Rational Methods of Steel Pipe Design Accounting for Poor Native Soils and Soil Migration

J. K. Jeyapalan[1], G. Leonhardt[2], P. Rajeev[3], and A. M. Britto[4]
[1]*Civic Enterprises, LLC, New Milford, CT, USA*
[2]*am Neuenhof 47 • 40629 Düsseldorf, Germany*
[3]*Dept of Civil and Construction Engineering, Swinburne University of Technology, Australia*
[4]*University of Cambridge, Cambridge, UK*
E-mail: jkjeyapalan@earthlink.net

ABSTRACT: In poor native soils there is always a concern whether sufficient embedment support around the haunch and spring line level exists to prevent over-deflection of steel pipe. Engineers become confused given the two extreme positions on trench width – steel pipe suppliers advocating two pipe diameters while a government agency like U.S. Bureau of Reclamation (USBR) recommending the use of five pipe diameters. Methods from the German ATV A127 or Leonhardt, rely on a ratio of the side fill E_n' to the embedment E_b' and the ratio of the trench width to the outer diameter of the pipe to select site specific trench width. When pipe suppliers quote Marston's work on rigid concrete pipe from 1913, to make their case that a relatively narrow trench is better in poor native soils even for flexible steel pipe, they introduce the risk of inducing the buyers to ask - has the pipeline industry not seen new developments over the past 100 plus years? This paper reviews the fallacies surrounding various methods on how to cope with poor trench wall conditions and provides a rational method. This paper also covers the phenomenon of soil migration, its significance in buried pipeline design and performance and the adverse consequences if not considered.

KEYWORDS: Steel pipe, Embedment, Native soil, Combined E', Soil migration

1. INTRODUCTION

A properly installed flexible pipe generally can deflect without structural distress to the pipe wall or to any coating or lining used to protect the pipe wall. Types of flexible pipes are steel, ductile iron, polyvinyl chloride, high-density polyethylene, fiberglass, and bar-wrapped concrete cylinder. The attributes of these pipes per AWWA (2002, 2004, 2008, 2009, 2014) are summarized in Table 1. Among the various flexible pipes, steel has been around the longest, over 100 years, there is some confusion about how best to determine the optimum trench width when it is laid in poor native soils. There is also confusion about how to classify soils into poor soils using the blow count from a standard penetration test. For example, some in practice think when the blow count is less than 4, the design engineer is faced with poor native soils, leaving the more important effective stress at the depth at which the blow count is measured out of consideration.

Table 1 PSR of Pipes per AWWA M9, M 11, M23, M41, M45, and M55

Pipe Type	PS(MPa)	E'(MPa)	PSR
M9 - C303	7 to 300	4.8[a]	3.5 to 152
M11 – STEEL	0.04 to 35	3.5 to 41.4	0.0023 to 25
M23 – PVC	0.1 to 5.6	0.35 to 41.4	0.0057 to 40
M41 – DIP	0.5 to 275	1 to 4.8	0.2415 to 648
M45 – FRP	0.06 to .5	0.9 to 64	0.0024 to 1.35
M55 – PE	0.02 to 2	0.2 to 64	0.0013 to 14

a - E'=4.8 MPa for all soil types, compaction densities and depths of soil cover.

When asked why to defy a fundamental principle that has been around from Terzaghi and Peck (1948), the answer is "*Dr. Watkins told us that it is always the blow count being lower than 4*." With the goal to encourage the reader to stay engaged in the reading of this paper, four common fallacies within rhetorical arguments and technical analysis are correlated. Based on the analysis, this is fallacy # 1 – **Appeal to Authority** which occurs when someone accepts a statement on blind faith just because someone they admire said it.

The "embedment" is the soil placed between the sides of the pipe and the trench wall. When one writes "*Of course, Marston was talking about rigid pipe but nonetheless, it points out his desire to use narrow trenches*," is a classical fallacy # 2 - **Sweeping Generalizations** - These fallacies occur when a very broad application is extracted from a single premise.

2. VARYING DEFORMATION OF STEEL PIPE

Load on a buried pipe is created by backfill soil placed over the top of the pipe and any surcharge and live load on the backfill surface over the pipe. Flexible pipe is designed to transmit the load on the pipe to the soil at the sides of the pipe. As the load on the pipe increases, the vertical diameter of the pipe decreases, while the horizontal diameter increases. The increase in horizontal diameter is resisted by the stiffness of the soil on the sides of the pipe. The shape of a flexible pipe goes through many changes during the installation of a pipeline. Generally, the pipe is considered to deform from a perfect circle to an ellipse due to loading. The largest diameter changes usually occur along the vertical diameter and the horizontal diameter, with the vertical diameter change slightly larger than the horizontal. Performance of the pipe is typically measured by the change in the vertical diameter divided by the original inside diameter of the pipe. The initial shape of a flexible pipe is rarely a perfect circle. The mass of the pipe wall, lining and the coating cause the pipe to deflect. The amount of deflection depends on the stiffness of the pipe and the fabrication method. In addition to the initial out-of-roundness, compaction of the embedment surrounding the pipe can cause elongation, an increase in the vertical diameter, of the pipe. The elongation is dependent on the pipe stiffness, type of compaction, the percent compaction, and whether the pipe is stulled. When the pipe is installed using saturation and internal vibration of embedment material, the elongation during installation is considered to effectively offset any out-of- roundness of the initial pipe shape according to Fuerst, Robertson and Bowles (2013). If the embedment of the pipe is power tampered or rolled, the vertical diameter can become larger than the horizontal diameter and create an additional safety factor in anticipated deflection of the pipe. In fact, it is common practice to vertically elongate the pipe by 1 inch (25 mm) by compacting the embedment.

3. DEFLECTION USING MODIFIED IOWA FORMULA

The deflection due to backfill load, live load, and time creates the change in pipe diameter, and in practice this deflection is calculated using the Modified Iowa formula as proposed by Watkins and Spangler (1958) but there are limitations due to the uncertainties in defining and choosing the modulus of soil reaction, E' per Jeyapalan and Britto (2014). When someone writes "*This lead(sic) to the most recent work on flexible pipe deflection, a collection of the life(sic) work of Dr. Watkins, published in the ASCE Manual of Practice 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 laboratory measured soil stress-strain tests and should not be confused with the classic, hybrid, E'. Using verifiable soil properties, flexible steel pipe can now be properly analyzed for a variety of loading conditions, soil types, trench widths, etc.,*" these words conflict with widely known principles of soil behavior. The most fundamental fact about soil behavior is that there are infinite number of secant moduli from a single stress strain test performed on a nonlinear elastic engineering material and that the whole exercise of going through using a secant modulus is not useful. Fallacy # 3 - **Begging the Question** - Also called **Circular Reasoning**. This type of fallacy occurs when the conclusion of an argument is assumed in the phrasing of the question itself.

Watkins and Anderson (2000) continue "*As long as the ring is circular, theoretically, embedment needs little horizontal strength. The coefficient of passive resistance, Kp, is (1+sin ϕ)/ (1-sin ϕ), and ϕ is the friction angle at soil slip.*" It is an open admission on the part of Watkins and Anderson that never in the real world, the pipe is circular; therefore, designing with the expectation that the embedment needs to offer only little horizontal strength meaning the trench must be wide enough in poor native soils for the embedment to have sufficient strength. The term "soil slip" is confusing because this is a term never used by any other geotechnical engineer ever in the history of geotechnical engineering. Furthermore, the Rankine passive pressure coefficient of 3 for a soil with a ϕ angle of 30 degrees is never attainable given that the movement of the pipe into the side embedment would have to be 10 times of that needed to develop Rankine active pressures. This is Fallacy # 4 - **Appeal to Pity** - These fallacies occur when someone seeks to gain acceptance by pointing out an unfortunate consequence that befalls them.

Even Professor Watkins has preached hundreds of times "*it is the soil, stupid.*" No dermatologists dare to practice as cardio thoracic surgeons. But somehow, some engineers do not follow the ASCE cannon 2 "*engineers shall perform services only in areas of their competence.*" Despite the claim that our pipes are aging, and we have a shortfall in funding to renovate our pipes before sink holes develop does not resonate well with the fact that the average age of our sewers is less than 50 years. Failures such as the one shown by Hartwig (2015) in this link https://www.youtube.com/watch?v=lfh3p_FTy28 happening nationwide are telling us loud and clear "the designers of such structures simply were unaware of the large body of knowledge among geotechnical engineers." This leads one to the inescapable conclusion "errors and omissions by the engineers and contractors and not the age is the predominant factor leading to premature failures of underground pipes and culverts in USA."

4. OPTIMUM TRENCH WIDTH THROUGH COMBINED E'

The claims by Watkins and Anderson (2000) such as "*Spangler's remedy appeared to be wider embedment especially in poor native soil. In fact, a wide trench is seldom justified -either by experience or by principles of stability,*" are not based on soil mechanics. The same Watkins and Anderson (2000) also wrote "*Trenches are kept narrow only for rigid pipes.*" Fallacy # 5 - **Appeal to Ignorance** - These fallacies occur when someone asserts a claim that must be accepted because no one else can prove otherwise. Watkins and those who follow him in blind faith use words such as critical density, soil slip to distract the effectiveness of arguments based on widely used principles of soil mechanics for many decades. This is fallacy # 6 - **Red Herring** - These fallacies occur when someone uses irrelevant information to distract from the argument. The performance of flexible pipe depends on the side soil support from the combination of the embedment soil and the trench wall soil. The width of the trench, to prevent excessive deflection, depends on the firmness of the embedment soil relative to the firmness of the trench wall material. Reduced trench widths are now possible when using the relationship between the stiffness of the embedment material to the trench wall material.

5. FINITE ELEMENT PIPE-SOIL MODEL – FIRST OF ITS KIND

The German method in ATV (1984) allows calculation of loads for all types of pipe and incorporates the effects of pipe stiffness and the variation of soil moduli near the pipe. The method is semi-empirical although the method is like Marston theory. Jeyapalan and Hamida (1988) showed that the Marston loads are always greater, and Jeyapalan and Jiang (1986) validated such findings with first of a kind finite element analyses. Given that the German approach yields correct loads because of better assumptions, Jeyapalan and Hamida concluded Marston theory is conservative, and the loads may be overestimated by as much as 100%.

6. LEONHARDT'S PIPE-SOIL MODEL

On January 20, 2018 Dr Ing Leonhardt wrote *"In Germany there was no knowledge before 1930 about the failure of the construction with concrete pipes. When the pipe damage had to be eliminated after the Second World War, Marquardt (1934) and Roske (1962) had spread the calculation method of Marston and Spangler from the USA. It soon became known that these calculations were not reliable and were not suitable for new piping materials. For this reason, in 1970 a working group was commissioned to develop a calculation method that is useful for all materials. In 1973 I had demonstrated in my dissertation that Marston was not usable because of the plastic behavior of the soil (Φ, c) assumed, but in fact more than 90% of the cases the soil near the pipe behaves elastic (E_b). The new model I developed was then the basis of a new calculation procedure that was suitable for all pipe types. I am sending you a work that comes from my dissertation and some other contributions. I am predominantly giving you the German versions. In the papers that I send you, you will find some basics of our work. I would like to make the following comments. The choice of laying a pipe is determined by two components. If a pipe is to be laid in which the interaction of the system composed of soil and pipe is not there, then you do not have to worry about how wide a trenching is made and the backfilling of the working space receives no compaction. The pipe then receives large variations in the stress on the construction, especially with flexible pipes. The embedding of a pipe is part of the overall concept of flexible building materials construction This means that the trench must be wide enough ($b \geq 2d$ or $b = d + 1.0$ m) to ensure uniform support by the soil. The working space must be wide enough to allow for layer-by-layer backfilling to ensure trenching and compaction of the soil. After I published the first version of the two equations for Sc in 1979, with additional research these equations were slightly changed."* Leonhardt (2018)

After a series of simplifications, this model using an elastic pipe ring interacting with the surrounding elastic embedment was written by Leonhardt (1979) as a pipe-soil system with a stiffness of V, where V = Sr/Sb, pipe stiffness divided by embedment stiffness. Sr = Ep /r^3 while Sb = 0.6 *ScEb, in which, Sc = fn (Eb/En, B/D). The width of the rectangular equivalent for the parabolic stress shown in Figure 1 forming the horizontal soil reaction can be found as bo = 1.154 r. The horizontal deformation of the pipe in the soil can be written as q*bo ($\Delta f_1/Eb + \Delta f_2/En$), where $\Delta f_1 + \Delta f_2 = 1.44$. The embedment stiffness can be expressed as Sb = 1.154/Eb [$\Delta f_1 + \Delta f_2/(En/Eb)$]. This in turn results in the two Leonhardt (1979) equations used in the next section with the definition that Sc= Sb/ (0.6 Eb).

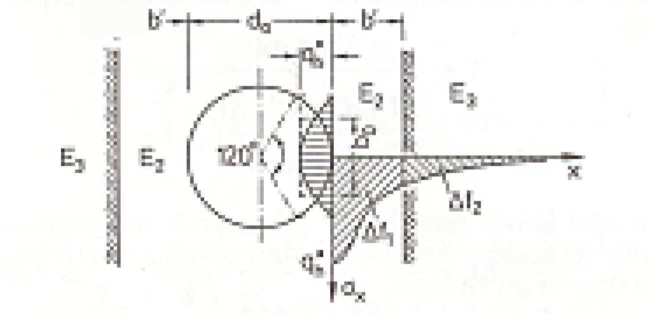


Figure 1 Leonhardt's Representation of Soil Reaction

7. COMBINED E'

To determine the combined E′ for a buried pipe, separate E′ values for the native soil, E′n, and the embedment soil, E′b, must be determined and then combined using the following equation:

$$E' = Sc E'b \tag{1}$$

where, E′ is combined modulus of soil reaction, Sc is Leonhardt correction factor and E′b = modulus of soil reaction of the pipe embedment. To determine the correction factor (Sc), the Leonhardt (1979), (ATV) A127 formula (1984, 2000) or the version Hornung and Kittel (1989) for □f is used. Leonhardt (1979) or (ATV) A127 formula [1984] are:

$$Sc. = 1.44/ [\Delta f + E_b/E_n (1.44 - \Delta f)] \tag{2}$$

$$\Delta f = (B/D)/ [0.577 + 0.444(B/D)] < 1.44 \tag{3}$$

Where, E′n is the modulus of soil reaction of the native soil at pipe spring line elevation; B is the trench width at pipe spring line; D is the pipe diameter.

Hornung and Kittel (1989) form is:

$$Sc. = 1.44/[\Delta f + E_b/E_n(1.44 - \Delta f)] \tag{4}$$

$$\Delta f = (B/D-1)/[1.154 + 0.444(B/D-1)] < 1.44 \tag{5}$$

ATV (2000) became

$$Sc. = 1.667/ [\Delta f + E_b/E_n (1.667 - \Delta f)] \tag{6}$$

$$\Delta f = (B/D-1)/[0.980 + 0.303(B/D-1)] < 1.667 \tag{7}$$

8. VERIFICATION WITH FINITE ELEMENT ANALYSES

A series of linear elastic finite element analyses(FEA) were performed to verify the validity of the combined soil modulus of reaction, formulated by Leonhardt (1979). Given that FEA was invented in 1957 and has built a phenomenal record of accuracy and repeatability, engineers using this simulation tool no longer construct field installations to verify the results from the FEA. Therefore, in this investigation, the results from FEA are compared with the closed form solutions Leonhardt developed in 1979. The parabolic shapes he used for the horizontal soil reaction in the vertical plane along the spring line of a 12 ft. (3.66 m) pipe buried in 12 ft. (3.66 m) soil cover filled with an embedment of E'b of 80 MPa surrounded by a poor native soil of E'n of 8 MPa with B/D of 1.5, 3 and 5 are shown in Figure 2. The FEA were run for fully bonded pipe-soil interface (B), and 0.3 frictional cases (FC). The Leonhardt model assumes a firm bottom but the authors felt that the FEA runs are useful for firm and soft foundations given that contractors may not always achieve firm and unyielding foundations. Likewise, the variations along the horizontal plane through the spring line are shown in Figure 3. Vertical stresses in the soil for B/D of 1.5 and 5 are shown in Figure 4. The horizontal stresses in the soils for B/D of 1.5 and 5 are shown in Figure 5.

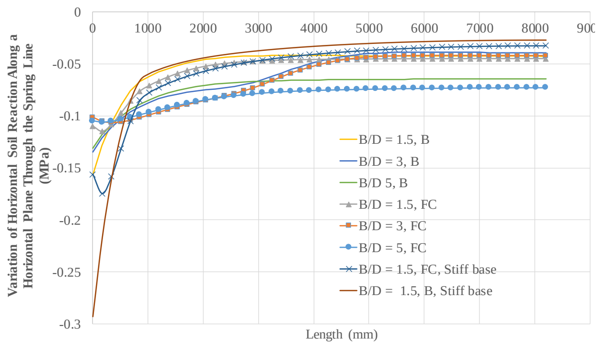


Figure 2 Horizontal Soil Reaction in the Vertical Plane for B/D= 1.5, 3, 5

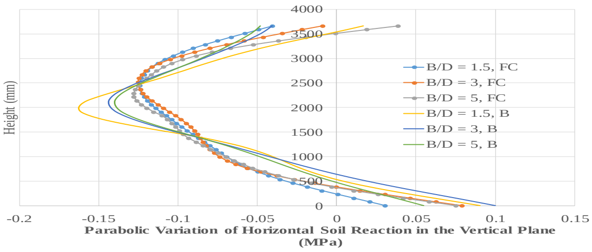
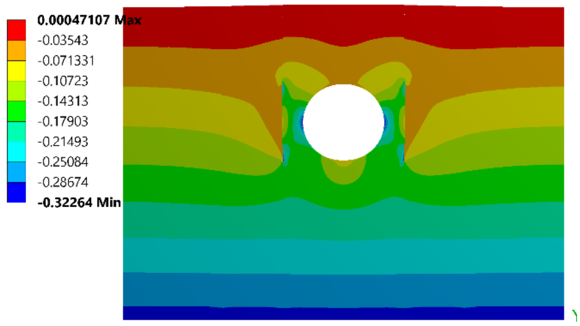
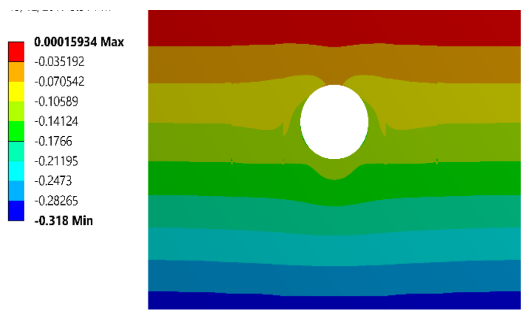


Figure 3 Horizontal Soil Reaction in the Horizontal Plane for B/D = 1.5, 3, 5

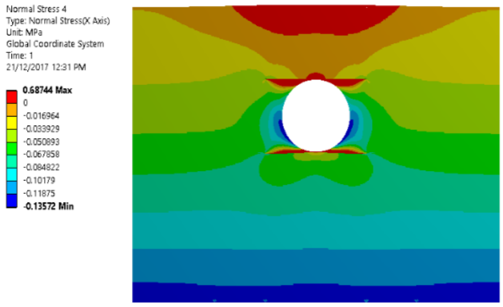


(a)

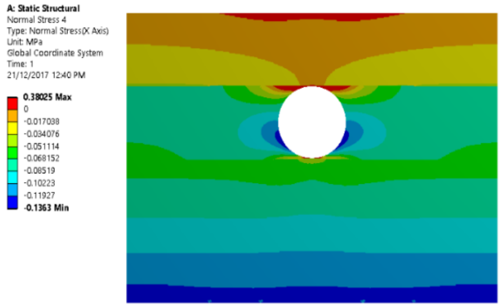


(b)

Figure 4 Vertical Stresses in Soils for (a) B/D = 1.5 and (b) B/D = 5



(a)



(b)

Figure 5 Horizontal Stresses in Soil for (a) B/D = 1.5 and (b) B/D = 5

When the trends in Figure 2 are examined closer, the horizontal soil reaction is the highest at the pipe- embedment interface when the foundation is stiff, and the interface is bonded to allow no slippage of the soil against the pipe wall when B/D = 1.5 and it is the lowest when the pipe-embedment interface is of a frictional coefficient of 0.2 for a foundation that is not firm at a B/D = 5. All the other cases considered fall within these lower and upper bounds.

The horizontal soil pressure seems to decay the slowest for the case of B/D= 5 compared to the rate at which this decay occurs for B/D = 1.5 due to the stiffer embedment than the softer native poor soils being filled in a much wider trench in the former case encourages slower decay. The trends in Figure 3 are as expected confirming Leonhardt (1979)'s assumptions. The results shown in Figures 4 (a) and (b) for the vertical stress in the soil for B/D of 1.5 and 5 are confirming that the former induces higher values compared to those in the latter.

Therefore, a narrow 2 pipe diameter wide trench in poor native soils is not a desirable option for steel pipes. Similar clear message is conveyed in Figure 5 when the horizontal soil stress is compared for B/D of 1.5 and 5. The intensity of the stress concentrations is higher and more widely spread for both vertical and horizontal stresses for B/D of 1.5 than for 5. To sum, in all accounts these comparative analyses confirm Leonhardt (1979) model while refuting the steel pipe manufacturers' guidance of using no more than 2 pipe diameters. Because of paper length limitations, the authors are unable to share results on the behavior of the pipe and other in this paper. The authors plan to offer a companion paper in the 2019 conference.

9. MIGRATION OF NATIVE SOILS INTO EMBEDMENT MATERIALS

The mechanism of soil migration has been best articulated by the clay pipe manufacturers although this applies to all pipe materials. Terzaghi's experiments in 1922 (Terzaghi and Peck, 1948) settled the design criteria used even today for filters in embankment dams, drainage pipes, dewatering wells, and buried pipe embedment's grain size curves as a function of native soils or the choice of geotextiles. The NCPI Clay Pipe Installation Handbook (1982) states "*Loss of pipe support can occur when open graded materials are used on sites having fine to / sands at the base of the trench and a water table that fluctuates rapidly in the pipe zone. Water moving rapidly through the fine sand to the coarse material may carry the fine sand with it. To prevent movement of the fine sands into the open-graded embedment material, the material should be encapsulated in geotextile drainage fabric. Overlaps should be provided, and care must be taken to prevent entry of sands into the crushed rock or aggregate base.*" The crushed rock or coarse aggregate embedment material, because of its free draining nature, creates a conduit for water to flow easily alongside the pipe, creating a French drain effect. The French drain effect exacerbates the migration of fine sands into the embedment. Therefore, in areas of high groundwater, in addition to encapsulating the embedment in filter fabric; cut-off walls or trench plugs are usually constructed at regular intervals to prevent the preferential flow path for flexible pipe materials, for which shear breaks are not a threat along the length. For example, the embedment materials consisted of minus ¾-inch crushed rock. The gradation of the embedment material used for a project is shown in Figure 6 and Table 2. The native materials surrounding the pipe zone and embedment over most of the alignment consisted of fine sands, fine silty sands and non-plastic sandy silts. Figure 6 illustrates the gradations of eight samples of native pipe zone materials obtained during the geotechnical investigation. Seven of the gradation curves shown on this figure are representative of the silty sands and non-plastic silts that surround the pipe zone. For much of the alignment, the pipe zone is surrounded by fine sands and non-plastic silts and is below the groundwater table.

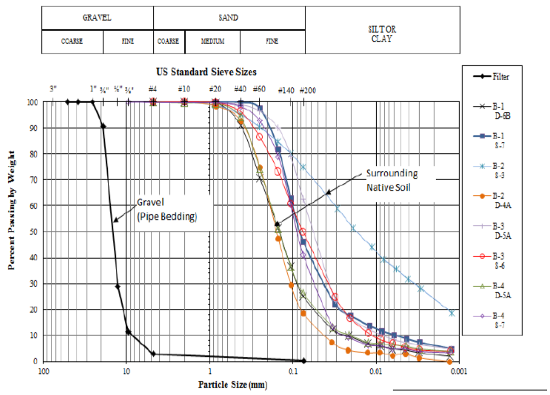


Figure 6 Grain Size Curves for Native Soils and Embedment

10. EMBEDMENT FILTER ANALYSIS

Without the filter fabric encapsulation, the embedment material itself will have to serve as a filter, to prevent migration of fine sands and silts from the surrounding native soils into the voids of the embedment materials, in the presence of water. The effectiveness of the filter is a function of the grain size distributions of both the embedment material and the native soils, and can be quantified by the filter criteria. The filter criteria can be expressed as:

1. $4 < D_{15F}/D_{15B} < 20$
2. $D_{15F}/D_{85B} < 5$
3. $D_{50F}/D_{50B} < 25$

Where D_{15}, D_{50} and D_{85} represent grain sizes at which 15%, 50% and 85%, respectively, are finer by dry weight, and the subscripts F and B refer to the filter material (embedment) and base material (native soils), respectively. Results of the filter analyses are summarized in Table 2. The gradations of seven samples of fine sands and non-plastic silts obtained from the pipe zone in borings B-1 through B-4 are compared to the gradation of the pipe embedment material to evaluate filter compatibility. Five of the samples of native soils are

Table 2 Summary of Soil Migration Evaluation

Boring	Sample Depth (ft.)	USCS	D15 (mm)	D50 (mm)	D85 (mm)	Pipe Embedment D_{15} (mm)	Pipe Embedment D_{50} (mm)	Filter Criteria Calculation $D15_F/D15_B$	Filter Criteria Calculation $D15_F/D85_B$	Filter Criteria Calculation $D50_F/D50_B$	Pass/ Fail
B-1	17	SM	0.04	0.145	0.35	10.0	14.5	250	2	10	Fail
B-1	18	SM	0.014	0.082	0.16	10.0	14.5	714	6	17	Fail
B-2	12	CL	0.0006	0.017	0.153	10.0	14.5	17606	6	85	N/A
B-2	14	SM	0.06	0.155	0.32	10.0	14.5	167	3	9	Fail
B-3	16	ML	0.017	0.056	0.12	10.0	14.5	588	8	25	Fail
B-3	17	ML	0.018	0.076	0.23	10.0	14.5	556	4	19	Fail
B-4	15	SM	0.038	0.145	0.32	10.0	14.5	263	3	10	Fail
B-4	17	SM	0.035	0.09	0.18	10.0	14.5	286	5	16	Fail
Range								**167 - 714**	**29 - 83**	**94 - 259**	
Recommended								**4 - 20**	**< 5**	**< 25**	

classified as silty sands (SM) and two are classified as non-plastic silt (ML). The results clearly show that the embedment material cannot function as a filter, and that the fine sands and non-plastic silts that surround the pipe zone can readily migrate into the void spaces of the embedment material. Recognizing the nature of the native soils, the gradation contrast between the native soils and the specified embedment material, and the high groundwater levels, the design, prudently needs to include a filter fabric wrap (burrito wrap) around the embedment material.

11. CONCLUSIONS

1. The design theories mentioned in this paper were developed 100 years ago and they have many limitations. We need to improve our calculations based on modern analysis.
2. The design practice we follow must be based solely on sound engineering principles that can meet the "standard of care" test applied by the judicial system. Classifying poor soils based solely on blow count is inappropriate
3. The choice of trench width in poor native soils is only possible when the designer has the knowledge to classify soils without any errors in accordance with widely accepted geotechnical engineering principles.
4. Marston's assumptions made more than 100 years ago such as the soil behavior can be represented by a Mohr-Coulomb failure criterion and the cohesion, if any, between the trench fill and the soil in the trench sides is ignored because of its variable and uncertain value, depending on the moisture condition are very far from what takes place.
5. In fact, all the modern research tools when applied to buried pipe design indicate that more than 90% of the soil mass surrounding the pipe stays within the elastic range.
6. The philosophy of keeping the trench width as narrow as 2 pipe diameters for steel pipe in poor soils is not based on fundamental principles of geotechnical engineering. Therefore, the above flawed practice needs to be abandoned.
7. Migration of native soils into embedment material is a common problem that leads to serious consequences and needs to be addressed during the design stage.

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