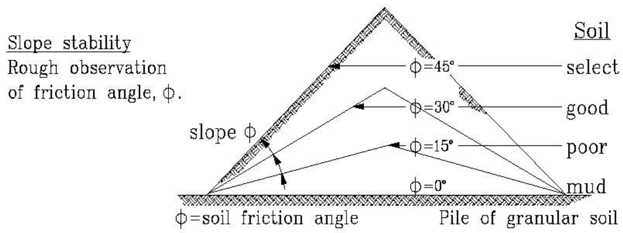

Figure 7 – Angle of "Repose"

Conservative frictions angles for various soils can be found in Figure 8. For clay soils the strength comes from cohesion. The strength of the soil assures the stability of the pipe/soil system.

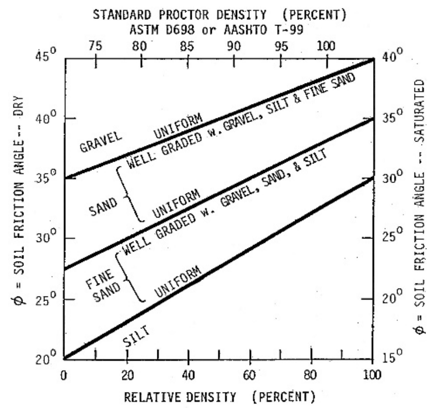

Figure 8 – Conservative Soil Friction Angles

Friction angle and cohesion for soil can be generalized by knowing the classification, and testing in the soil lab can verify and refine the specific values for the soil being considered. The soils lab can also determine the soil stiffness, E', of a compacted soil (not to be confused with the Modulus of Soil Reaction E' that cannot be determined in a soil lab). These soil properties are helpful in determining the how the pipe/soil system will interact.

Embedment compaction stiffens the soil and is needed to stabilize the system. It is recommended for granular embedment to be compacted to a minimum 85% Standard Proctor when liquefaction is possible, Watkins (2000). At 85% compaction, the density is above the critical density and will prevent liquefaction if the soil is saturated during earth tremors.

Trench Wall Soil Considerations

Trench width is important when considering the support needed for flexible pipe. The pipe/soil interaction system derives up to 97% of its strength from the embedment soil strength with the rest coming from the pipe stiffness. As the native soil becomes weaker according to the Unified Soil Classification System, the width of the trench becomes more important in order to prevent soil slip, which would erode the embedment soil support required by the pipe. Therefore, it is very important to consider a trench wall in poor native soil if that is the situation, as that is the worst case trench wall scenario.

Therefore, it is prudent to calculate the width of the trench from the outside of the pipe to the inside of the trench wall to ensure there is a proper amount of embedment material to assist in keeping the pipe within roundness tolerances when it is externally loaded. See Figure 9 for trench configuration terminology.

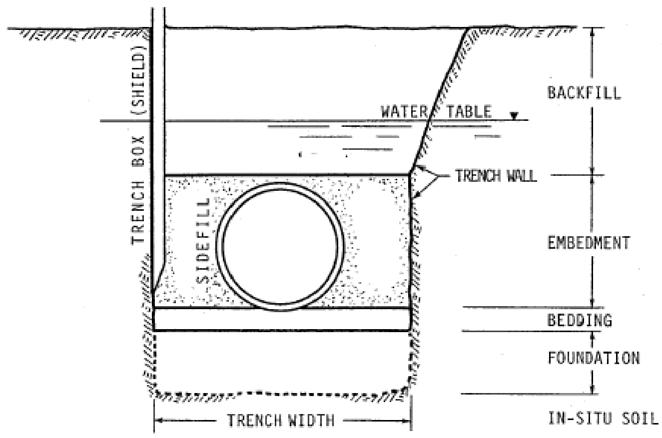

Figure 9 – Trench Terminology

A general rule of thumb is that if the embedment material is "good" or "select", the distance from the pipe edge to inside trench wall can be very narrow. The trench only needs to be wide enough to allow for the alignment of pipe and to provide enough space (between the outside edge of pipe and inside trench wall) to place embedment, at adequate density, and in full contact with the pipe and the trench wall. A wider trench is not justified. According to Dr. Watkins, "Ideally, the pipe would be bored into place." (Watkins 1995) If the embedment material is "poor" and the trench wall is "poor" or "mud", then the width of trench from the pipe edge to the inside trench wall needs to fall somewhere in between the previously mentioned minimum and a distance equal to ½ the diameter of the pipe. At worst case scenarios, the maximum overall trench width would be equal to 2 times the pipe diameter, that is, ½ diameter on either side of the pipe as shown in Figure 10.

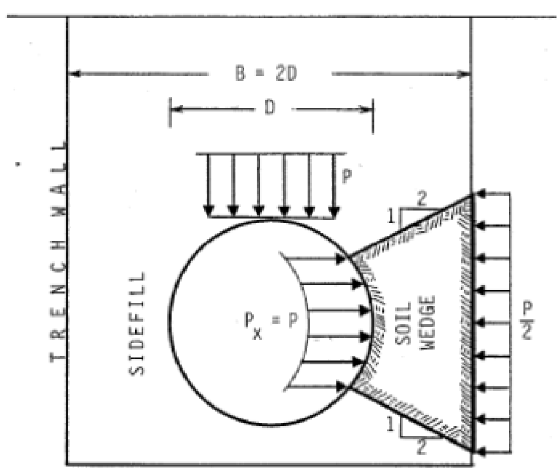

Figure 10 – Trench Width

Distribution of Loads to Trench Wall

The vertical pressure on the pipe, earth load and live load is designed as P. For a stable, flexible pipe, the load times the radius is equal all around the pipe as shown in Equation 6.

$$\text{Eq. 6: } P_x r_x = P_y r_y$$

If the deflected ring is an ellipse, then

$$\text{Eq. 7: } r_y / r_x = (1+d)^3/(1-d)^3$$

Where d=Δ/D, See Figure 11 for both the circular and deflected pipe states of equilibrium.

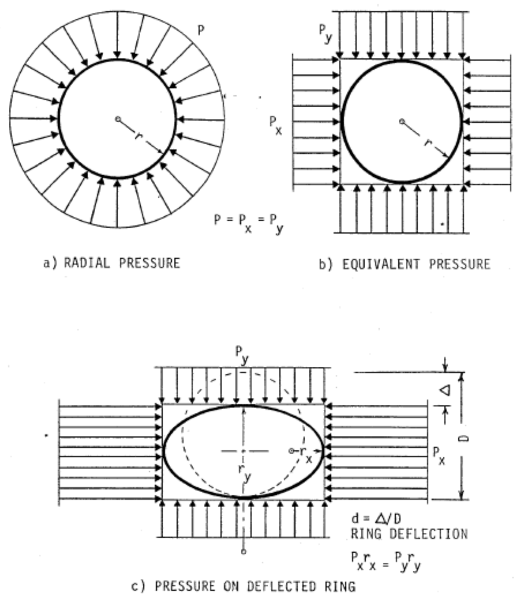

Figure 11 – Pipe Equilibrium

Figure 12 demonstrates the infinitesimal soil cube B is in equilibrium as long as pressure on the pipe, P_x, does not exceed side fill soil strength, $\boldsymbol{\sigma}_x$. For stability,

$$\text{Eq. 8: } P_x < \sigma_x = K\sigma_y$$

where K = (1+sin**φ**)/(1-sin**φ**), and **φ** is soil friction angle at soil slip.

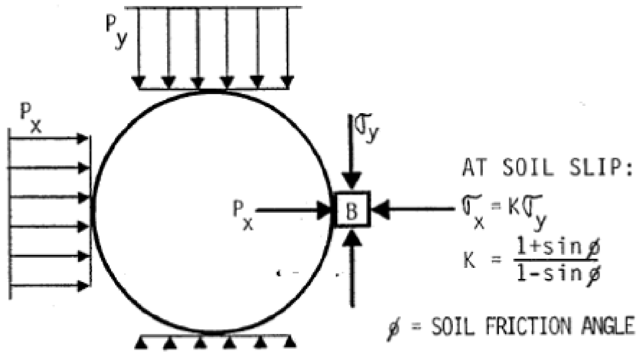

Figure 12 – Infinitesimal Cube at Spring Line

Looking back at Figure 10 which depicts the soil wedge at incipient slip of side fill soil (failure), showing how pressure, P, is transferred to the trench wall where it is distributed and reduced by half if the trench width is 2 times the diameter. Note: The height of soil cover, H, is not a pertinent variable in the analysis of trench width. As soil load is increased, the pressure on the pipe increases; but the strength of the side fill soil increases in direct proportion.

Examples and Calculations

Example – a 54 inch ID, 55.75 inch OD steel pipe is installed with 10 inches of clearance to the trench wall (Figure 13). The trench wall is a "poor" soil, but will stand in a vertical cut. Assuming a maximum pipe deflection of 5%, what is the friction angle of the trench wall material needed to resist soil slip due to the load? For a poor soil to stand in a vertical cut it must have cohesion, but to be conservative cohesion will be neglected.

Therefore:

$r_y/r_x = (1+d)^3/(1-d)^3$

$r_y/r_x = (1+0.05)^3/(1-0.05)^3 = 1.4$

Max $P_x \approx 1.4\boldsymbol{\sigma_y}$

$\boldsymbol{\sigma_x} \approx 34/70P_x$

$\boldsymbol{\sigma_x} \approx 0.5P_x$

$\boldsymbol{\sigma_x} \approx 0.7\boldsymbol{\sigma_y}$

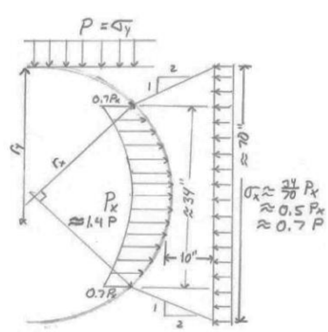

Figure 13 - Example

It can be seen that the friction angle for mud (liquid) produces a K of 1, [(1 + Sin 0°)/(1 - Sin 0°)] and since $\boldsymbol{\sigma_x} = K\boldsymbol{\sigma_y}$, in this case 0.7 < 1 and the example will not have soil slip in the trench wall soil for any material.

Checking for soil slip in the embedment material, assume a poor but acceptable embedment material with a friction angle of 15° and check for soil slip in the embedment.

$K = (1 + \text{Sin } 15°)/(1 - \text{Sin } 15°)$

$K = 1.7$
Soil slip in the embedment will not occur because $1.7\boldsymbol{\sigma}_y > \boldsymbol{\sigma}_x$

Now assume the deflection is larger, 10% with a 2D wide trench (D = Pipe OD) and the trench wall is a membrane against the embedment material with water on the other side. In this case:

$r_y/r_x = 1.8$
Max $P_x \approx 1.8\boldsymbol{\sigma}_y$
$\boldsymbol{\sigma}_x \approx 0.3P_x$
$\boldsymbol{\sigma}_x \approx 0.6\boldsymbol{\sigma}_y$

It can again be seen that the "trench wall" will be stable in this condition. It has been shown that a trench can be excavated next to an existing pipe and be stable in this scenario (ASCE 2009). These conditions are depicted in Figure 14.

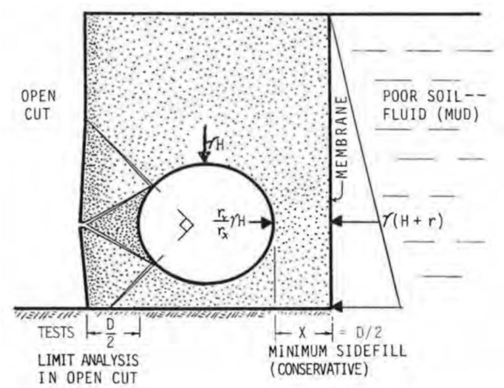

Figure 14 – Open cut and Fluid next to Pipe Embedment

From the above example, as long as the ring is nearly circular, the embedment does not need high strengths, and if the ring deflection of the pipe is kept to less than 5%, the effect of the deflection can be neglected.

Conclusions and Recommendations

In 1913 Marston wrote, "The width of the ditch at the level of the pipe makes a great difference in the weight of the filling resting on the pipe, this weight being greater the wider the ditch. Also, the narrower the ditch at the mid-height of the pipe, the more effective is the side support against the collapsing of cracked pipe." Of course Marston was talking about rigid pipe but nonetheless, it points out his desire to use narrow trenches.

Then, in 1948, in his summary Spangler wrote, "For example, the theoretical analysis of ditch conduits indicates that the width of ditch has a marked effect upon the load which the conduit must carry and field observations tend to verify this indication. Good practice, therefore, requires that the design width of ditch be held to a practical minimum value and that this design width be adhered to in construction." (Spangler 1948)

Finally, Dr. Watkins writes, "The best buried pipe installations are those which disturb the native soil the least. A bored tunnel of exact pipe OD into which the pipe is inserted, would cause the least disturbance.

A common installation is a narrow trench with only enough side clearance to align the pipe and to permit placement of embedment. Regardless of trench width or shape, the embedment is a transfer medium that fits the pipe to the trench and stabilizes pipe-soil interaction." (Watkins 2000)

When designing buried steel pipe, there are usually concerns with the trench width. Let us not forget the great researchers of the past who thoroughly investigated earth loads on pipe and the conclusions they arrived at (as pointed out above). The goal is to minimize the amount of disturbed native soil when putting pipe in the ground. As shown by example, even in the poorest native soils there is no need to have a trench width greater than 2 times the pipe outside diameter. This can be easily calculated by following the examples herein or by utilizing ASCE Manual of Practice No. 119.

References

ASCE (2012) – "Buried Flexible Pipes – Deflections and Stresses Caused by an Increase in Soil Cover – Highway Crossing", Dr. Reynold K. Watkins, PE & Robert J. Card, PE

ASCE (2009) – "Buried Flexible Steel Pipe: Design and Structural Analysis" by ASCE Committee, MOP No. 119

ASTM (2011) – "ASTM D2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)", ASTM 2011

Marston (1913) – "The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe", by A. Marston and A. O. Anderson

Marston (1930) – "The Theory of External Loads on Closed Conduits in Light of the Latest Experiments" by Anson Marston

Spangler (1941) – "The Structural Design of Flexible Culverts" by M. G. Spangler

Spangler (1948) – "Underground Conduits – An Appraisal of Modern Research" by M. G. Spangler, ASCE Paper No. 2337, 1948

Watkins (1958) – "Proceedings, Highway Research Board 47", pages 576 – 583, by Reynold K. Watkins and M.G. Spangler

Watkins (1995) – "Trench Widths for Buried Pipes", by Reynold King Watkins

Watkins (2000) – "Structural Mechanics of Buried Pipes", by Reynold King Watkins & Loren Runar Anderson, CRC Press, 2000