LONG-TERM PLASTIC PIPE STIFFNESS

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ABSTRACT

The parallel-plate loading mechanism (ASTM D2412 standard test method) was used for investigating the long-term pipe stiffness values of HDPE, PVC and ABS pipes. Both conventional and accelerated test procedures were used. The nominal inside diameters of the test pipes were 300 and 400mm. S-type long-term deflection curves were observed for the test plastic pipes on a semi-log scale. Long-term pipe deflection is a function of pipe material properties, pipe geometry, and external loading conditions. Load deflection rate increases with increasing pipe diameter. However, the relationship between load-deflection and different plastic pipe materials is still unclear. Long-term pipe stiffness values decrease with increasing test duration on a semi-log scale. The elevated temperature test procedure can be used as an acceleration method for estimating the long-term pipe deflection and pipe stiffness values in conjunction with the parallel-plate loading mechanism.

INTRODUCTION

Many of today's plastics were developed during and just before World War II. Some were introduced into piping systems in the 1930's. Plastic piping systems obtained wide acceptance in the late 1950's and early 1960's. Since then plastic pipe usage has increased at an astounding rate. The primary benefits associated with all of these plastic piping products are the following: sustainability, corrosion resistance, chemical resistance, low thermal conductivity, flexibility, low friction loss, long term performance, light weight, variety of jointing methods, nontoxic, biological resistance, easy identification, low maintenance. In general, thermoplastic piping is relatively flexible as compared to metal (rigid) piping. There are several types of thermoplastics, which are commonly used in the manufacture of pipe, such as Polyvinyl chloride (PVC), Acrylonitrile-butadiene-styrene (ABS), Polyethylene (PE), Polybutylene (PB), and Polypropylene (PP). Water mains, hot and cold water distribution, drain, waste, and vent (DWV), sewer, gas distribution, irrigation, conduit, fire sprinkler and process piping are the major markets for plastic piping systems throughout the world. Underground piping makes up the largest part of the market.

Three parameters are most essential in the design or the analysis of any flexible pipe installation. They are load (depth of burial), soil stiffness in pipe zone, and pipe stiffness. Among of them, external loads and surrounding soil stiffness are controlled by site conditions. However, pipe stiffness is closely related to material properties and is an important design parameter.
FLEXIBLE PIPE DESIGN

In the late 1920’s and 1930, Spangler developed a rational design procedure to predict the deflection of an installed flexible conduit. This design procedure calculated the horizontal deformation of the conduit as a function of the vertical load, the bedding support provided, and soil pressures acting laterally to resist the horizontal movement of the pipe. Based upon the assumption the pipe was sufficiently rigid, the deformed shape would be that of an ellipse, the vertical deflection assumed to be approximately equal to the horizontal. Therefore, the Spangler Equation is modified as follows:

\[ \Delta x = \Delta y = D_e K W_c / (0.149 \ PS + 0.61 \ E') \]  

where:

- \( \Delta x \) = horizontal deflection of pipe (mm),
- \( \Delta y \) = vertical deflection of pipe (mm),
- \( D_e \) = deflection lag factor,
- \( K \) = bedding constant, dependent upon the support the pipe received from the bottom of the trench,
- \( W_c \) = vertical load per unit of pipe length (N/m),
- \( PS \) = pipe stiffness (kPa),
- \( E' \) = modulus of soil reaction (kPa).

As shown in the equation, pipe approximate deflections under earth load are a function of pipe stiffness, soil modulus, and the handing and installation characteristics of a pipe during the very early stage of soil around the pipe.

The EI of a pipe is a function of the material’s flexural modulus (E) and the wall thickness (t) of the pipe. Since \( I = t^3/12 \). As such it is a fixed value for any given set of material and dimensional parameters. However, the quantities pipe stiffness (PS) and stiffness factor (SF) are computed values determined from the test resistance at a particular deflection. These values are highly dependent on the degree of deflection, for as the pipe deflects the radius of curvature changes. The greater the deflection at which PS or SF are determined, the greater the magnitude of the deviation is from the true EI value. By application of the correction factor \( C = [1 + (\Delta y/2d)]^3 \), the measured PS or SF values can be related to the true EI of the pipe as long as the pipe remains elliptical. Therefore:

\[ PS = F C / \Delta y = F/\Delta y (1 + \Delta y/2d)^3 \]  

\[ SF = EI = 0.149 r^3 (PS) \]  

where:

- \( D \) = initial inside diameter,
- \( r \) = mean radius of the pipe.
Typically, pipe stiffness (PS) at 5 and 10% deflection is determined for plastic pipe for each specimen. If specifically requested, the stiffness factor (SF) also can be calculated at 5 or 10% deflection for each specimen. At present, ASTM D2412 is the most commonly used test standard. However, PVC sanitary sewer lines have been found to continuously deflect 13 years after installation (Rinker, 2004). The long-term deflection of plastic pipes installed deep in the ground is always a concern for sewerage engineers. According to the Modified Spangler’s equation, flexible pipe deflection is a function of pipe stiffness. Therefore, the long-term deflections of HDPE pressure pipe, PVC jacking pipes, and ABS jacking pipes under the parallel-plate loading mechanism were investigated. Moreover, the change of pipe stiffness versus time for these pipes were also determined based upon the test results.

**TEST PIPES AND EQUIPMENT**

HDPE smooth wall pipe are commonly used for applications such as water mains. PVC and ABS jacking pipes are the most commonly used pipes in sewerage systems in Japan and Taiwan. Due to the flexibility of these pipes, pipes with diameter of 200 to 450 mm are used in sewerage construction. Moreover, pipes with diameter of 300 and 400 mm are the most commonly used pipes used in jacking pipe construction. Therefore, 300 and 400 mm HDPE, PVC and ABS plastic pipes were selected for the study. The typical physical properties of these pipes are listed in the Table 1. Pipe stiffness (PS) values of these pipes were determined according to ASTM D2412 standard test method. The initial pipe stiffness (Initial PS) will be used as the reference data for further analyses. Typical material properties of these pipes are summarized in the Table 2. These data are the average values based upon six sets of tests.

### Table 1 - Typical Physical Properties of the Test Plastic Pipes

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Diameter (mm)</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Mass per Length (kgf/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Outside</td>
<td>Inside</td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>300</td>
<td>317.70</td>
<td>285.30</td>
<td>16.03</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>422.21</td>
<td>378.71</td>
<td>21.38</td>
</tr>
<tr>
<td>ABS</td>
<td>300</td>
<td>316.34</td>
<td>290.61</td>
<td>12.84</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>442.29</td>
<td>401.69</td>
<td>19.88</td>
</tr>
<tr>
<td>HDPE</td>
<td>300</td>
<td>317.03</td>
<td>275.83</td>
<td>19.62</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>403.96</td>
<td>358.80</td>
<td>23.84</td>
</tr>
</tbody>
</table>

### Table 2 - Typical Material Properties of the Test Plastic Pipes

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Diameter (mm)</th>
<th>Tensile Strength (MPa)</th>
<th>Ovality (%)</th>
<th>Initial Pipe Stiffness (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>300</td>
<td>52.31</td>
<td>0.27</td>
<td>2092.04</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>50.88</td>
<td>0.89</td>
<td>2069.73</td>
</tr>
<tr>
<td>ABS</td>
<td>300</td>
<td>42.77</td>
<td>0.17</td>
<td>858.43</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>45.11</td>
<td>0.48</td>
<td>1285.94</td>
</tr>
<tr>
<td>HDPE</td>
<td>300</td>
<td>28.91</td>
<td>0.19</td>
<td>1206.75</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>27.91</td>
<td>2.06</td>
<td>970.78</td>
</tr>
</tbody>
</table>
In order to measure the long-term vertical deflection of the test pipes under constant load, a custom-made parallel-plate loading apparatus was designed and built. Dead load was used in the system. A double balance beam system was used to transfer the dead load to the parallel load plates. The transfer load ratios were 8 to 1 and 2.5 to 1, respectively. The total transfer ratio is 20 to 1. A load cell can be attached to the test apparatus to monitor the actual loading during the test as needed. Vertical deflection was measured using a LVDT with accuracy of 0.01mm. The maximum allowable deflection is 40 mm. Twelve units of this apparatus were built for conducting the standard long-term tests. These apparatuses were placed in a temperature and humidity controlled room. A closer view of the setup of these test apparatuses is shown in the Figure 1. A diesel electrical generator is connected to the electricity system to prevent any interruption of the test due to the electricity supply. HOBO U12 Temp/RH external data logger is used to trace the condition of the room. All the data were collected in a data acquisition system.

Figure 1. Setup of the long-term pipe stiffness test apparatuses.
Conducting the standard long-term test is a very time consuming process to achieve the desired test results. Therefore, a series of accelerated tests was also performed. The custom-made parallel-plate loading apparatus was placed in a temperature controlled chamber. The accelerated parallel-plate load tests were performed using different elevated temperatures up to 60°C. The setup of the accelerated test apparatus is shown in Figure 2. Based upon the test results, the relationships between pipe stiffness and test duration could be expressed in the form of one of the following equations for predicting the long-term pipe stiffness or test duration based upon the accelerated test results (Koerner et al. 1990):

\[
\log (t_f) = A_0 + A_1 T^{-1} + A_2 T^{-1} P S
\]  
(1)

\[
\log (t_f) = A_0 + A_1 T^{-1} + A_2 \log PS
\]  
(2)

\[
\log (t_f) = A_0 + A_1 T^{-1} + A_2 T^{-1} \log PS
\]  
(3)

where:

- \( t_f \) = test duration,
- \( T \) = test temperature,
- \( P \) = test load,
- \( A_0, A_1, \) and \( A_2 \) = constants.

Figure 2. Setup of the accelerated pipe stiffness test apparatus.
LONG TERM PIPE DEFLECTION

Since the test materials included HDPE, PVC and ABS pipes and the test pipe sizes consisted of 300 and 400 mm, nondimensional deflection and pipe stiffness (PS) calculated at 5.0% deflections were used for the presentation. Even the initial inside diameter and pipe stiffness are different for each type of pipe. However, the use of this term makes the presentation easier.

A series of tests were performed using different percentage of the average initial pipe stiffness (Initial PS) value determined according to the ASTM D2412 standard test method. The tests were started from high percentage of initial PS load, such as 90%, 85%, and 80%, etc. The vertical deformation of the pipes was monitored using a LVDT and the data was collected using an automatic data collection system. Each test was terminated as the vertical deformation reaching 5.0% deflection of the initial inside diameter of the pipe.

Typical pipe deflection curves for PVC 400 mm pipe under various loadings are shown in Figure 3. Since the required time to reach 5.0% deflection was quite different for various percentage of initial PS loading, the test data are presented on a semi-log coordinate system. The test duration (horizontal axis) is presented in log scale. The required time to allow the pipe to reach 5.0% deflection increased rapidly while decreasing the applied loading. The test performed using 80% initial PS loading reaches 5.0% deflection at a time near 10,000 hours. S-type deflection curves are shown in the figure on a semi-log coordinate system.

Figure 3 - Long-term deflection curves for 400 mm PVC plastic pipes.
The deflection curves under 80% of initial PS loading for HDPE, PVC 300 & 400 mm, and ABS 300 mm pipes are shown in the Figure 4. In general, these curves are almost parallel to each other. For the PVC pipes, the pipe stiffness values are about the same (around 2000 kPa). However, the curve associated with PVC 400 mm pipe shows greater deflection than that for 300 mm PVC pipe. Therefore, it is concluded that pipe deflection would increase almost proportional to the diameter of test pipe with similar initial PS value under parallel-plate loading mechanism. Based upon the PS values shown on the Table 2, the PS value for the 300 mm ABS pipe (858 kPa) is about 2.43 times less than that for 300 mm PVC pipe (2092 kPa). For the data shown on Figure 4, the deflection associated with ABS pipe is slightly greater than that for PVC pipe. The difference in deflection is only about 20% between each other. The reason for causing this behavior requires further study.

Figure 4. Long-term deflection curves for different types of plastic pipe under 80% initial PS loading.

LONG-TERM PIPE STIFFNESS

Based upon the data shown above, plastic pipe will continue to deflect under a parallel-plate loading mechanism. However, the required time to reach 5.0% deflection will increase along with decreasing the applied loading. Based upon this observation, it can be concluded that pipe stiffness would decrease while increasing the duration time under parallel-plate loading. For a series of tests for different pipe materials and diameters, the decreasing trend of PS value can be calculated for different deflection values. For the data observed in the study, Figure 5 shows
the PS values for the test pipes associated with 5.0% deflection. For a 5.0% deflection, PS data for 300 mm ABS pipes require a very long time duration. Only a few data were obtained at present and are not shown in the figure. Even 300 and 400 mm PVC pipes consisted of similar initial pipe stiffness values, however, 400 mm PVC pipe deflected much faster than that for 300 mm PVC pipe under similar load. It is implied that, for the test pipes, the deflection of 400 mm PVC pipe could be a safety concern in comparison to 300 mm PVC pipe during service life. As shown in the figure, the PS value decreases with increasing duration time on a semi-log scale for 400 mm PVC and ABS pipes and 300 mm PVC pipe with 5.0% deflection. The observation of this behavior is still on going.

![Graph](image)

Figure 5. Long-term pipe stiffness values for different types of plastic pipes.

**ACCELERATED TEST RESULTS**

The elevated temperature concept was used to accelerate the load deflection creep behavior in this study. Elevated temperatures of 40°C and 60°C were used. At present, only the accelerated tests of 300 mm and 400 mm HDPE pipes are completed. Typical time-deflection curves for 300 mm HDPE pipes tested under 40°C are plotted in a semi-log scale in Figure 6. In addition, the pipe stiffness values can be computed based upon the accelerated test results. The computed pipe stiffness values versus duration plotted on a semi-log scale at different elevated temperatures for the 300 mm and 400 mm HDPE pipes are shown in Figures 7 and 8. The pipe stiffness values were further formulated on a log-log scale with parameters of duration time, test temperature, and pipe stiffness based upon current limited test data. The calculated pipe stiffness
values based upon the developed equations (4) and (5) are shown as solid lines in the Figures 7 and 8, respectively.

\[
\log(t) = -5.44 + 9388.75 \times T^{-1} - 0.98 \times \log(PS) \quad (4)
\]

\[
\log(t) = -40.43 + 22046.40 \times T^{-1} - 3568.21 \times T^{-1} \times \log(PS) \quad (5)
\]

where:

- t = duration time (hour),
- T = test temperature, and
- PS = pipe stiffness.

Figure 6. Accelerated parallel load plate test results for 300 mm HDPE pipe at 40°C elevated temperature.
Figure 7. Pipe stiffness values for 300 mm HDPE tested at different elevated temperatures.

Figure 8. Pipe stiffness values for 400 mm HDPE tested at different elevated temperatures.
SUMMARY AND CONCLUSIONS

The long-term deflection of HDPE, PVC and ABS plastic pipes under parallel-plate loading mechanism was investigated using conventional and accelerated test procedures. The nominal inside diameters of the test pipes were 300 and 400mm. The ASTM D2412 standard test method was used in the study. The following conclusions are made based on the previous discussions:

1. S-type long-term deflection curves were observed on a semi-log scale for HDPE, PVC and ABS plastic pipes under parallel-plate loading test.
2. 300 mm and 400 mm PVC test pipes consisted of similar initial pipe stiffness values, however, 400 mm PVC pipe show an almost 35% greater deflection in comparison with 300 mm PVC pipe under similar loading conditions. The deflection rate approximately increases with increasing pipe diameter. However, the relationship between load-deflection and different plastic pipe materials is still unclear.
3. It would take around 10,000 hours for 400 mm PVC and ABS plastic pipes to reach 5% deflection under conventional parallel-plate loading test. However, it would take a very long time for the 300 mm PVC and ABS pipes to reach 5% deflection.
4. Long-term pipe deflection is a function of pipe material properties, pipe geometry, and loading conditions based upon the limited conventional parallel-plate loading tests. However, the deflection lag factor of Spangler’s formulation should not be a constant value for estimating the pipe deflection.
5. Long-term pipe stiffness values decrease with increasing test duration as plotted on a semi-log scale for the test plastic pipes.
6. A comparison of the initial pipe stiffness values between 300 mm PVC and ABS pipes, finds that the stiffness value of PVC pipe is about 2.43 times higher than that for ABS pipe. However, the deflection of ABS pipe is only about 20% higher than that for PVC pipe.
7. The use of higher test temperature for conducting parallel-plate loading test accelerates the load-deflection response for plastic pipes and reduces the test duration time.
8. The formulation for estimating long-term pipe stiffness value was developed based upon the accelerated test results at different elevated temperatures for HDPE pipes. The use of this procedure for PVC and ABS pipes is still being investigated.

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