Investigating parameters affecting buried flexible pipe behavior

Emre Akınay  
*PhD. Candidate, Yıldız Technical University, Istanbul, Turkey, emreakinay@yahoo.com.tr*

Havvanur Kılıç  
*Assist. Prof. Dr., Yıldız Technical University, İstanbul, Turkey, kilic@yildiz.edu.tr*

**KEYWORDS:** Iowa Formula, modulus of soil reaction, stiffness ratio, trench width

**ABSTRACT:** A buried flexible pipe and surrounding soils act as the elements of a system. In order to determine the behavior of a buried flexible pipe, it is not only the properties of the pipe that needs to be considered, but also the properties of the soils have to be known in detail. In this study, a series of numerical analyses are carried out with the purpose to investigate the effect of changes in (1) stiffness of embedment soil (2) stiffness of native soil and (3) ratio of trench width to pipe diameter on buried flexible pipe behavior. Both recommended short term value and adjusted value (according to load duration and temperature) of Young’s Modulus of pipe material are taken into consideration. In conclusion, it is proven that in case of using embedment soil with higher stiffness and selecting appropriate trench width by considering native soil conditions, lower vertical stress will act on the pipe crown and lesser deflections will occur.

1 INTRODUCTION

Iowa Formula (Spangler 1941) (Watkins & Spangler 1958) is widely used in order to predict the deflections of buried flexible pipes. This semi-empirical formula that gives the horizontal deflection (elongation) can be basically expressed with the Equation (1) (Moser 2008).

\[
\Delta x / D = (KPD_0) / (EI/r^3 + 0.06 E')
\]  

where \( \Delta x / D \) = horizontal deflection (dimensionless), \( K \) = bedding constant (dimensionless), \( D_0 \) = deflection time lag factor (dimensionless), \( P \) = vertical pressure acting over pipe (F/L²), \( E \) = Young’s Modulus of pipe material (F/L²), \( I \) = moment of inertia of pipe wall per unit length (L⁴/L), \( r \) = mean radius of pipe = (ave. outside diameter – 2 · ave. wall thickness)/2 (L) (ASTM D2412 – 11) and \( E' \) = modulus of soil reaction (FL²).

Modified Iowa Formula, as developed by Spangler and Watkins (1958) is presented in Equation (2).

\[
\Delta x / D = (KPD_0) / (EI/r^3 + 0.06 E')
\]  

In Modified Iowa Formula, modulus of soil reaction (\( E' \)) is a parameter representing the pipe-soil system stiffness and has a key role in buried flexible pipe design. This empirical parameter can be back-calculated only under actual field conditions, and it is not a function of soil alone but of the soil-pipe system (Hartley & Duncan 1987) (Greenwood & Lang 1991) (Watkins & Jeyapalan 2004).
Therefore, the modulus of soil reaction, back-calculated through Modified Iowa Equation, embodies all of the parameters that need to be considered.

With the purpose to investigate the effect of changes in (1) stiffness of embedment soil, (2) stiffness of native soil and (3) ratio of trench width to pipe diameter (B/D) on buried flexible pipe behavior, a series of numerical analyses are carried out by using PLAXIS V9 Finite Element Code.

2 NUMERICAL ANALYSES

Geometry of the trench was established in compliance with the ASTM D2321-11. The height of soil above the pipe crown level (i.e. burial depth) is twice the pipe diameter. The slope of the trench walls is 1H:2V. The height of initial backfill layer and bedding layer is equal to one quarter of the pipe diameter. Trench geometry is presented in Figure 2. Due to symmetrical nature, analyses are carried out on a half model.

Well-graded sand (SW) from the study of Boscardin et al. (1990) with relative compaction of 61%, 80% and 90% and poor-graded sand (SP) from the study of Sargand et al. (2002) with relative compaction of 86% are used as embedment soil. Sandy silt (ML) with relative compaction of 85%, 90% and 95% from the work of Boscardin et al. (1990) is used as native soil. In the study of Boscardin et al. (1990) triaxial test samples were prepared with the optimum water contents. Therefore, the unsaturated unit weights of the modeled soils are calculated by considering the optimum water content and relative compaction degree (Table 1).

Bedding, embedment soil and initial backfill soil are modeled with the same soils (SW61, SP86, SW80, SW90). Final backfill soil was modeled with ML95 in all analyses.

Hardening Soil Model is used as the material model in the analyses. In determining the parameters for the Hardening Soil Model, the stress-strain relationship defined with the Hyperbolic Model is taken into consideration (Duncan & Chang 1970) (Boscardin et al. 1990). The Hyperbolic Model Young Modulus parameters and Hardening Soil Model parameters of the soils are presented in Table 1 and Table 2, respectively.

The analyses are repeated for three values of trench width / pipe diameter ratio (B/D = 3, B/D = 4 and B/D = 5).

Thermoplastic pipe is chosen from the study of Arockiasamy et al. (2006) (PE36a). Engineering parameters of the pipe are presented in Table 3. Analyses are carried out for both short-term and adjusted values of the Young’s Modulus of pipe material. On one hand, short term value recommended by AASHTO is used (Table 3). On the other hand, Young’s Modulus is calculated for an average temperature of T = 77 °F (25 °C) and for a load duration of t = 10080 minutes (1 week) by using the equation developed by Sargand et al. (1998) (Table 3).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bedding + Embedment + Initial Backfill Soil</th>
<th>Native Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW61*</td>
<td>SP86*</td>
</tr>
<tr>
<td>K</td>
<td>54</td>
<td>156</td>
</tr>
<tr>
<td>n</td>
<td>0.85</td>
<td>0.17</td>
</tr>
<tr>
<td>R_f</td>
<td>0.90</td>
<td>0.82</td>
</tr>
<tr>
<td>c (kN/m²)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>φ₀ (°)</td>
<td>29</td>
<td>36.5</td>
</tr>
<tr>
<td>Δφ (°)</td>
<td>0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*Boscardin et al. (1990)
**Sargand et al. (2002)
Investigating parameters affecting on buried flexible pipe behavior
Akinay, E & Kılıç, H

Table 2. Hardening Soil Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bedding + Embedment + Initial Backfill Soil</th>
<th>Native Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW61</td>
<td>SP86</td>
</tr>
<tr>
<td>γ&lt;sub&gt;unsat&lt;/sub&gt; (kN/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>14.19</td>
<td>17.70</td>
</tr>
<tr>
<td>E&lt;sub&gt;50&lt;/sub&gt; (ref) (kN/m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>3,372.6</td>
<td>9,369.8</td>
</tr>
<tr>
<td>E&lt;sub&gt;oed&lt;/sub&gt; (ref) (kN/m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>3,372.6</td>
<td>9,369.8</td>
</tr>
<tr>
<td>E&lt;sub&gt;ur&lt;/sub&gt; (ref) (kN/m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>10,117.8</td>
<td>28,109.4</td>
</tr>
<tr>
<td>m</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>c (kN/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>29</td>
<td>36.5</td>
</tr>
<tr>
<td>ψ (°)***</td>
<td>0</td>
<td>6.5</td>
</tr>
<tr>
<td>R&lt;sub&gt;f&lt;/sub&gt;</td>
<td>0.90</td>
<td>0.82</td>
</tr>
<tr>
<td>p (ref) (kN/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>103.5</td>
<td>103.5</td>
</tr>
<tr>
<td>δ&lt;sub&gt;inert&lt;/sub&gt;</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*E<sub>oed</sub> (ref) = E<sub>50</sub> (ref) (default)
**E<sub>ur</sub> (ref) = 3E<sub>50</sub> (ref) (default)
***ψ = φ – 30 (default) (for cohesive soil ψ is assumed as zero.)

Table 3. Engineering properties of pipe (PE36a) (Arockiasamy et al. 2006)

<table>
<thead>
<tr>
<th>Property</th>
<th>Property</th>
<th>pipe material</th>
</tr>
</thead>
<tbody>
<tr>
<td>E&lt;sub&gt;short&lt;/sub&gt; (kN/m&lt;sup&gt;2&lt;/sup&gt;)*</td>
<td>HDPE</td>
<td>760,000</td>
</tr>
<tr>
<td>E&lt;sub&gt;adjusted&lt;/sub&gt; (kN/m&lt;sup&gt;2&lt;/sup&gt;)**</td>
<td>341,921</td>
<td></td>
</tr>
<tr>
<td>D&lt;sub&gt;nom&lt;/sub&gt; (mm)</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>D&lt;sub&gt;in&lt;/sub&gt; (ave.) (mm)</td>
<td>914</td>
<td></td>
</tr>
<tr>
<td>D&lt;sub&gt;out&lt;/sub&gt; (ave.) (mm)</td>
<td>1,059</td>
<td></td>
</tr>
<tr>
<td>A (mm&lt;sup&gt;2&lt;/sup&gt;/mm)</td>
<td>10.19</td>
<td></td>
</tr>
<tr>
<td>I (mm&lt;sup&gt;4&lt;/sup&gt;/mm)</td>
<td>6,555</td>
<td></td>
</tr>
</tbody>
</table>

*AASHTO (1998)
**Adjusted for T = 77°F (25°C), t = 10080 mins. (1week) (Sargand et al. 1998)

2.1 RESULTS OF ANALYSES

Horizontal deflections and vertical stress acting on the pipe crown are obtained from the analyses and the modulus of soil reaction (E') is back-calculated through Modified Iowa Formula. With the proportioning of ring stiffness (EI/r<sup>3</sup>) to soil stiffness (0.061E') the pipe-soil stiffness ratio (R<sub>c</sub>=EI/0.061E'r<sup>3</sup>) is obtained as a dimensionless parameter which characterizes the pipe-soil system.

For native soils ML85, ML90 and ML95 relationships between vertical stress acting on the pipe crown and stiffness ratio are presented in Figure 3a, Figure 4a and Figure 5a, respectively.

Vertical arching factor is obtained by proportioning vertical stress acting on pipe crown (σ<sub>v</sub>) to vertical geostatic stress (σ<sub>g</sub>) (VAF=σ<sub>v</sub>/σ<sub>g</sub>) (Adams et al. (1988) defined vertical arching factor as VAF=[σ<sub>v</sub> - σ<sub>g</sub>]/σ<sub>g</sub>). For native soils ML85, ML90 and ML95 relationships between vertical arching factor and stiffness ratio are presented in Figure 3b, Figure 4b and Figure 5b, respectively. In Figure 3, Figure 4 and Figure 5 results obtained from analyses, where short-term value for Young’s Modulus of pipe material was used, are presented. For short-term value and adjusted value of Young’s Modulus of pipe material, vertical stress acting on pipe crown are compared in Figure 6a, vertical arching factors are compared in Figure 6b.
Figure 2. Trench geometry

Figure 3. Stiffness ratio versus (a) vertical stress on pipe crown (b) vertical arching factor for native soil of ML85

Figure 4. Stiffness ratio versus (a) vertical stress on pipe crown (b) vertical arching factor for native soil of ML90

Figure 5. Stiffness ratio versus (a) vertical stress on pipe crown (b) vertical arching factor for native soil of ML95
Relationship between deflections and stiffness ratio are presented in Figure 7a and Figure 8a. It can generally be said that as stiffness ratio increases, more vertical and horizontal deflections occur. For short-term value and adjusted value of Young’s Modulus of pipe material, vertical deflections are compared in Figure 7b, horizontal deflections compared in Figure 8b.

For native soils ML85, ML90 and ML95 relationships between deflections and stiffness ratio are presented in Figure 9, Figure 10 and Figure 11, respectively. In Figure 9, Figure 10 and Figure 11 results obtained from the analyses, where short-term value for Young’s Modulus of pipe material was used, are presented.

Figure 6. Comparison of (a) vertical stress acting on pipe crown (b) vertical arching factors for short-term and adjusted value of Young’s Modulus of pipe material

Figure 7. (a) Stiffness ratio versus vertical deflections (b) comparison of vertical deflections for short-term value and adjusted value of Young’s Modulus of pipe material

Figure 8. (a) Stiffness ratio versus horizontal deflections (b) comparison of horizontal deflections for short-term value and adjusted value of Young’s Modulus of pipe material
Figure 9. Stiffness ratio versus (a) vertical deflections (b) horizontal deflections for native soil of ML85

Figure 10. Stiffness ratio versus (a) vertical deflections (b) horizontal deflections for native soil of ML90

Figure 11. Stiffness ratio versus (a) vertical deflections (b) horizontal deflections for native soil of ML95

(1) Relative displacement of pipe crown and (2) relative displacement of backfill soil (on trench wall) cause mobilization of shear strength on interfaces and upward shear forces bear a part of the vertical soil load (Positive arching phenomenon). According to this, results obtained from Figure 3, Figure 4 and Figure 5 are summarized as follows:

- As stiffness of embedment soil increases, relative displacement of pipe crown increases.
- As stiffness of embedment soil decreases, relative displacement of backfill soil (on trench wall) decreases.
- As stiffness of native soil and/or stiffness of backfill soil increase, higher shear forces are developed on backfill soil-native soil interface (on trench wall) (Figure 12).
- As the B/D ratio increases, the effect of the shear forces, developing on trench wall, on vertical stress acting on pipe crown decreases.
In this study, a series of numerical analyses are carried out to investigate the effect of changes in stiffness of embedment soil, stiffness of native soil and ratio of trench width to pipe diameter on the buried flexible pipe behavior and results obtained from analyses are evaluated. In conclusion, it is proven that (1) type and density of embedment soil, (2) type and density of native soil, (3) ratio of trench width to pipe diameter (4) pipe material (5) pipe geometry (6) load duration and (7) temperature have significant effects on buried flexible pipe behavior. According to this:

- It is a known fact that as stiffness of embedment soil increases, degree of positive arching will be higher.
- In case stiffness of native soil is low, an appropriate width for trench should be selected. The pipe should not be affected from poor (i.e. soft) native soil conditions.
- In case stiffness of native soil is high, keeping the trench width as narrow as possible provides advantage. According to ASTM D2321-11, minimum trench width shall be not less than the greater of either the pipe outside diameter plus 400 mm or pipe outside diameter times 1.25 plus 300 mm. Due to relative displacements, upward shear forces develops on backfill soil-native soil interface and these forces bear a part of vertical soil load. As trench width increases the effect of shear forces on vertical load acting on pipe crown reduces.

3 CONCLUSIONS

Results obtained from Figure 9, Figure 10 and Figure 11 are summarized as follows:

- As stiffness of embedment soil increases, lesser vertical and horizontal deflections occur.
- As stiffness of native soil increases, lesser vertical and horizontal deflections occur.
- In case stiffness of embedment soil is higher than stiffness of native soil, lesser horizontal and vertical deflections occur as the B/D ratio increases.
- In case stiffness of embedment soil stiffness is lower than stiffness of native soil, more horizontal and vertical deflections occur as the B/D ratio increases.

With consideration of temperature and load duration (time) (by means of adjusting Young’s Modulus of pipe material),

- Relative displacement of pipe crown increases.
- Vertical stress acting on pipe crown decreases, vertical stress acting on embedment soil at the sides of the pipe increases.
- As stiffness of embedment soil increases, much more vertical deflections and much lesser horizontal deflections occur.

According to results of analyses evaluated above, it is proven that deflections and stresses acting on a buried flexible pipe depend on

- The type and density of the soils (bedding layer, embedment soil, backfill soil),
- Ring stiffness of the pipe (pipe material, pipe geometry, temperature and time),
- B/D ratio.

Figure 11. Shear stress at trench wall versus depth for (a) native soil of ML95 and B/D=2 (b) embedment soil of SW61 and B/D=2

Results obtained from Figure 9, Figure 10 and Figure 11 are summarized as follows:

- As stiffness of embedment soil increases, lesser vertical and horizontal deflections occur.
- As stiffness of native soil increases, lesser vertical and horizontal deflections occur.
- In case stiffness of embedment soil is higher than stiffness of native soil, lesser horizontal and vertical deflections occur as the B/D ratio increases.
- In case stiffness of embedment soil stiffness is lower than stiffness of native soil, more horizontal and vertical deflections occur as the B/D ratio increases.

With consideration of temperature and load duration (time) (by means of adjusting Young’s Modulus of pipe material),

- Relative displacement of pipe crown increases.
- Vertical stress acting on pipe crown decreases, vertical stress acting on embedment soil at the sides of the pipe increases.
- As stiffness of embedment soil increases, much more vertical deflections and much lesser horizontal deflections occur.

According to results of analyses evaluated above, it is proven that deflections and stresses acting on a buried flexible pipe depend on

- The type and density of the soils (bedding layer, embedment soil, backfill soil),
- Ring stiffness of the pipe (pipe material, pipe geometry, temperature and time),
- B/D ratio.

3 CONCLUSIONS

In this study, a series of numerical analyses are carried out to investigate the effect of changes in stiffness of embedment soil, stiffness of native soil and ratio of trench width to pipe diameter on the buried flexible pipe behavior and results obtained from analyses are evaluated. In conclusion, it is proven that (1) type and density of embedment soil, (2) type and density of native soil, (3) ratio of trench width to pipe diameter (4) pipe material (5) pipe geometry (6) load duration and (7) temperature have significant effects on buried flexible pipe behavior. According to this:

- It is a known fact that as stiffness of embedment soil increases, degree of positive arching will be higher.
- In case stiffness of native soil is low, an appropriate width for trench should be selected. The pipe should not be affected from poor (i.e. soft) native soil conditions.
- In case stiffness of native soil is high, keeping the trench width as narrow as possible provides advantage. According to ASTM D2321-11, minimum trench width shall be not less than the greater of either the pipe outside diameter plus 400 mm or pipe outside diameter times 1.25 plus 300 mm. Due to relative displacements, upward shear forces develops on backfill soil-native soil interface and these forces bear a part of vertical soil load. As trench width increases the effect of shear forces on vertical load acting on pipe crown reduces.
• In practice, the part of bedding layer under pipe is generally maintained loose (uncompacted) in order to increase the relative displacement of pipe crown. In addition, attention has to be paid to ensure that the soil placed in haunch zone is as dense as possible. These applications are not included within the scope of this study.

REFERENCES

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