The Reclamation E' Table, 25 Years Later

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Abstract

The Reclamation table of E’ (Modulus of Soil Reaction) values for use in estimating the deflection of buried flexible pipe was first published in 1977. The E’ value represents the stiffness of the embedment soil placed on the sides of the pipe. The table gave E’ values that depended on soil classification and placement density. A new 2006 Reclamation Table of E’ values is presented as a revised and updated version of the 1977 table. The 2006 E’ table is based on vertical deflections, rather than horizontal deflections, and on new data. The new table has been slightly reorganized, soil classifications updated, and the crushed rock category clarified. A composite E’, based on both the embedment soil and trench wall material, can be used when very stiff or very weak trench walls are encountered. The Reclamation Equation was used to develop the E’ values. Accordingly, the E’ values should be used only with the Reclamation Equation to estimate the vertical deflection of flexible pipe.

HISTORY OF E’

In 1941, M. G. Spangler (1) published the Iowa Formula for predicting the horizontal deflection of flexible pipe. As with other deflection equations, the Iowa Formula is basically:

\[
\text{Deflection} = \frac{\text{load on pipe}}{\text{Pipe stiffness + Soil stiffness}}.
\]

Spangler referred to the soil stiffness as “e,” the modulus of passive resistance. In 1958, Watkins and Spangler (2) modified the soil stiffness to E’, the “modulus of soil reaction.” A single value of E’ was recommended for “compacted soils.” In 1977, Howard (3) published a table of E’ values that depended on the embedment soil classification and placement density. These values were based on over 100 field installations where horizontal deflections were measured. In 1996, Howard (4) presented some revised E’ values based on the measured vertical deflections from the same sources. Currently, most standards, manuals, and handbooks for pipe design use, or reference, the 1977 E’ table.

UPDATED E’ VALUES

A recent analysis by Howard (5) of over 150 field measurements (combining data from new additional studies with the 1977 data) indicates that some of the 1977 and 1996 E’ values should be revised. The updated table is shown as Table I and will be referred to as the 2006 Reclamation Table of E’ Values. The 2006 changes from the 1977 table are:

**Different E’ values** Five of the updated E’ values are higher and one value is lower. The previous 1977 values are shown as strikeouts.
Vertical Deflections The revised values are based on vertical deflections instead of horizontal deflections. The vertical deflection is easier to measure and in most cases of well compacted embedment soil, the horizontal deflection is only 25% to 50% of the vertical deflection. While the vertical deflection generally keeps increasing with time, the horizontal deflection often does not increase or increases less than the vertical deflection.

Updated Soil Classifications There are five basic soil groups in the table. The descriptions of the soil groups have been reworded emphasizing the Unified Soil Classification System (USCS) according to the current ASTM D 2487. To the first group, the soils Organic Clay (OH), organic silt (OL), and Peat (Pt) have been added. The percentage of sand/gravel used to separate some soil groups has been changed from 25% to 30% to reflect changes made to ASTM D 2487 in 1984.

Terminology The term “bedding” was changed to “embedment” to better reflect current usage of the term bedding as the material that the pipe is laid on, not side soil support.

Restricted Use of Fine Sand A caveat has been added to the soil group, GW, GP, SW, SP, about soils classified as poorly graded sand (SP) that are primarily fine sand (minus No 40 sieve). These SP soils are difficult to work with and compact. If a fine sand is used, it should be considered a silt, ML, for purposes of the E’ table.

Clarification of Crushed Rock The soil type, “crushed rock” is typically ¾ in (19 mm) to 1 ½ in (37.5 mm) in size. Crushed rock cannot be evaluated for percent Proctor because the Proctor compaction test can only be performed on soil passing the ¾ inch sieve (19 mm) and the test is not applicable for free-draining materials such as crushed rock. The Relative Density (RD) test to evaluate the density is inappropriate because of the typically small difference between minimum and maximum density for crushed rock. Accordingly, in the 2006 table, the level of compaction for crushed rock is shown simply as uncompacted or compacted. “Compacted” means some type of equipment has been used to densify the crushed rock. A definition of “crushed rock” has been added, specific to this table. This soil group only pertains to clean, large size crushed rock. The material should not contain more than 12% fines, and 75% or more of the particles must be larger than the 3/8-inch (9.5 mm) sieve. The maximum size is typically based on other concerns. Additionally, all the faces of the individual particles must be a fracture surface.

Effect of Increasing E’ Values The most significant increase in the new recommended E’ values is for the soil group comprised of clean sands and gravels (GW, GP, SW, SP), and for the “crushed rock” group. The increase in E’ from 3000 to 4000 lbs/in^2 (21 to 28 MPa) for GW, GP, SW, and SP soils does not affect estimated deflections very much. For low stiffness pipe under 20 ft (6 m) of cover, the estimated deflection would decrease from 0.9% to 0.7%. At 40 ft (12 m) of cover, the estimated deflection would decrease from 1.8% to 1.3%. The increase in E’ from 3000 to 6000 lbs/in^2 (21 to 42 MPa) for crushed rock also does not affect estimated deflections very much. For 20 ft of cover, the estimated deflection would decrease from 0.9% to 0.5%. At 40 ft of cover, the estimated deflection would decrease from 1.8% to 0.9%. While this is a 50% difference for crushed rock, the estimated deflection value is still rather small. The new recommended values better represent the empirical data. When the first table of E’ values was proposed in 1977, the value of 3000 lbs/in^2 (21 MPa) was extremely conservative. In most literature at the time, there was one recommended value of E’, 700 lbs/in^2 (4.8 MPa), for “compacted” soils. The 1977 proposed increase in E’ from 700 to 3000 was so significant that a very conservative number was used in the table. When used properly, the new 2006 values still provide for a conservative approximation of the pipe deflection.
# 2006 RECLAMATION TABLE OF E’ VALUES

E’ values are shown in lbs/in² (MPa)

## Degree of Compaction Of Pipe Embedment (note 7)

<table>
<thead>
<tr>
<th>Soil-Classification of Embedment (notes 4, 5, 6)</th>
<th>Dumped</th>
<th>Slight</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dumped</td>
<td>50</td>
<td>200</td>
<td>400</td>
<td>1500</td>
</tr>
<tr>
<td>Slight</td>
<td></td>
<td>(0.3)</td>
<td>(1.4)</td>
<td>(2.8)</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td>150</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td>(1.1)</td>
<td>(2.8)</td>
<td>(7)</td>
</tr>
<tr>
<td>Highly compressible, plastic, or organic clays/silts, peat, top soil</td>
<td><strong>DO NOT USE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clays and Silts with less than 30% sand and/or gravel</td>
<td>400</td>
<td>200</td>
<td>1000</td>
<td>2500</td>
</tr>
<tr>
<td>CL, ML</td>
<td></td>
<td>(1.1)</td>
<td>(2.8)</td>
<td>(7)</td>
</tr>
<tr>
<td>Sandy or Gravelly Silts and Clays with 30% or more sand and/or gravel</td>
<td>150</td>
<td>700</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>GC, GM, SC, SM</td>
<td></td>
<td>(1.4)</td>
<td>(5)</td>
<td>(14)</td>
</tr>
<tr>
<td>Sands and Gravels with 13% or more fines</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GC, GM, SC, SM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sands and Gravels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW, GP, SW, SP (note 8)</td>
<td>200</td>
<td>1000</td>
<td>2000</td>
<td>4000</td>
</tr>
<tr>
<td>(note 8)</td>
<td></td>
<td>(1.4)</td>
<td>(5)</td>
<td>(14)</td>
</tr>
<tr>
<td>Compacted</td>
<td></td>
<td>(7)</td>
<td></td>
<td>(42)</td>
</tr>
</tbody>
</table>

## NOTES:

1. Values only valid for pipe cover of 50 ft (15 m) or less
2. The E’ values shown are only valid when used with a prism load.
3. Using these E’ values will give an estimated initial average pipe vertical deflection.
   Time-lag factors must be used for long term deflection
   The actual deflection should agree with the estimated deflection within:
   ± 0.5% percentage points for high degree of compaction
   ± 1% percentage points for moderate degree of compaction
   ± 2% percentage points for dumped/slight degree of compaction
4. Unified Soil Classification based on ASTM D2487 or D2488
5. “Soil Classification of Embedment” also applies to dual symbol or borderline soils beginning with the symbol shown in column.
6. Fines are soil particles that pass a No. 200 (75 micrometer) sieve (clays and silts)
7. “P” is standard Proctor density (ASTM D 698, AASHTO T-99)
   “RD” is Relative Density (ASTM D 4253 and D 4254)
8. Does not apply to SP soils containing more than 50% fine sand (passing No 40 sieve)
   Consider these soils as ML soil for the purposes of this table
9. All faces of “Crushed Rock” should be fractured
**E’ increase with Depth**  There have been proposed changes to the 1977 Reclamation Table for E’ to vary with depth by Hartley and Duncan (6), and this has appeared in some design guides. A report by Howard and Howard (7), advocates that this change is not necessary and that field data indicates there is a strong linear relationship between vertical deflection and depth of cover. Over twenty case histories were studied. The correlation coefficient for a linear deflection-depth relationship for all cases ranged from 0.85 to 0.99 with an average of 0.96. While their theory is not disputed, it should be noted that the ranges in the Hartley-Duncan numbers are less than the variations that can occur in E’ due to assumed backfill density, hard or soft bedding, how close the compaction comes to the pipe (soft zone on sides), elongation due to compaction of embedment, and other inherent deflection differences due to installation.

**Emphasize Deflection – Not E’**  Any evaluation of whether an estimated pipe deflection is acceptable should be based on the calculated deflection value, not the E’ number used in the calculation. For example, a pipeline designed with an E’ of 3000 lbs/in² (21 MPa), a pipe stiffness (EI/r³) of 5 lbs/in² (1 kPa), and 20 feet (6 m) of cover at a density of 120 lbs/ft³ (1920 kg/m³), would typically have measured vertical deflections, as shown below, that range from 0.1% to 1.0% with an average of 0.5%. The maximum allowable deflection is 5%. The back-calculated E’ values would be about:

<table>
<thead>
<tr>
<th>Measured Vertical Deflection %</th>
<th>Back-Calculated E' Prime lbs/in² (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>20,000 (140)</td>
</tr>
<tr>
<td>0.5</td>
<td>4000 (28)</td>
</tr>
<tr>
<td>1.0</td>
<td>2000 (14)</td>
</tr>
</tbody>
</table>

The installation has the same soil type, the same contractor, the same time-line, same measuring equipment, and the same compaction method. Generally, the soil support at the sides of the pipe doesn’t vary 1000%. The difference in the measured deflection between 0.1% and 1.0% is simply due to the inherent variations in soils and installation procedures.

On the other hand, if the measured deflections were much higher, such as:

<table>
<thead>
<tr>
<th>Measured Vertical Deflection %</th>
<th>Back-Calculated E' Prime lbs/in² (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 (minimum)</td>
<td>2000 (14)</td>
</tr>
<tr>
<td>5.0 (average)</td>
<td>400 (2.8)</td>
</tr>
<tr>
<td>10.0 (maximum)</td>
<td>200 (1.4)</td>
</tr>
</tbody>
</table>

then something is amiss; the variation should not be this large. This difference in the measured deflection is probably due to extreme variation in the soil support at the sides of the pipe, typically due to lack of compaction.

In the first instance, the concern should not be whether a value of 4000 lbs/in² (28 MPa) or 2000 lbs/in² (14 MPa) is correct, but whether or not the pipe is estimated to deflect more than the allowable limit. At either 0.5% or 1.0%, the estimated pipe deflection is substantially less than the maximum allowable 5% deflection.
For pipe with an allowable limit of 5%, for cover of 20 feet (6 m) or less, an $E'$ of 1000 lbs/in$^2$ (7 MPa) should suffice for most installations. For over 20 feet of cover, the $E'$ should be at least 2000 lbs/in$^2$ (14 MPa); cursory testing and inspection is required. However, for pipe with an allowable deflection of only 3% or less, the embedment material must be carefully selected, and then be tested and inspected during compaction.

**COMPOSITE $E'$**

The Reclamation table of $E'$ values is only applicable when the trench walls are as stiff or stiffer than the embedment soil beside the pipe. The deflecting pipe pushes on the embedment soil which pushes on the trench wall. If the trench wall is weak, the embedment soil is not as effective. Treatments for weak trench walls have included compacting the embedment for a width of two pipe diameters on each side of the pipe, using rigid pipe rather than flexible pipe, or encasing the pipe with concrete or flowable fill. A more effective solution is to calculate a composite $E'$. In certain circumstances, a composite $E'$ can be calculated for a combination side support representing both the embedment material and the trench walls. To determine the composite $E'$, first determine the $E'$ for the embedment material, and then the $E'$ for the native material in the trench wall, referred to as $E'n$. Then use the following equation to calculate the composite $E'$ ($E'\text{com}$):

$$E'\text{com} = S \times E'$$  \[1\]

where:

- $E'\text{com}$ = composite modulus of soil reaction, lbs/in$^2$ (MPa)
- $S$ = soil support modulus combining factor from Table II, dimensionless
- $E'$ = modulus of soil reaction for the embedment material, lbs/in$^2$ (MPa)

Before using Table II to get the $S$ values, the following numbers must be determined:

- $E'n$ = $E'$ of the native soil at the pipe springline, lbs/in$^2$ (MPa)
  - from Table I using the soil classification and compaction level, or
  - from reference (9) or (4) using SPT or unconfined compression tests
- $B$ = trench width at pipe springline, inches (mm)
- $D$ = pipe diameter, inches (mm)

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.15</td>
<td>0.30</td>
<td>0.60</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
</tr>
<tr>
<td>0.2</td>
<td>0.30</td>
<td>0.45</td>
<td>0.70</td>
<td>0.85</td>
<td>0.92</td>
<td>1.00</td>
</tr>
<tr>
<td>0.4</td>
<td>0.50</td>
<td>0.60</td>
<td>0.80</td>
<td>0.90</td>
<td>0.95</td>
<td>1.00</td>
</tr>
<tr>
<td>0.6</td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>0.95</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>0.8</td>
<td>0.85</td>
<td>0.90</td>
<td>0.95</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>1.5</td>
<td>1.30</td>
<td>1.15</td>
<td>1.10</td>
<td>1.05</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2.0</td>
<td>1.50</td>
<td>1.30</td>
<td>1.15</td>
<td>1.10</td>
<td>1.05</td>
<td>1.00</td>
</tr>
<tr>
<td>3.0</td>
<td>1.75</td>
<td>1.45</td>
<td>1.30</td>
<td>1.20</td>
<td>1.08</td>
<td>1.00</td>
</tr>
<tr>
<td>5 or more</td>
<td>2.00</td>
<td>1.60</td>
<td>1.40</td>
<td>1.25</td>
<td>1.10</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table II Values of $S$ (Soil Support Combining Factor)

From AWWA Fiberglass Pipe Design Manual (9) 1996, or Howard 1996 (4)
This approach to using a composite $E'$ was first published in the AWWA Fiberglass Pipe Design Manual No. 45, in 1996 (9). The table of $S$ values was developed by a committee working on the AWWA manual and was based on work done by Leonhardt (10). The composite $E'$ also incorporates the concept that two pipe diameters of compacted embedment on both sides of the pipe are necessary if the support for the pipe must come primarily from the compacted embedment and the trench walls cannot be counted on for any support. Some references in the literature to this composite $E'$ have not given proper credit to the source, AWWA Manual 45.

**USE OF THE RECLAMATION $E'$ TABLE**

**Use Reclamation Equation, not Iowa Formula** The next section after this discusses why it is inappropriate to use the Reclamation $E'$ values in the Iowa Formula and why the Reclamation $E'$ values are only valid for use with the Reclamation Equation for estimating pipe deflection.

**Estimation of Deflection** When used in the Reclamation Equation, the Reclamation $E'$ values are used to estimate vertical deflection due to backfill load. The actual deflection is affected by the pipe elongation due to compaction, type and application of compaction equipment, construction live loads, uniformity of embedment material, and the quality of construction and inspection.

**Use Prism Load, not Marston Load** Spangler (1) used the Marston Load Equation to calculate the soil load on a buried flexible pipe when he first developed the Iowa Formula. However, a prism load was used when the back-calculated, empirical $E'$ values were developed for the Reclamation $E'$ Table. The prism load is the weight of a column of soil over a unit length of the pipe with a width equal to the pipe diameter and a height equal to the cover over the top of the pipe. Since the $E'$ values were developed using the prism load, the $E'$ values should only be used with a prism load, not the Marston load. The Marston load is less than or equal to the prism load, resulting in lower predicted deflection values. Thus, the prism load is more conservative. All design guides, manuals, and trade association literature should use the prism load when using the Reclamation $E'$ table.

**Calculated deflection** The 1977 Table was based on back-calculations of horizontal deflections. The 2006 Table is based on back-calculations of vertical deflections. As with the 1977 table, using the 2006 $E'$ values result in the initial average vertical deflection. The initial deflection is the deflection of the pipe the day that the backfill is completed. The average deflection is the deflection that is the mean of all the deflections that occur along the pipeline. Typically, the deflections along a pipeline will vary plus or minus 1 percentage points about the average, i.e. if the average deflection is 2.3%, the deflections at discrete points along the pipeline can range from 1.3 to 3.3%. The actual initial average deflection should agree with the estimated deflection within ±0.5% percentage points for high degree of compaction (and compacted crushed rock), ±1% percentage points for moderate degree of compaction (and uncompacted crushed rock), or ±2% percentage points for dumped/slight degree of compaction.
Installation E’ value  The construction of the pipeline must be consistent with the design E’ value. If the specifications require compacted Crushed Rock, E’ = 6000 lbs/in\(^2\) (42 MPa), and, instead, the contractor dumps topsoil around the pipe, the ensuing problems cannot be attributed to the Reclamation E’ table.

**RECLAMATION EQUATION**

The initial deflection, typically measured within 30 days of backfill completion, is an important value for acceptance of a pipeline project. However, the Iowa Formula technically does not predict the initial deflection. The Marston load used in the Iowa Formula to determine the load on the pipe does not occur until three to six months (or longer) after installation. Since acceptance of a pipeline relies on the initial deflection, the Reclamation Equation, using a Time Lag factor of 1.0, should be used to estimate the initial deflection since it uses E’ values that were determined from initial deflections.

The Iowa Formula is based on a deflection-lag factor, the Marston load formula, a variable bedding constant, and the result is a predicted horizontal deflection. The Reclamation E’ table is based on vertical deflection, prism load, time lag, and a bedding constant of 0.1. The Reclamation Equation is:

\[
\Delta Y(\%) = \frac{T_f 0.07 \gamma h}{EI/r^3 + 0.061 F_d E'} \tag{2}
\]

Where:
- \(\Delta Y(\%)\) = Vertical deflection, percent
- \(T_f\) = Time Lag factor, dimensionless
- \(\gamma\) = Backfill soil density, lb/ft\(^3\) (kg/m\(^3\))
- \(h\) = Depth of cover over pipe, ft (m)
- \(EI/r^3\) = Pipe stiffness, lbs/in\(^2\) (MPa)
- \(F_d\) = Design Factor, dimensionless
- \(E'\) = E prime, Modulus of Soil Reaction, lbs/in\(^2\) (MPa)

Equation 2 was first presented in this form in 1996 by Howard (4). This equation was used to back-calculate the values shown in the 2006 Reclamation Table of E’ Values, Table I.

**Time Lag**  Probably the most confusion about estimating deflection concerns the deflection lag, or time lag, values. In the original Iowa Formula, Spangler (1) presented a “deflection lag” factor that represents the increase in deflection of flexible pipe with time, conceptually as follows:

\[
\text{Deflection} = \text{deflection lag} \times \frac{\text{load on pipe}}{\text{Pipe stiffness} + \text{Soil stiffness}}
\]

What is overlooked is that the deflection lag that Spangler proposed is the increase in deflection after the maximum load is reached on the pipe. **The maximum load on the pipe**
does not occur until three to six months (or longer) after completion of backfilling. Therefore, Spangler’s suggested value of 1.5 for deflection lag is not the increase in deflection from the day that the pipe is backfilled, as is generally assumed. His value of 1.5 was the increase in the pipe deflection from when the equivalent maximum load was reached on his test pipe (typically about 6 months) to his last reading several years later. Spangler measured the load on the pipe in his experiments and knew when the maximum load had been reached. In Spangler’s experiments, the actual increase in deflection over time was about twice the initial deflection (the deflection the day that backfilling was completed). This is illustrated in Figure 1. In his experiment No. 1, the vertical deflection the day the backfilling was completed was 3.3%. About six months later, when the equivalent of his maximum load was reached, the vertical deflection was 4.3% (30% higher). Thirteen years later, the vertical deflection was 6.2%. Spangler’s deflection lag of 1.4 for this experiment was calculated by dividing the 13 year reading by this equivalent six month reading. In fact, the increase in deflection from the day of final backfilling to 13 years later was an increase from 3.3% to 6.2%, almost double.

Figure 1   Time Lag vs Deflection Lag (Spangler Test 1)

In 1981, Howard (8) used the term “time-lag” to represent the increase from the initial deflection to the long term deflection. He also presented a table of time-lag values similar to the E′ table. These values range from 1.5 to 3 and, like the E′ values, vary according to the degree of compaction and soil type. The values are based on a limited number of field measurements from studies on buried pipe where the vertical deflections were initially measured and then monitored over time. These time-lag values are shown in Reference 4 and should be used only for design purposes for estimating long term deflection.

Design Factor  A “Design Factor,” Fd, can be used with the Reclamation Equation for different purposes, depending on the need of the user. These “Design Factors” are given in Reference 4. The numbers in Table I are representative E′ values; that is, about half of the back-calculated E′ values were higher than the Table I numbers and half lower. This is why the range of deflection is a plus or minus value around the estimated average deflection. To reduce the possibility that the actual deflection will exceed the predicted value, a Design
Factor can be used. The Design Factor, $F_d$, effectively reduces the $E'$ value so that the installed deflection will not be excessive, with a certain degree of confidence. Values of $F_d$ vary according to the embedment soil classification and degree of compaction.

CONCLUSIONS

1. Based on additional studies, the 1977 Reclamation table of $E'$ values has been revised and updated. The new table is referred to as the 2006 Reclamation Table of $E'$ Values.

2. The 2006 Reclamation $E'$ Values should be regarded as presumptive values useful in estimating the initial average vertical deflection of buried flexible pipe. The values were derived using a prism load, initial deflections, and vertical deflections measured from actual field installations.

3. The $E'$ values represent the stiffness of the embedment soil placed beside the pipe and are only applicable when the trench walls are as stiff as, or stiffer than, the embedment soil. A composite $E'$ can be used when the trench walls are weaker or stiffer than the embedment.

4. The Reclamation $E'$ values cannot be used with the Iowa (Spangler) Formula. The Reclamation Equation provides a method of estimating the vertical deflection of buried flexible pipe using the Reclamation $E'$ values. The Reclamation Equation provides for time-lag factors to estimate the long term deflection and for design factors to match specific design requirements.

5. The actual initial average deflection should agree with the estimated deflection within ±0.5% percentage points for high degree of compaction (and compacted crushed rock), ±1% percentage points for moderate degree of compaction (and uncompacted crushed rock), or ±2% percentage points for dumped/slight degree of compaction.

6. The Reclamation Equation and $E'$ values estimate the deflection due to backfill load. The actual deflection is affected by the pipe elongation due to compaction, type and application of compaction equipment, construction live loads, uniformity of embedment material, and the quality of construction and inspection.

ACKNOWLEDGEMENT

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REFERENCES

1  Spangler, M. G., “The Structural Design of Flexible Pipe Culverts,” Bulletin No. 153, Iowa State Engineering Experiment Station, 1941


4  Howard, Amster, Pipeline Installation, Relativity Publishing, Lakewood CO, 1996 (amsterk@comcast.net)

5  Howard, Amster, “The 2006 Reclamation Table of E' Values,” Relativity Publishing, Lakewood CO, 2006 (amsterk@comcast.net)


7  Howard, Amster., and Bruce Howard, “Study of E’ Increase with Depth,” Relativity Publishing, Lakewood CO, 2006 (amsterk@comcast.net)

