

Physical modeling and effect of boundary conditions on buried pipe deformations

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ABSTRACT: Polyethylene pipes are commonly used in new gas distribution pipelines as well as in replacing aging pipeline systems. A laboratory test was performed on a 150-mm-diameter high density polyethylene pipe to study deformations during burial, simulating trench backfilling. The tests were performed in a sandbox with plan dimensions of 915 mm by 1220 mm. The depth of pipe burial was 760 mm, once the trench was fully backfilled. The change in vertical and horizontal pipe diameters along the length of the pipe were monitored during the backfilling process. The size of sandbox and end effects on pipe deformations during burial were investigated and the results compared with the results obtained from numerical analysis and analytical solutions. The pipe diameter changes measured during the test performed, effect of size and boundary conditions analyzed using numerical modeling, and comparative assessment of results from physical and numerical modeling are presented in this paper.

KEYWORDS: Pipe deformations, physical modeling, numerical modeling, boundary conditions, soil-pipe interaction.

1 INTRODUCTION

Buried pipelines form a critical part of gas, water, and sewer infrastructure. Flexible plastic pipes, such as polyvinyl chloride (PVC) and high-density polyethylene (HDPE), are widely used in new distribution lines and rehabilitation of aging systems. When installed underground, these pipes are subjected to soil pressures and deformation as the trench is backfilled. In contrast to rigid pipes, flexible pipes can experience more deformations under applied loads and pressures. Understanding these deformations is important because excessive deflection may compromise the pipe's capacity or damage joints.

A practical challenge in studying buried pipe behavior through laboratory models is the influence of boundary conditions imposed by the test setup. Physical model tests often use soil boxes with finite dimensions, which can constrain soil movement and induce artificial boundary effects. Rigid walls may inhibit the lateral expansion of soil and create friction along the sides of the box, altering the stress distribution around the pipe compared to actual conditions in the ground. The ends of the pipe within a box represent boundaries beyond which the soil (and pipe) are not continuous; near these ends, the pipe might experience different loads (or less confinement) than it would if it were an infinitely long embedded segment. A 150 mm diameter HDPE pipe was instrumented in a sandbox built in a laboratory to monitor its diameter change during backfilling. The box was 914 mm × 1,220 mm in plan area and provided 760 mm burial depth when filled with soil. The study showed significant "end effects" on pipe deformations: the vertical and horizontal diameter changes were uniform in the middle portion of the pipe but deviated near the box end walls, due to stress relief and arching differences close to the free boundaries. The test box width and length relative to pipe diameter were also investigated by numerical analyses to understand the boundary effects on physical model test setup and on the results obtained from those tests to identify optimal model size to obtain pipe deformations free of significant boundary interference.

Due to the viscoelastic nature of the polyethylene, the stress relaxation of the pipe during direct burial was also taken into account during the numerical modeling.

The experimental setup and procedures, including the instrumentation used to measure pipe deformations are presented in this study. The finite element modeling and analysis was used to replicate the physical model used in the lab. Then different model sizes, where boundary dimensions and conditions were varied beyond the physical limitations of the test box, were investigated.

This paper presents the pipe diameter changes measured during the test performed, effect of size and boundary conditions analyzed using numerical modeling, and comparative assessment of results obtained from physical and numerical modeling.

2 PHYSICAL MODELING

The laboratory experiments were performed in a soil box designed to model a buried pipe. The wooden test box was constructed with inside dimensions of about 914 mm in width, 1,220 mm in length, and 851 mm in depth (equivalent soil depth with weight placed on soil surface). An HDPE pipe of 150 mm nominal diameter with a standard dimension ratio of 11 was used. The physical properties of the test pipe are summarized in Table 1. The pipe was placed horizontally in the box at a burial depth of 597 mm, measured from the sand surface to the pipe's base, giving roughly 522 mm of cover to the pipe crown. The dead weights were placed at the soil surface to obtain an equivalent burial depth of approximately 760 mm. The profile and plan views of the test box are given in Figure 1. The backfill soil used in this study was classified as a poorly graded sand (SP) according to the Unified Soil Classification System (USCS). It consisted of approximately 98% sand and 2% fines by weight. The gradation parameters, coefficient of uniformity and (C_u) and coefficient of curvature (C_c), were 2.6 and 0.89, respectively. Pipeline specifications and guidelines used for design and construction typically require sandy soils under the pipe as a bedding and around the immediate vicinity of the pipes. These soils allow free drainage and uniform support around the pipe.

Table 1. Physical properties of test pipe.

Parameter	Value
Modulus of elasticity, E (MN/m ²)	900
Poisson's ratio, ν	0.4
Tensile strength, Ultimate, σ_u (MN/m ²)	34.5
Tensile strength, Yield, σ_y (MN/m ²)	22.1

Standard Proctor compaction tests, conducted in accordance with ASTM D698, were performed to establish the moisture–dry unit weight relationship. The maximum dry unit weight was found to be approximately 18.1 kN/m³ with optimum moisture content of 15%.

Both soil and pipe were instrumented to monitor performance throughout the testing program to gather data for various investigations. The instrumentation setup included four

types of devices: temperature sensors, a load cell, linear variable differential transformers (LVDTs), and clinometers.

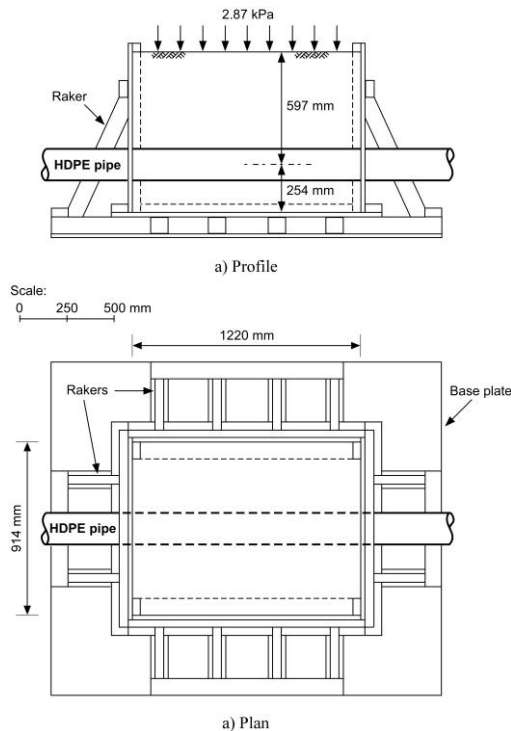


Figure 1. Schematic of model test box: (a) profile; (b) plan view.

3 NUMERICAL MODELLING

Finite element analysis (FEA) was carried out using PLAXIS 3D, a geotechnical numerical modeling software, in order to complement the physical tests and extend the investigation beyond the limitations of the laboratory test setup. The FE model geometry was designed to simulate the physical model experiment as closely as possible, including the pipe dimensions and material properties, soil properties, and relevant boundary conditions. The primary aims of the numerical modeling were: (1) to verify that the model can reproduce the key deformation measurements observed in the lab (both vertical and horizontal pipe diameter changes during burial, i.e. soil loading), and (2) to perform parametric studies by varying the test box dimensions and boundary restraints, thereby exploring scenarios not physically tested (such as larger box lengths, greater widths, or different end fixities) which might capture pipe deformations better without the influence of boundary conditions.

3.1 Model geometry and finite element mesh

In the baseline simulation, the soil domain was a rectangular prism matching the inner dimensions of the test box; i.e. 914 mm wide, 1,220 mm long, and 851 mm deep. The pipe was modeled as a horizontal cylindrical tube of 168.3 mm outer diameter with 15.3 mm wall thickness, matching the test pipe dimensions. The pipe was positioned at the same depth as in the experiment (approximately 254 mm soil depth from the pipe springline to the bottom of test box). The pipe was modeled with plate elements having elastic properties of HDPE pipe. The viscoelastic nature of the polyethylene pipe material was captured by using the relaxation modulus relevant to pipe burial duration for the elastic modulus for the pipe. The soil was modeled with a Mohr-Coulomb constitutive model representing dense sand. The soil parameters needed were chosen based on typical values for dense sand: friction angle $\phi=32^\circ$, dilation

angle $\psi=5^\circ$ (assuming some dilation at high density), cohesion $c = 1 \text{ kPa}$ (for numerical stability), and Young's modulus E of 30 MPa. The dry unit weight of the sand was set to 18.1 kN/m^3 to match the lab conditions. A three-dimensional mesh was generated with adequate refinement around the pipe to better capture the soil-pipe interaction.

3.2 Boundary conditions

The base of the soil domain (box bottom) was modeled as a rigid boundary (no vertical displacement) and no slip (fully rough contact, simulating very stiff box bottom with rough plywood surface preventing soil movements). The side walls of the soil domain in the numerical analysis were modeled as rigid vertical frictionless boundaries. The top of the soil was a free surface (atmospheric boundary). The pipe ends in the numerical model were handled carefully: Although the pipe extended about 200 mm outside at the end walls of test box in physical model, the pipe was flush with the soil domain end boundaries in numerical model. To mimic the fact that the pipelines are continues in the field and are not capped in the box, the pipe's end nodes were left free in numerical model against ovalization or movement, so the pipe could deform at the tips.

3.3 Simulation stages

The numerical analysis proceeded in two main stages corresponding to the experiment sequence:

Stage 1: Initialization of geostatic stresses. The soil weight was applied under gravity, with the pipe "wished in place" (i.e. initially the pipe was installed with a null state, then soil weight applied). This establishes the at-rest earth pressure condition in the soil box (lateral earth pressure coefficient likely close to 1.0 due to confinement in the box).

Stage 2: Pipe installation and soil backfilling. The pipe placement and backfilling by activating the pipe element in the model and applying the sand weight were performed in four steps, including the application of dead load. Applied soil heights in each lift are shown in Figure 2. The result of this stage simulated the pipe under static soil load. Any resulting deformation of the pipe was recorded – specifically the vertical diameter contraction and horizontal diameter expansion at various sections along the pipe.

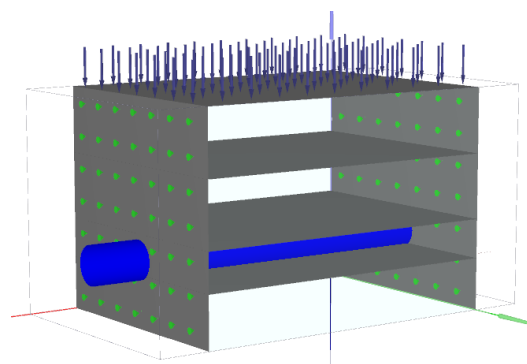


Figure 2. Backfill soil layers and load stages in PLAXIS.

3.4 Parametric variations

With the model calibrated to the baseline case, i.e. physical model test box, a series of simulations was performed to investigate the effect of model dimensions on the pipe deformations.

Box Length: The soil domain lengths (and pipe lengths) analyzed were: 610 mm (half length of the actual test box), 1,220 mm (full length of the actual test box), 2,440 mm (double

length of the actual test box), and 3,660 mm (triple length of the actual test box). This was to check if a longer pipe would exhibit different deformation in the middle compared to the measured values of 1,220 mm pipe. The burial depth and box width were kept the same as actual test box dimensions for this assessment.

Box Width: Cases were analyzed with box widths of 457 mm, 914 mm, 1,828 mm, and 2,742 mm, corresponding to test box width to pipe diameter ratios, W/D , equal to approximately 3.0, 6.1, 12.2, and 18.3, respectively. The larger widths effectively represent a semi-infinite lateral extent, as a sufficiently wide box symmetrical about the pipe can be considered in halves. In these wider cases, the side boundaries were positioned far enough from the pipe to make any frictional influence on its behavior minimal.

4 PHYSICAL VERSUS NUMERICAL MODELLING

The PLAXIS 3D finite element analysis used in this study does not directly produce time-dependent deformation data for the buried pipe under static backfilling loads. Instead, the simulation outputs correspond to discrete calculation stages, each representing a progressive application of the load. In contrast, the laboratory tests measured pipe vertical and horizontal diameter changes continuously over time during the backfilling process. In both cases, however, the loads were applied gradually at a same rate over the loading period. Therefore, the finite element analysis calculation stages were proportionally mapped to the elapsed time in the laboratory tests, effectively creating a normalized time scale. This approach allowed the vertical and horizontal diameter changes from PLAXIS to be directly compared against the corresponding laboratory measurements (Figure 3).

5 PARAMETRIC STUDY, RESULTS & DISCUSSION

5.1 Effects near pipe ends

In both the laboratory tests and the baseline PLAXIS simulation, the buried HDPE pipe exhibited the expected ovalization due to soil weight above and resulting vertical soil pressures acting on the pipe. The vertical diameter of the pipe reduced (pipe became slightly “squashed” vertically) due to soil pressures, while the horizontal diameter increased (pipe pushed outward against the soil laterally). The pipe’s diameter changes were not uniform along its length. Near the ends of the pipe (where it passed through the box walls), the vertical diameter reduction was less pronounced than at the mid-span.

The finite element analysis allowed to visualize the distribution of hoop stress and circumferential strain in the pipe. It is confirmed that the maximum hoop compression (indicating vertical squeezing) occurred in the central region. While the deformations almost the same along the buried pipe length inside the box, they gradually decreased approaching the end zones inside the box. The zone of influence was approximately 0.2 m inside the box from each end for the 150 mm pipe modelled as shown in Figure 4.

5.2 Effect of box/pipe length on pipe deformations

A set of numerical modeling was performed to investigate if the length of test box (and hence the pipe length) influenced the pipe deformation magnitudes observed at the mid-span. If the pipe was longer, would the middle section deform more (because the ends are farther and their influence smaller), or would it be similar? The numerical results indicated that box/pipe length had no significant influence on the mid-span deformations, provided the pipe length exceeded a certain threshold.

The effect of box length was examined using pipe length to pipe diameter ratios, L/D , ranging from 4.05 ($L = 0.61$ m) to 24.40 ($L = 3.66$ m). For the shortest box (i.e., $L/D = 4.05$), the reduction in vertical diameter was 0.279 mm and the increase in horizontal diameter was 0.222 mm. Extending the numerical models, i.e. increasing the pipe lengths such that $L/D = 8.10$ and 16.20 caused negligible differences in pipe deformations. Within the range investigated, reduction in vertical deformation varied between 0.275 mm and 0.279 mm and extension in horizontal deformation varied between 0.220 mm and 0.221 mm. The longest box ($L/D = 24.40$) produced values very comparable to the shortest configuration. These results suggest that box length, within the tested range, has minimal influence on pipe deformation, implying that the boundary effects at the ends are already sufficiently small at $L/D = 4$. The effect of box/pipe length on pipe deformations at mid-span are shown in Figure 5.

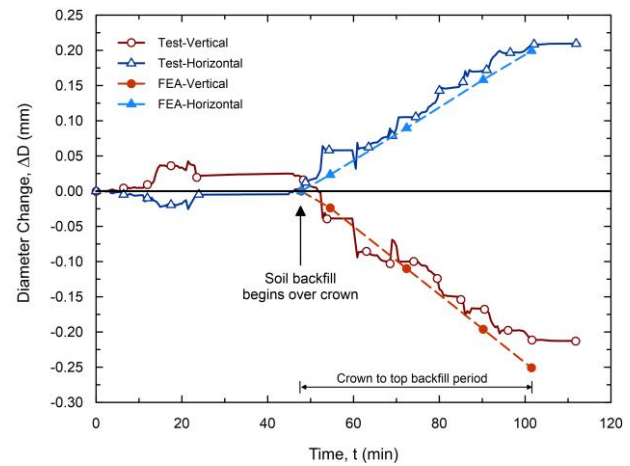


Figure 3. Lab test vs FEM results: pipe diameter change.

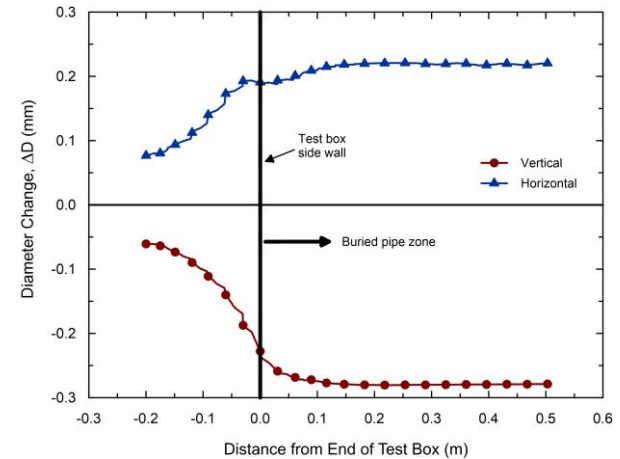


Figure 4. Pipe diameters change versus distance from end of test box.

5.3 Effect of box width on pipe deformations

The effect of the width of test box was investigated by numerical modeling and the results show that, the width of test box has a significant impact on the measured pipe deformations (Figure 6). Figure 6 shows that, in the narrow box (box width $W = 457$ mm, i.e. $W/D = 3.05$), the changes in pipe diameter were noticeably smaller than the ones buried in the wider box ($W = 1,828$ mm, $W/D = 12.2$). For example, at mid-span in the narrow box test, the vertical diameter decrease was around 0.262 mm, where in the wide box test it was about 0.284 mm. (8.4% increase in vertical deformation magnitude). The horizontal diameter increase showed a similar trend with larger

magnitudes (0.194 mm in the narrow box versus 0.226 mm in the wide box, 16.5% increase). This clearly indicates that the narrow box provided additional confinement, thereby restraining the pipe from deforming as much. The rigid walls at 3.05 diameters away likely induced a higher lateral earth pressure coefficient (K) in the soil or prevented outward movement of soil that normally accompanies pipe deflection, resulting in a stiffer system. In contrast, when the walls were moved out to a distance of 12 times the pipe diameter, the soil had more room to displace laterally and compress around the pipe, and the pipe was able to deform more under essentially the same gravity load. Figure 6 also shows that as the width of test box increases, the effect on the pipe deformations decreases. For W/D ratios at or above 10, the effect is negligible, if any.

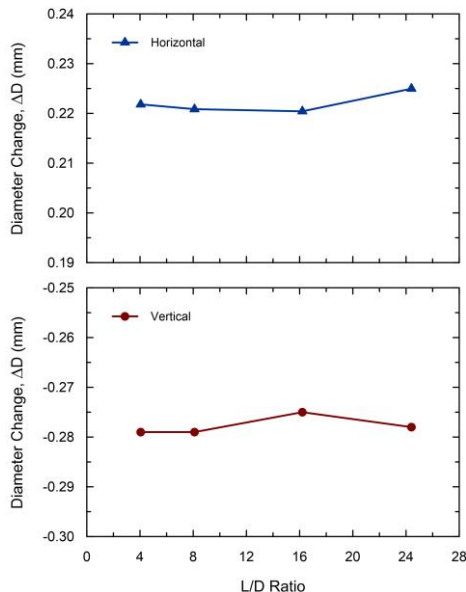


Figure 5. Influence of test box (pipe) length on pipe diameter changes.

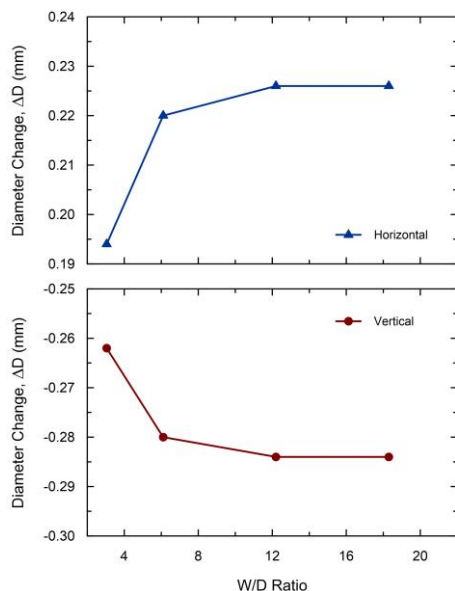


Figure 6. Influence of test box width on pipe diameter changes.

6 CONCLUSIONS

This study presented a combined physical and numerical modeling investigations into how boundary conditions affect the deformations of a buried flexible pipe. A small-scale

laboratory test on a 150 mm HDPE pipe buried in sand was used to measure changes in pipe diameter during burial, while finite element simulations using PLAXIS 3D explored variations in box size and constraints. From the results, the following conclusions can be drawn:

End Boundary Effects: Notable end effects were observed in pipe deformations within approximately 0.2 m of the boundary wall inside the test box. In these end zones, the pipe's ovalization observed in the middle part of the pipe tapered off, and the soil pressures were relieved due to the proximity of the free surface at the box ends. This is mainly because of the pipe at the edge of the wall only feels half of the applied stress from the soil/surcharge above. The central portion of the pipe (sufficiently away from the ends) experienced the maximum and uniform diameter changes.

Box Length: For the pipe and soil conditions examined during the numerical modeling, the length of the soil test box (and pipe) did not significantly influence the magnitude of pipe deformation in the mid-span region, as long as the pipe length was about four (4) times the pipe diameter or greater. A pipe section with $L/D = 4.5$ exhibited essentially the same maximum ovalization as longer sections, indicating that the central portion had reached a fully developed deformation state.

Box Width: The width of the soil box had a pronounced effect on pipe deformations. A narrow width ($W/D = 3$) provided extra confinement and arching that artificially reduced the pipe's vertical deflection and horizontal expansion. When the width was increased to $10 \times D$, the simulated pipe deformations investigated by the FEA grew to their asymptotic free-field values. Little difference was observed between $W/D = 10$ and larger widths, implying that boundary influence becomes negligible beyond about ten pipe diameters of lateral clearance. Thus, to avoid underestimating pipe deformation (or overestimating stiffness) in experiments and numerical modeling investigating pipe deformations, a model width of at least $10 \times D$ is recommended.

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