Pipe Zone Bedding and Backfill: A Flexible Pipe Perspective

Reynold Watkins[1], Brent Keil[2], Rich Mielke[3], Shah Rahman[4]

ABSTRACT
Bedding and backfill materials play a critical role in the long-term structural integrity of buried municipal pipelines. Soil strength is resistance to soil slip, and is a function of soil friction angle and any cohesion in the soil. It determines the stability of the soil. Soil stiffness is the modulus of soil elasticity, E', and is a function of soil type and the applied level of compaction. E' is also affected by depth of burial which increases confining pressure. E' determines the ring deflection of flexible rings. The Modified Iowa equation is used to predict ring deflection of buried flexible pipes. Common types of backfill material can range from native soils (which usually have fines, silt and clay) to imported crushed rock, to soil-cement slurry (or flowable fill/CLSM). Whenever backfill material other than native soils is specified on a project, the reason for doing so must be justified. This paper reviews and recommends best practices for the selection of common bedding and backfill materials for flexible pipes and conducts an economic analysis of the various options utilized. Theoretical aspects of pipe-soil interaction as it relates to ring deflection of pipe for various soil types are discussed.

INTRODUCTION
Flexible pipes, when buried, are designed to deflect vertically. It is through the process of vertical deflection, which results in an equal horizontal expansion of the pipe, that a flexible pipe such as gasket-joint or welded-joint spiral welded steel pipe (WSP) engages the passive resistance of surrounding soils. The pipe-soil system eventually reaches a point of equilibrium where the soil above the pipe forms an arch and further deflection of the pipe ceases. In this pipe-soil interaction dynamic, the role played by the soil far outweighs that of the pipe's stiffness. In structural mechanics, deflection of flexible pipes is referred to as ring deflection. In buried pipe systems, soil quality and placement, and boundaries, are relatively imprecise. So prediction of ring deflection typically does not justify very complex analyses. For practical design, predicted ring deflection is roughly equal to, and no greater than, the vertical compression of the sidefill soil. Moreover, ring deflection is limited by specification.

It is important to note that the concern for soil pressure on a pipe is limited to empty pipe or gravity flow pipelines where the conduit never flows full. WSP, with physical/mechanical characteristics such as a high tensile strength of 60 ksi, yield strength of 42 ksi, and allowable elongation of 22%, is used most often in municipal pressure systems. Examples include distribution and transmission of raw and potable water, and sanitary sewer force mains. After installation, when a line is placed into service, pressure inside the pipe is typically much greater than soil pressure on the pipe. Internal

---

[1] Professor Emeritus, Department of Civil and Environmental Engineering, Utah State University, Logan, UT 84322; Tel: (435) 797-2864; Fax: (435) 797-1185; Email: reynold@cc.usu.edu
[2] Corporate Chief Engineer, Northwest Pipe Company, 430 North 600 West, Pleasant Grove, UT 84062; Tel: (801) 785-6922; Fax: (801) 785-6922; Email: bkeil@nwpipe.com
[3] Director of Engineering, Northwest Pipe Company, 10512 New Arden Way, Raleigh, NC 27613; Tel: (919) 847-6077; Fax: (919) 847-5977; Email: rmielke@nwpipe.com
[4] Western Regional Engineer, Northwest Pipe Company, 1101 California Avenue, Suite 100, Corona, CA 92881; Tel: (951) 739-4681; Fax: (951) 681-4197; Email: srahman@nwpipe.com

pressure, therefore, supports the soil load. When designing a pressurized steel pipe system, an Engineer should first determine the pipe's wall thickness based on the expected system performance (working pressure, surge, etc.), then follow this up with a simple calculation to ensure that the pipe will remain within the allowable ring deflection limits in the specified soil backfill system. A third step is to select the appropriate corrosion protection to ensure that the intended design-life of the pipeline is met.

Despite the facts already stated, the topic of pipe-soil interaction receives a disproportionate attention from the design engineering community for flexible pressure pipelines. On many projects, large sums of money are unnecessarily spent in an effort to improve the buried deflection calculated from elaborate analysis that does not take into account that a pressure line will re-round itself when placed into service. There isn't much discussion in publications that addresses this issue, nor are there good tools to provide a solution. The same quality of construction can be achieved by lower cost means if a clear understanding of some of the issues and associated costs exist. For example, while flowable fill or Controlled Low Strength Materials (CLSM) provide a good bedding for both flexible and rigid pipelines, they can cost almost 20 times more than granular backfill material that can be manipulated to provide a similar level of structural support to buried pipe. There has never been a better time to understand the pertinent issues than now, when we are faced with a financial crisis of epic proportions, and funds are dwindling for critical public infrastructure projects. This paper is intended to educate the reader on the basics of pipe-soil interaction, pipe and soil stability, and the selection of appropriate backfill systems for pressurized pipelines so that the knowledge can be related to the overall cost of a project.

RING DEFLECTION

The first analysis of soil pressures on buried pipe was proposed by Marston et. al (1913), Dean of Engineering at Iowa State College, for culverts to de-water muddy rural roads. The Marston load (Marston 1930) on buried pipe was the total weight of soil in the trench above the pipe, reduced by frictional resistance of the trench walls, Figure 1a. The pipe had to support the Marston load. The pipes were rigid (concrete or clay). Marston's student, Merlin G. Spangler showed that flexible corrugated steel pipe does not need to support Marston load because it deflects as the soil embedment is compressed during backfilling (Spangler 1941). For flexible pipe design, the load on the pipe is PD, where $P = P_d$ (dead load pressure at top of pipe) + P_l (live load pressure at top of pipe) and D is pipe diameter. The prism load, PD, is conservative because installers do not compact soil against the pipe. The pipe is embedded in a "packing" of less dense soil that serves the same way as does packing around an item in a shipping container. The pipe is relieved of part of the prism load which the soil then picks up in arching action over the pipe, Figure 1b.

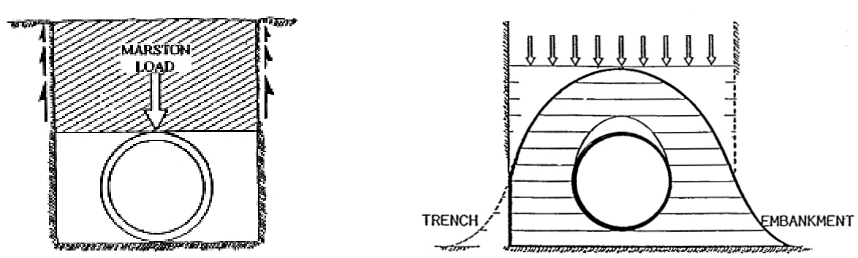


Figure 1a, b: Marston Load (ASCE 2009), and Soil Arching (Watkins 2001)

Flexible pipes, when buried, are expected to undergo vertical deflection due to the dead weight of soil and the effect of live loads, on top of the pipe. When deflection of a flexible conduit takes place, it engages the passive resistance of surrounding soils, and in doing so, the pipe and soil work together to provide the necessary conditions for the pipe to maintain its long-term structural integrity. The deflection of flexible conduits is also referred to as ring deflection.

Ring deflection is the percent change in diameter of the pipe or a measurement of the out-of-roundness of the pipe. In cement-mortar lined and coated pipe, excessive ring deflection can result in cracking of the mortar from the pipe wall. System hydraulics is usually unaffected until a deflection of 10 to 15 percent has occurred. Other negative impacts of gross ring deflection may include leaks in gasket-sealed joints.

A classical example of the importance of soil in a buried pipe system is ring deflection. Per AWWA Manual M11 (AWWA 2004), the maximum recommended ring deflection in steel pipe is 5% if the pipe is bare or has flexible lining and coating, 3% if the lining is rigid and the coating is flexible, and 2% if both the lining and coating are rigid. Ring deflection is controlled primarily by the soil during the placement and compaction of embedment and backfill.

Soil quality and placement, and boundaries are so imprecise that prediction of ring deflection does not typically justify complex analyses. For practical design, predicted ring deflection is roughly equal to, and no greater than, the vertical compression of the sidefill soil, i.e. d = ϵ; where ϵ is the vertical strain in the soil at the spring-line due to vertical stress. Stress-strain data from soils laboratories from uni-axial stress in confined compression tests are adequate and worst-case. At spring-line, the strain may be slightly less because stresses are bi-axial to an undetermined degree. But for design, d = ϵ.

The value of classical, complex analysis is the Modified Iowa equation, first derived by M. G. Spangler (1941), father of buried flexible pipe analysis, and later modified by Reynold Watkins (Watkins et. al 1958). Shown below is the Modified Iowa equation.

$$d = D_L \frac{KP}{EI/r^3 + 0.06E'} \tag{1}$$

Where:

d	= ring deflection
D_L	= deflection lag factor (1.0 when using prism load)
K	= bedding constant (use 0.10 for steel pipe applications)
P	= sum of vertical pressure on pipe (dead and live loads), psi
EI/r^3	= pipe ring stiffness, psi
E'	= empirical soil stiffness, psi
r	= pipe radius, inches (imprecision does not justify distinguishing mean radius from nominal D/2)
I	= moment of inertia of pipe wall, $t^3/12$
t	= thickness of pipe walls, in.

It can be seen that the ring deflection is a function of the vertical pressure on the pipe, the pipe ring stiffness, and soil stiffness. For steel pipe with rigid lining and coating, the ring stiffness is $\sum EI/r^3$, the sum of ring stiffness of the steel, and the mortar lining and coating. Flexible linings and coatings do not contribute to ring stiffness. Soil stiffness is 0.06 E'.

The Modified Iowa equation shows the relationship between soil stiffness and ring stiffness in the control of ring deflection. Values of E' are also listed in Manual M11 as "modulus of soil reaction" for some of the important soil classifications, Table 1.

Noteworthy is the prevailing effect of soil stiffness over ring stiffness. From the Modified Iowa equation, ring deflection for a plain steel pipe is $d\% = 10P/(EI/r^3 + 0.06E')$. The first term in the denominator is ring stiffness (pipe resistance). For a typical pipe with D/t = 240, pipe resistance is 1.45 psi. The second term in the denominator is soil resistance. If, for the poorest soil, E' = 500 psi, soil resistance is 30 psi. Pipe resistance is therefore only 5% of the total resistance. Soil resistance is 95% of the total.

Table 1: E' Values by Soil Type and Compaction from AWWA M11

Soil Stiffness Category	Soil Type	AASHTO Soil Groups	Depth of Cover	Compaction Level			
				85%	90%	95%	100%
SC1	Clean, coarse grained soils: SW, SP, GW, GP, or any soil beginning with one of these symbols with 12% or less passing a No. 200 sieve	A1, A3	2-5	700	1000	1600	2500
			5-10	1000	1500	2200	3300
			10-15	1050	1600	2400	3600
			15 +	1100	1700	2500	3800
SC2	Coarse-grained soils with fines: GM, GC, SM, SC, or any soil beginning with one of these symbols more than 12% fines. Sandy or gravelly fine-grained soils: CL, ML (or CL-ML, CL/ML, ML/CL) with more than 25% retained on a No. 200 sieve	A-2-4, A-2-5, A-2-6, or A-4 or A-6 soils with more than 25% retailed on a No. 200 sieve	2-5	600	1000	1200	1900
			5-10	900	1400	1800	2700
			10-15	1000	1500	2100	3200
			15 +	1100	1600	2400	3700
SC3	Fine-grained soils: CL, ML (or CL-ML, CL/ML, ML/CL) with 25% or less retained on a No. 200 sieve	A-2-7, or A-4 or A-6 soils with 25% or less retained on a No. 200 sieve	2-5	500	700	1000	1500
			5-10	600	1000	1400	2000
			10-15	700	1200	1600	2300
			15 +	800	1300	1800	2600

Note: E' values in M11 are based on Hartley, J. D., and J. M. Duncan, "E' and its Variation with Depth," Journal of Transportation, Division of ASCE, Sept. 1987.

From Table 1, it can be seen that many, if not most native soil types, are captured in the table and therefore can be analyzed using the Modified Iowa equation.

It can be shown by analysis that in most cases native soils are capable of limiting pipe deflections below the recommended AWWA limits. As an example, assuming most steel pipe installations for water transmission are buried with 3 to 15 foot of cover, below are deflection calculations for a 96" diameter pipe using the lowest E' values available from the AWWA M-11 table.

Case 1 Assumptions:
96" Diameter
3% recommended max deflection
0.40" wall thickness (D/T of 240)
0.50" Mortar Lining; Flexible Coating

E' Values From Table 1:
3 to 5 foot of cover minimum E' = 500 psi
Maximum deflection calculated is 1.3%
5 to 10 foot of cover minimum E' = 600 psi
Maximum deflection calculated is 2.2%
10 to 15 foot of cover minimum E' = 700 psi
Maximum deflection calculated is 2.8%

Case 2 Assumptions:
96" Diameter
2% recommended max deflection
0.40" wall thickness (D/T of 240)
0.50" Mortar Lining; 1.0" Mortar Coating

E' Values From Table 1:
3 to 5 foot of cover minimum E' = 500 psi
Maximum deflection calculated is 1.2%
5 to 10 foot of cover minimum E' = 600 psi
Maximum deflection calculated is 2.0%
10 to 15 foot of cover minimum E' = 700 psi
Maximum deflection calculated is 2.6

In all cases, Maximum deflection is below 3%.
The recommended deflection limit is satisfied.

Deflection exceeds 2% at 12 feet of cover.
Further consideration is required for depths over 12 ft.

Noteworthy are the percentages of deflection that are controlled by the soil (in the denominator of Modified Iowa equation) — from 87% to 89% to 90% as soil cover, H, increases from 5 to 10 to 15 ft. Allowable ring deflection for mortar lined and coated steel pipe is d(%) = 2%. For H = 15 ft of soil cover, if E' is increased to 1200 psi by compaction (density) of embedment to 90%, then the ring deflection becomes, d(%) = 1.7%, which is less than the 2% maximum allowable.

If increasing the compaction of the soil is impractical for the project, or if the complexity of the project warrants it, a more sophisticated analysis can be completed of the pipe-soil interaction. From that it can be verified if native soils will work for the project, or if other soil improvements will be needed to satisfy the deflection recommendations. A brief summary of this analysis is provided in this paper. A complete analysis can be found in the ASCE Manuals and Reports on Engineering Practice No. 119 (ASCE 2009).

SOIL STABILITY

Soil stability is soil strength based on friction angle, φ, which can be determined in a soils laboratory. Soil strength is the resistance to soil slip. Soil strength is the ratio of maximum to minimum soil stresses at soil slip, $\sigma_{max}/\sigma_{min}=(1+\sin\varphi)/(1-\sin\varphi)$ where φ= friction angle. Cohesion in the soil increases soil strength. Cohesion is caused by a clay fraction, by carbonates, by organics, and even by moisture in fine grained soil. Note, for example, the strength of flowable fill with Portland cement added for cohesion.

<u>Slope Stability</u>: The concept of soil strength is demonstrated by the maximum slope, φ, of a pile of soil. Any more soil dumped on the pile, would slip down the slope. The maximum slope is the angle, φ. Figure 2 shows the soil friction angle, φ, for different qualities of soil.

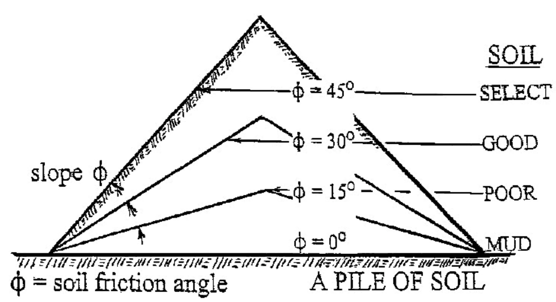


Figure 2: Soil Friction Angle, φ, for Various Soil Types

$\varphi = 45^o$ Select, granular soil. Slope, φ, may be even greater if soil is well compacted.
$\varphi = 30^o$ Good soil. The soil may be uncompacted, or possibly moist.
$\varphi = 15^o$ Poor soil. Poor soil may contain a high percentage of fines, and may be wet.
$\varphi = 0^o$ Mud. The soil is liquid, and has no slope angle, φ

<u>Soil Strength</u>: For granular, cohesionless, soil, strength is $\sigma_{max}/\sigma_{min} =(1+\sin\varphi)/(1-\sin\varphi)$. For active soil resistance, Figure 3 shows how soil strength is increased by increasing the soil friction angle, φ.

For example, soil strength is doubled by increasing soil friction angle from 30° to 45°. In poor soil (low strength), a flexible pipe can be deflected by surface live loads, and loose soil embedment - especially loose soil under the haunches. It is possible for good soil with excessive fines, to become poor soil when it gets wet. Water can get into the soil from a water table, storm-water, or leaks in pipes. If strengths for stability are critical, tests should be performed on saturated soil.

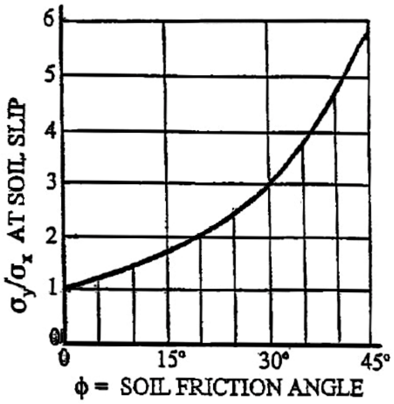
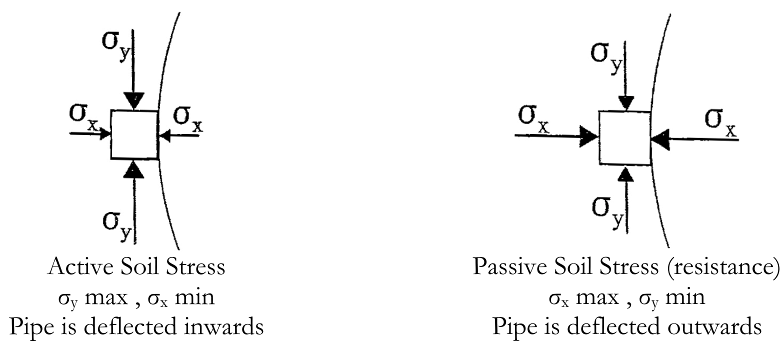


Figure 3: Soil Strength

PIPE STABILITY

Flexible pipes, by design, are expected to deflect when buried. Figures 4a, and 4b show a soil cube at the side of a flexible pipe. It has both active stress and passive resistance.



Figures 4a, b: Active and Passive Soil Stresses

Active Soil Stress: At active soil stress, the horizontal soil stress, σ_x, is minimum. It presses against the pipe. At soil slip, the pipe deflects inward. Active soil stress could be caused by a surface wheel load approaching the pipe.

Passive soil stress (passive resistance): At passive soil resistance, the horizontal stress, σ_x, is maximum. When soil slips, the pipe deflects outward. This instability could be caused by a live load crossing over the pipe with less than minimum (adequate) soil cover.

Pipe stability is controlled primarily by stability (strength) of the soil embedment.

Soil Tests: The literature is replete with soil tests. For buried flexible pipe-soil interaction, the following are the most important properties to be controlled. Appropriate laboratory tests are available.

1. Soil strength - tri-axial tests; on both dry and wet soil.
2. Soil density - to assure soil quality and required compaction at optimum moisture content.
3. Soil compression - stress-strain diagram (confined compression, or tri-axial, or modified)
4. Particle size gradation - to control fines, to reduce soil particle migration, to allow drainage.

For cases where poor soils may be used for embedment or backfill, other tests, such as liquid limit and plasticity index, may be of value. Chemicals in the soil could pose a problem. Conditions for potential liquefaction require limits on the soil friction angle and on soil density. For most installations, there is no need to encumber the required tests with these conditions.

IMPORTANCE OF SOIL

Basic properties of both pipe and soil are strength and stiffness:

Pipe	**Soil (granular)**
strength = yield stress of steel	strength = $\sigma_{max}/\sigma_{min} = (1 + \sin\varphi)/(1 - \sin\varphi)$ at soil slip
stiffness = EI/r^3 (ring stiffness), psi	stiffness = E'= modulus of elasticity in compression

The importance of soil is demonstrated in the following example of allowable vertical external pressures, P, including internal vacuum on a buried steel pipe, with 1.0-inch thick mortar coating and 0.5-inch thick mortar lining.

Pipe		**Soil**	
D	96-inch Diameter	SC3	Soil Classification
r	48-inch (radius)	γ	115 pcf, soil density at 85% standard density
t	0.40-inch wall thickness	γ_s	135 pcf, saturated soil density
$\sum EI/r^3$	7 psi (ring stiffness)	E'	Soil Stiffness
E	$30(10^6)$ psi modulus of elast.	H	Height of soil cover
σ_f	$42(10^3)$ psi, yield stress	E_S	Vertical Soil Modulus

From the AWWA M11 manual, the allowable vertical pressures on the buried pipe are shown in Table 2. Soil stiffness varies from lightly compacted, E' = 700 psi, to compacted, E' = 2300 psi. Allowable external pressure, P, is based on "failure," with a safety factor included.

Table 2: Allowable External Pressures, P

Soil Stiffness, E'	P @ H = 4-ft		P @ H = 15-ft	
700 psi	29 psi (dry)	24 psi (sat.)	37 psi (dry)	30 psi (sat.)
2300 psi	52 psi (dry)	43 psi (sat.)	67 psi (dry)	55 psi (sat.)
0 psi (mud)	$P = (3/2)\sum EI/r^3 = 10$ psi with a safety factor of 2. Collapse at P =21 psi			

Pressure, P, includes vertical soil pressure on the pipe, and any vacuum in the pipe. In the case of dry soil, and height of cover, H = 15-ft, applied pressure is P = 12 psi. With vacuum, 14.7 psi, the applied pressure is 26.7 psi which is well below the allowable P = 37 psi.

In Table 2, internal vacuum, 14.7 psi, can be added to the soil pressure without exceeding the allowable pressure, P. The only exception is the liquefied soil embedment (mud). Of possible concern is height of cover, H = 4-ft, in saturated soil, for which allowable P = 24 psi. Saturated soil pressure on the pipe is 3.2 psi. With vacuum, 14.7 psi, applied pressure is 17.9 psi. The pipe is therefore adequate.

The conditions in Table 2 meet allowable ring deflection, d = 2% for CML/CMC pipe. The worst case for ring deflection is, H = 15-ft of dry soil, and E' = 700 psi vertical soil modulus for which vertical compression (strain) of sidefill soil is 2.0%. Ring deflection should be controlled. The AWWA values for allowable pressure, P, are conservative because of concern for out-of-roundness, imprecision in soil properties, and non-uniform soil placement and compaction.

Ring deflection is about equal to the vertical compression of the sidefill soil. Vertical compression is the average vertical strain, ε, of the soil in the sidefill. Strain is $\varepsilon = \sigma/E_S$ where σ is the vertical stress at springline, and E_S is vertical soil modulus from a confined compression test in a laboratory.

For example, consider the case of H = 15 ft of dry soil, lightly compacted, unit weight = 115 pcf. The average vertical soil strain in the sidefill occurs at springline where vertical stress is σ = 115 pcf(15 + 2.5)ft = 14 psi. From the soils lab, the vertical soil modulus is $E_S \geq 700$ psi. Therefore, average strain in the sidefill is $\varepsilon = \sigma/E_S = 14/700 = 2\%$. The allowable ring deflection, d = 2%, is not exceeded, but ring deflection should be controlled during installation.

If native material can not meet the requirement of the project, importing material or flowable fill can be considered.

FLOWABLE FILL

Flowable fill is soil-cement that flows under the pipe and becomes uniform bedding, which in turn reduces the differential settlement of adjoining pipes. Portland cement or fly ash improves flowability and adds strength. It is assumed that all voids are filled without the need for compaction due to the "flowing" characteristics of the material. The term Controlled Low Strength Material (CLSM) is also used to describe flowable fill.

Advantages of flowable fill include:

1. The need to level and compact bedding for alignment is avoided.
2. Native soil can be used for bedding and embedment instead of imported select soil.
3. Multifunctional trenching and installing is facilitated.
4. Trenches can be narrow. Tunnels need to be only slightly larger in diameter than the pipe.
5. Flowable fill helps to protect the pipe in the event of future excavations.
6. Flowable fill provides additional stiffness.

Disadvantages of flowable fill include:

1. Cost of adding Portland cement and making the slurry is high. Delivery in mixers is costly. Costs can be higher by a factor of 20 than granular backfills.

2. Delays occur in setting forms for each "pouring" and in curing time before backfilling.
3. Due to cure time delays, productivity on a project is reduced, sometimes by as much as much as 40%, according to data received from Contractors.
4. During placement of the fill, care is required to prevent flotation of the pipe. Constraints for prevention of flotation can cause variability of the geometry of the flowable fill embedment.
5. Care must also be taken during fill placement to prevent collapse by external hydrostatic pressure.
6. Flowable fill around the pipe may crack when internal pressure re-rounds the pipe. If the flowable fill is high-strength and cracks under soil movement, stress concentrations on the pipe are much greater for high-strength than for low-strength embedment.

CLSM must be fluid enough to flow under the pipe, and strong enough to hold the pipe in shape. A slump of 10 inches on a flow table of 12 inch diameter is often specified. Strength should be low enough that future excavations do not damage the pipe. Unconfined strength of the CLSM within a range of 40 psi to 100 psi is recommended. Only a small amount of Portland cement is added if the native soil has enough fines to make the slurry flowable. Most native soils have fines, silt and clay. CLSM does not require concrete quality aggregate. As much as 60% silt in native soil with one sack of Portland cement per cubic yard has been used successfully.

Figure 5a shows bedding schematic for pipe using CLSM. Figure 5b is a graph of the ring deflection term as a function of flowable fill angle, α. The ring deflection term is dimensionless and, therefore, applies to any size of pipe. Assumptions of no side support are worst-case. From the graph, ring deflection is reduced as angle, α, is increased.

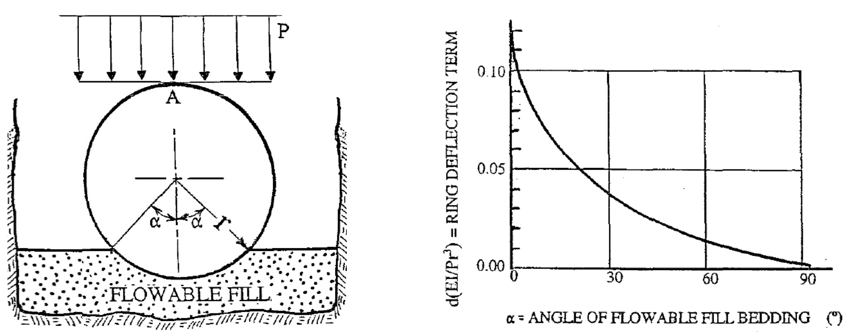


Figure 5a, b: Flowable Fill Bedding, Ring Deflection-Bedding Angle Relationship (ASCE 2009)

α	angle of flowable fill	r	radius of the ring
d	ring deflection, (Δy/D)	P	vertical pressure
E	modulus of elasticity of pipe	I	moment of inertia of wall
Δy	vertical displacement of the crown, A, due to P		

Example:
What is ring deflection of a steel pipe for which D/t = 240, P=600 psi?

From Figure 5b:
At α=30°, **d = 2.4%**
At α=60°, **d = 0.8%**

Deflection at α=60° is only one third of ring deflection at α=30°. The height of flowable fill at α=30° is 0.07D. When α=60°, the height of flowable fill is 0.25D.

PIPELINE CONSTRUCTION COSTS

From discussions with Contractors during the writing of this paper, the Authors discovered that it is difficult to obtain real meaningful cost information from the construction community as they do not quantify costs in a manner that is conducive to providing breakdowns on the different subroutines of a pipeline installation. These subroutines can be categorized as excavating trenches, installing pipe, installing pipe zone backfill, compaction of the backfill, installing trench backfill, rough grading and final grading. While each of these subroutines exists on all projects, the reality is that the cost for each is interrelated, whereby each item can change by a litany of variables that exist on every project. Establishing median costs or unit pricing for large diameter pipeline construction projects is difficult because of the wide range of variables and intangibles that impact costs, some of which are discussed below. Ultimately, it is overall productivity that can be achieved by the entire construction crew that drives costs for installation on every project.

A few significant considerations/variables that can impact productivity and ultimately installation costs are listed below:

1. type of pipe materials permitted for use on a project
2. pressure class of the pipe material specified --- higher pressure classes raise the cost of the pipe
3. depth of bury of the pipeline and how that impacts productivity
4. impact of existing utilities, fence lines, etc. to productivity
5. in-situ soil conditions and how they effect productivity
6. cost of backfill materials/aggregates, which are impacted greatly by distance from quarry (hauling costs)
7. backfill compaction requirements and how they impact productivity
8. cost of flowable fill backfill materials if specified on a job, whether it has to be imported or whether it can be manufactured on site, equipment necessary to manufacture it on site
9. condition of the raw materials commodity markets and how that impacts cost of fuel, concrete, pipe, bedding etc.
10. easement restrictions, if any, and how that impacts productivity
11. in urban areas, if the route of the pipeline is it in the pavement, how the removals and restorations impact productivity
12. if roads can not be closed and traffic maintenance is required, how that impacts productivity
13. work time restrictions and how that impacts productivity
14. whether excess trench materials can be left at the site, or location of the nearest dump
15. in rural areas, what restrictions are there for access and how many points of access exist
16. how do restoration requirements impact productivity
17. time frame for the pipeline to be constructed and contract time limitations

In their efforts to quantify construction cost differences between the use of native material versus granular import backfill versus CLSM, the Authors gathered the data shown in Tables 3 through 6.

The installed cost of native material versus importing can be seen in Tables 3 and 5 by comparing the "Cost of compaction labor and equipment per linear cubic yard" to the "Total cost per cubic yard for embedment installed". The installed cost when import is included is between 2 and 3.5 times the cost of simply using native material.

For 36-inch through 48-inch diameter pipe, the difference between the cost of CLSM versus native material is approximately $86/cu.yard, a factor of 17 over the cost of using native material. For 60-inch through 66-inch pipe, the cost difference of CLSM versus native material is roughly $150/cu.yard, a factor again of 17 over the cost of granular material. Construction productivity goes down by a factor of almost 3 when CLSM is used instead of native or granular import backfill.

Table 3: Cost of Granular Fill (36-in thru 48-in)

Trench Width (ft.)	6.5
Embedment Height (ft.)	5
Embedment Envelope (yd^3)	1
Pipe Diameter (ft)	3.5
Pipe Volume	0
Conversion & Waste Factor	1.1
Cubic Yards Per Linear Foot	**0.93**
Cost of compaction labor and equipment/day	$2,800.00
Productivity (LF/day)	500
Cost of compaction labor and equipment/LF	$5.60
Cost of compaction labor and equipment/Lyd^3	$5.22
Cost of embedment materials/yd^3	$8.50
Hauling/yd^3	$6.00
Total Cost / yd^3 for Embedment Installed	**$19.22**

Table 4: Cost of CLSM (36-in thru 48-in)

Trench Width (ft.)	6.5
Embedment Height (ft.)	5
Trench Length	1
Embedment Envelope (yd^3)	1
Pipe Diameter (ft)	3.5
Pipe Volume	0
Conversion & Waste Factor	1.1
Cubic Yards Per Linear Foot	**0.93**
Cost of compaction labor and equipment/day	$9,500.00
Productivity (LF/day)	500
Cost of compaction labor and equipment/LF	200
Cost of compaction labor and equipment/Lyd^3	$28.50
Cost of embedment materials/yd^3	$26.57
Hauling/yd^3	$65.00
Total Cost / yd^3 for Embedment Installed	**$91.57**

Table 5: Cost of Granular Fill (60-in thru 66-in)

Trench Width (ft.)	8.5
Embedment Height (ft.)	7
Embedment Envelope (yd^3)	2
Pipe Diameter (ft)	5.5
Pipe Volume	1
Conversion & Waste Factor	1.1
Cubic Yards Per Linear Foot	**1.46**
Cost of compaction labor and equipment/day	$2,800.00
Productivity (LF/day)	350
Cost of compaction labor and equipment/LF	$8.00
Cost of compaction labor and equipment/Lyd^3	$11.65
Cost of embedment materials/yd^3	$8.50
Hauling/yd^3	$6.00
Total Cost / yd^3 for Embedment Installed	**$26.15**

Table 6: Cost of CLSM (60-in thru 66-in)

Trench Width (ft.)	8.5
Embedment Height (ft.)	7
Trench Length	1
Embedment Envelope (yd^3)	2
Pipe Diameter (ft)	5.5
Pipe Volume	1
Conversion & Waste Factor	1.1
Cubic Yards Per Linear Foot	**1.46**
Cost of compaction labor and equipment/day	$16,000.00
Productivity (LF/day)	400
Cost of compaction labor and equipment/LF	150
Cost of compaction labor and equipment/Lyd^3	$66.67
Cost of embedment materials/yd^3	$97.11
Hauling/yd^3	$65.00
Total Cost / yd^3 for Embedment Installed	**$162.11**

CONCLUSION & RECOMMENDATIONS

1. For all buried pipe projects, consideration must first be given to the use of native soils for the backfill. In most typical situations, proper installation and backfill compaction at burial depths of 3 to 15 ft, can make use of native soils, even when they meet the description of the worst soils permitted by Table 1. Only when these conditions can not be met should an engineer consider

further analysis and importing backfill material. The cost savings of using native materials over importing or using CLSM can be significant.

2. The cost of importing granular backfill materials can be as high as 2 to 3.5 times the cost of using native materials.
3. For pipe diameters in the 36-inch through 48-inch range, the cost of using CLSM can be 17 times higher than the cost of using native materials. For 60-inch through 66-inch diameter pipe, the cost difference of CLSM versus native materials is again higher by a factor of 17.
4. Construction productivity can be reduced by a factor of almost 3 when CLSM is utilized instead of native or granular import backfill materials.
5. While engineers often search for and associate an E' value with CLSM/flowable fill, and while the Authors have seen values ranging from 3000 psi to recommendations as high as 25,000 psi (Howard 1996), in reality this is meaningless. E', as used in the Modified Iowa equation, is a horizontal modulus of elasticity; it is not linear and is not constant. The Modified Iowa equation does not typically apply to soils with cohesion. A CLSM backfill system, on the other hand, is essentially "rigid" and therefore, has cohesion. E', therefore, does not apply to CLSM backfill systems.
6. The topic of pipe-soil interaction receives a disproportionate attention from the design engineering community for flexible pressure pipelines. The concern for soil pressure on a pipe is limited to empty pipe or gravity flow pipelines where the conduit never flows full. In pressure piping systems, the internal pressure is typically much greater than soil pressure on the pipe; internal pressure essentially supports the soil load.
7. The prism load is used for calculating the deflection in a buried, non-pressurized flexible pipe. The prism load is the *maximum* long-term load that a buried flexible pipe can experience after installation. Per AWWA M11, deflection of steel pipe is calculated using the prism load. In pressure pipes, long-term deflections are prevented by internal pressure. Design deflection lag factor, D_L =1.0.
8. Ring deflection is about equal to the vertical compression of the embedment. This is worst-case. When using a rigid lining, and/or rigid coating for the corrosion protection of steel pipe, the additional stiffness decreases ring deflection.
9. Resistance provided by the pipe material stiffness is typically only 5% of the total resistance to deflection. The remaining 95% of the resistance to deflection is provided by the soil.
10. For granular, cohesionless soil, the soil strength is increased by increasing the soil friction angle, φ. Soil strength is doubled by increasing φ from 30^o to 45^o.
11. The percentage of high PI soils in a backfill system (certain clays), must be limited by specification in order to prevent loss of strength when the soil gets wet.

ACKNOWLEDGEMENTS

The Authors would like to thank Mr. Scott Parrish, Vice President, Garney Construction, Kansas City, MO, for his assistance with the construction costs discussed in this paper.

REFERENCES

ASCE (2009), "Buried Flexible Steel Pipe: Design and Structural Analysis," ASCE Manuals and Reports on Engineering Practice No. 119, Reston, VA

AWWA (2004), "Steel Water Pipe: A Guide for Design and Installation (M11)," *AWWA-M11*, American Water Works Association, Denver, CO

Howard, A. (1996), *Pipeline Installation*, 3rd ed., Relativity Publishing, Lakewood, CO

Marston, M. G., and A. O. Anderson (1913), "The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe," Iowa State University Engineering Experiment Station, Bulletin 31, Ames, Iowa

Marston, M. G. (1930), "The Theory of External Loads on Closed Conduits in the Light of the Latest Experiments," Iowa State University Engineering Experiment Station, Bulletin 96, Ames, Iowa

Spangler, M. G. (1941), "The Structural Design of Flexible Pipe Culverts," Iowa State University Engineering Experiment Station, Bulletin 153, Ames, Iowa

Watkins, R. K. and M. G. Spangler (1958), "Some Characteristics of the Modulus of Passive Resistance of Soil – A study in Similitude," Proceedings Highway Research Board 39: 389-397

Watkins, R. K. (2001). "Non-elastic Behavior of Buried Pipes," Pipelines 2001: Advances in Pipelines Engineering & Construction, J. Castronovo, ed., ASCE, Reston, VA