*tional Journal of Rock Mechanics and Mining Science*, Vol. 9, 1972, pp. 669–697.

17. F. Descoeudres and G. Rechsteiner. Etude des correlations entre la geologie, les propriétés mecaniques et la forabilité des roches de Crespera-Gemmo. *Schweizerische Bauzeitung*, March 1973, pp. 9–16.
18. R. Goodman, D. G. Moye, A. Van Schalwyk, and I. Javandel. Groundwater Inflows During Tunnel Driving. *Association of Engineering Geologists Bull.*, Vol. 2, No. 1, Jan. 1965, pp. 39–56.
19. P. A. Persson and R. L. Schmidt. Mechanical Boring or Drill and Blast Tunneling. 1st U.S.-Swedish Underground Workshop, Swedish Detonic Research Foundation, Stockholm, Dec. 1976.

*Publication of this paper sponsored by Committee on Tunnels and Underground Structures.*

# Experimental Study of Buried Fiber-Reinforced Plastic Pipe

NAFTALI GALILI AND ITZHAK SHMULEVICH

**An experimental study of interaction between soil and fiberglass-reinforced plastic pipes was performed in a large laboratory soil box. Seven pipe specimens of different diameters and stiffnesses were tested at various loads and under various laying conditions. Sand and clay were the soil backfill. Five different and independent sets of measurements were taken in each test: vertical and horizontal pressures in the backfill soil, normal and tangential stresses at the pipe-soil interface, radii of curvature of the pipe, vertical and horizontal pipe deflections, and hoop strains at the internal and external perimeters of the pipes. Measurements were taken during backfilling and when superimposed pressures were applied. Short-term effects of load, soil type and density, split backfill, and installation quality on pipe performance were considered. The main findings of the study are analyzed and discussed in qualitative terms.**

Flexible pipe-soil interaction has been studied extensively during the last decade. However, few experimental studies (*1, 2*) have been done on the response of fiberglass-reinforced plastic (FRP) pipes to different loads and laying conditions. Several numerical methods, all based on finite element analysis, have been developed to predict the behavior of buried pipes. These theoretical evaluations have to be proved experimentally, especially those of the range of flexible pipes the strains and deflections of which when buried may be considerably affected by uneven soil construction.

The purpose of the present study was to obtain data in well-controlled laboratory conditions as a contribution to the knowledge of the behavior of buried FRP pipes. In particular, it was intended to provide answers to some practical questions, such as the possibility of safely replacing the usually recommended granular backfill, entirely or partly ("split backfill"), by the available in situ cohesive soil and the effects of well-compacted or poorly compacted haunches.

Faculty of Agricultural Engineering, Technion-Israel Institute of Technology, Technion City, Haifa 32000, Israel.

## METHOD

### Experimental Setup

Seven pipe specimens, each 2.0 m (78.7 in.) long with outside diameters ranging from 400 to 1028 mm (15.75 to 40.47 in.), wall thicknesses of from 6.0 to 15.7 mm (0.24 to 0.62 in.), and stiffnesses ($STIS = EI/D^3$) of from 1.19 to 10.84 kPa (0.172 to 1.515 lb/in.$^2$) were tested in a large rigid laboratory soil box. A list of the tested pipes is given in Table 1. Two types of soil were used as backfill material: a fine uniform sand (SP) and a terra rossa clay (CH). Soil classifications are given in Table 2; details of the mechanical properties of the soils are given in Table 3.

TABLE 1 MECHANICAL PROPERTIES AND DIMENSIONS OF THE TESTED PIPES

| Pipe Code | Outside Diameter, $D_0$ (mm) | Wall Thickness, $t$ (mm) | Pipe Stiffness, *STIS* (kPa) |
|---|---|---|---|
| A | 400 | 6.0 | 1.35 |
| B | 618 | 8.0 | 1.19 |
| C | 1,028 | 13.4 | 1.24 |
| D | 616 | 15.7 | 10.84 |
| E | 616 | 8.2 | 1.27 |
| F | 630 | 13.5 | 5.28 |

Note: 1 mm = 0.039 in.; 1 kPa = 0.145 lb/in.$^2$.

Superimposed loads were applied to the surface of the soil backfill through a rubber membrane at the bottom of a semi-cylindrical steel cupola fixed to the top of the box and filled with pressurized air. Measurements were taken close to the midway cross section of the pipes. The measuring instrumentation included

TABLE 2 SOIL CLASSIFICATION

| Type of Soil | Uniform Classification | Specific Gravity | Liquid Limit (%) | Limit of Plasticity (%) | Plasticity Index (%) | Graduation: Percentage Passing by Weight Through Standard Size No. 4 | No. 10 | No. 20 | No. 40 | No. 100 | No. 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Clay | CH | 2.69 | 71 | 25 | 46 | 99.6 | 98.2 | 97.1 | 96.3 | 95.1 | 94.2 |
| Sand | SP | 2.66 | – | – | – | | 99.8 | 98.6 | 97.8 | 31.2 | 1.8 |

TABLE 3 SOIL PROPERTIES

| Type of Soil | Compaction Standard Proctor (%) | Angle of Friction (degrees) | Cohesion ($kN/m^2$) | Unit Volume Weight ($kN/m^3$) | Confined Modulus, *Ms* (kPa) |
|---|---|---|---|---|---|
| Sand (SP) | 85 | 29.7 | – | 14.48 | 4,100 |
| | 90 | 31.9 | – | 15.34 | 10,100 |
| | 98 | 33.7 | – | 16.70 | 18,800 |
| Clay (CH) | 80 | 14.0 | 23.1 | 13.72 | 910 |
| | 85 | 18.6 | 24.3 | 14.59 | 1,590 |

Note: 1 $kN/m^3$ = 6.24 $lb/ft^3$; 1 kPa = 0.145 lb/in.$^2$.

• Thirteen soil pressure transducers were placed in different locations in the soil box. The transducers were a commercial diaphragm strain gauge type with 88 mm (3.46 in.) sensitive surface diameter and 20 mm (0.89 in.) disk thickness. Six transducers were used to measure the vertical soil pressure distribution across the width of the soil box, 0.25 m (10 in.) above the crown of the pipe, as shown in Figure 1 (7–12 in the figure); six more (1–6) were used for measuring the horizontal soil pressure. An additional transducer (13) measured the pressure under the rubber membrane.

• Ten Cambridge-type plane-stress transducers (*3*) were used for measuring both normal and tangential stresses at the pipe-soil interface. The transducers were mounted so that the surfaces of the cells were flush with the surface of the pipe. Their location is shown in Section A-A of Figure 2.

• Twenty-four strain gauges were bonded to each pipe specimen to measure hoop strains (Section B-B in Figure 2). Special measures were taken to prevent temperature and moisture effects (*4*).

• Changes in diameter lengths were measured by a sliding, spring-loaded linear potentiometer. Two such gauges were installed in the pipe (Figure 2) to determine pipe deflections in vertical and horizontal directions. The vertical and horizontal deflections were also measured manually.

• A radius of curvature meter (RCM) was developed for measuring the radius of curvature of the deflected pipe. The RCM device consists of a commercial dial-gauge mounted on a small three-wheel carriage and moved on a premarked perspex strip that was bonded to the inner circumference of the pipe (Figure 3). This procedure was applied to ensure the correct location of the carriage

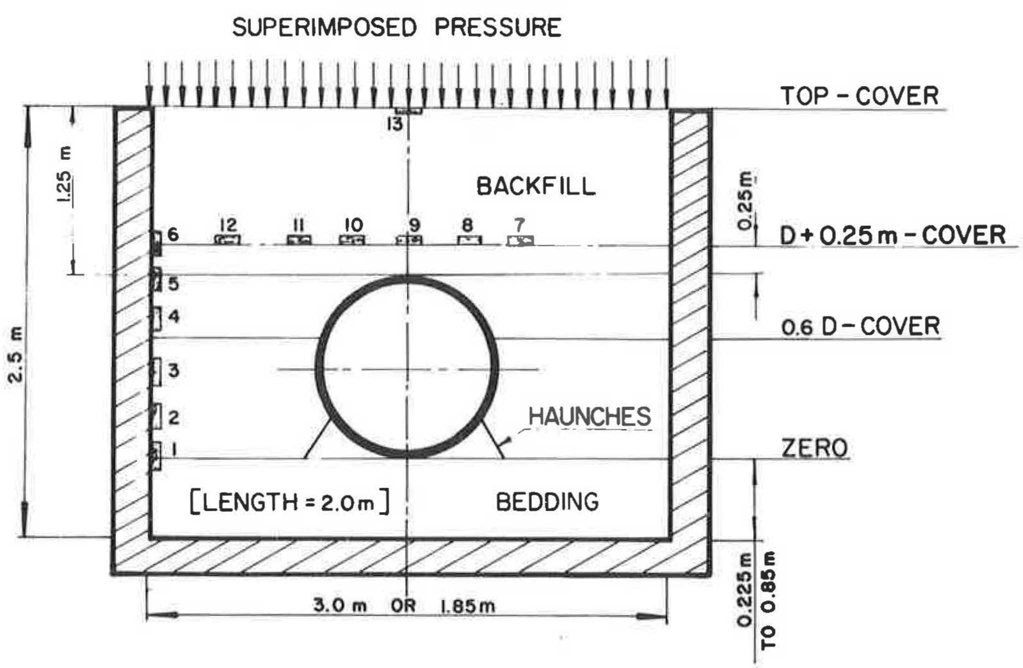


**FIGURE 1 Cross-sectional view of soil box with pipe and soil-pressure transducers.**

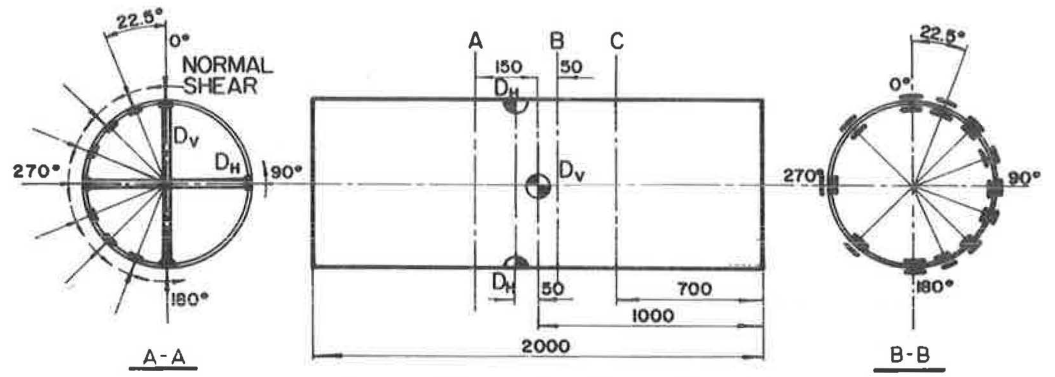


**FIGURE 2 Sections of measurement: (A) normal and tangential soil-stress transducers, (B) internal and external hoop strain gauges, and (C) radius of curvature.**

and the repeatability of the measurements. The RCM measurements were taken manually.

• A multichannel data logger system was used for calibration and recording, calculating, and storing measurements. The data were printed out and later transferred to a personal computer for further analysis.

### Testing Procedure

The pipe segments were tested in the soil box 1.85 m (72.8 in.) wide except the pipe with 1.28-m (40.47-in.) outside diameter, which was tested at a width of 3.0 m (118 in.) to simulate wide trench conditions. The testing procedure began with preparation of the bedding. In all tests the rigid bottom of the soil box was covered with a layer of fine sand of a variable thickness compacted to about 98 percent standard Proctor so that the height of cover remained 50 in. (1.25 m) for all pipes. Three installation designs were used:

• Code A: Backfill compacted in layers to a height of 0.25 m (10 in.) above the crown of the pipe and the remaining soil box height backfilled with dumped soil,

• Code B: Backfill compacted in layers up to a height of 60 percent of the pipe's outer diameter and the rest with dumped soil as in Code A,

• Code C: Dumped soil backfill from the compacted foundation to the top of the soil box.

Compaction of the backfill above the pipe foundation (Codes A and B) was carried out in layers, starting from the soil box walls and moving toward the pipe, to reach 90 percent standard Proctor for sand and 85 percent standard Proctor for clay. The dumped soil (Code C) was slightly compacted to get a uniform backill. Hence, the actual degree of compaction of the Code C backfill was up to 85 percent of standard Proctor for sand and up to 80 percent of standard Proctor for clay. The quality of the installation was defined by the degree of compaction under the haunches of the pipe. Well-compacted haunches (Code ch) and dumped haunches (Code dh) were included.

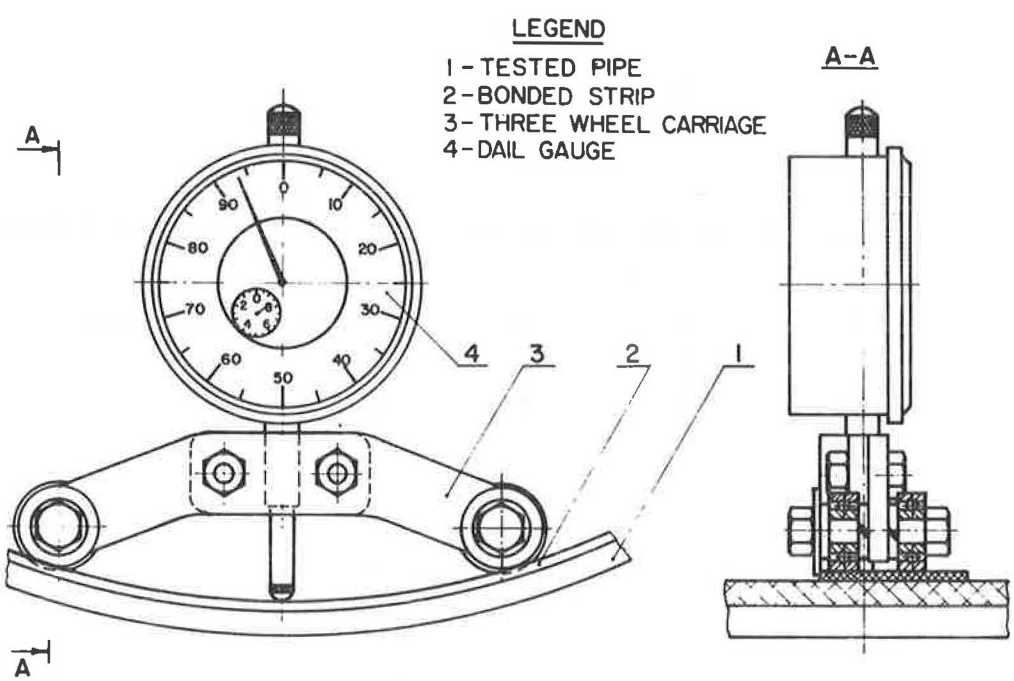


**FIGURE 3 Radius of curvature meter.**

The response of the pipe specimens to external loading was established by the previously mentioned measurements of soil stresses, pipe strains and deflections, and radii of curvature of the pipe. The measurements were recorded in eight stages in each test series:

- When the pipe was resting free on the foundation;
- When the backfill reached a height of 60 percent of the vertical pipe diameter;
- When the backfill reached a height of 0.25 m (10 in.) above crown level;
- When the backfill reached the top of the soil box, approximately 1.25 m (50 in.) above pipe crown;
- At up to four surcharge pressures of as much as 29 lb/in.2 (200 kPa) or until strain of up to 2000 microstrains was recorded.

All measurements were taken after a stabilization time of 1 hr at each stage in order to cancel short-term time effects.

## DISCUSSION OF RESULTS

A total of 21 full-scale test series were performed within the framework of the study. Seventeen of these tests were short-term ones (up to 24 hr each); in each of the remaining test series, measurements were taken during 1 month under sustained load. The main findings of the short-term study are presented and discussed.

### Normal and Tangential Stresses at Pipe-Soil Interface

Typical results of contact stresses at the pipe-soil interface are shown in Figures 4 and 5. In most of the tests soil stresses at the invert of the pipe were quite small, and vertical equilibrium of pipe load was not satisfied; this phenomenon could be the result of lifting the pipe during compaction of the bedding and backfill. For the same surcharge pressure and installation design, normal soil stresses at the pipe-soil interface were smaller in sand (Figure 4) than in clay (Figure 5) and increased with pipe stiffness. In general, tangential stresses reached up to half the magnitude of the normal ones, and therefore they cannot be ignored when soil loads are calculated. Similar results were reported in an earlier study of soil stress distribution around buried pipes (*3*).

### Vertical and Horizontal Soil Pressure Distributions in the Soil Box

Typical soil pressure distributions along the vertical wall of the soil box, and in the horizontal plane 10 in. (0.25 m) above the crown of the pipe are shown in Figures 6 and 7. It can be seen that the stiffness of the FRP pipe affects the soil pressure distributions even though it was measured at a distance of half the diameter above the pipe and one diameter from its side. In the case of a low-stiffness pipe (Figure 6) the lateral soil pressure is greater and the vertical soil pressure is smaller than in the case of the high-stiffness pipe (Figure 7). Note that sometimes sharp changes occurred in soil pressure distribution. This could be the result of local arching, poor contact between a specific transducer and the surrounding soil, or other local effects.

### Vertical and Horizontal Pipe Deflections

Vertical and horizontal diametral deflections, during installation and when surcharge pressure was applied to the top of the soil box, are shown in Figure 8. As expected, vertical and horizontal pipe deflections are greater in clay backfill and in installation design

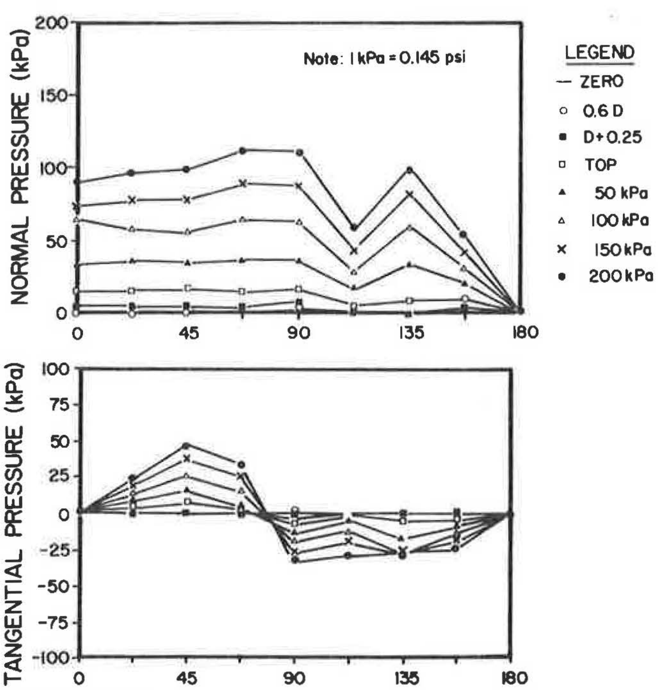


**FIGURE 4 Normal and tangential soil stresses around 4.62-kPa pipe in sand, Code B/ch installation design.**

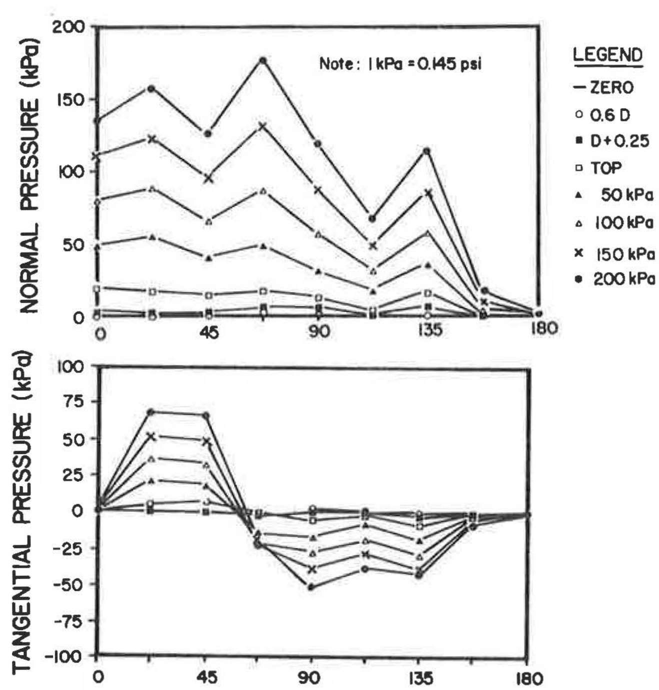


**FIGURE 5 Normal and tangential soil stresses around 4.62-kPa pipe in clay, Code B/ch installation design.**

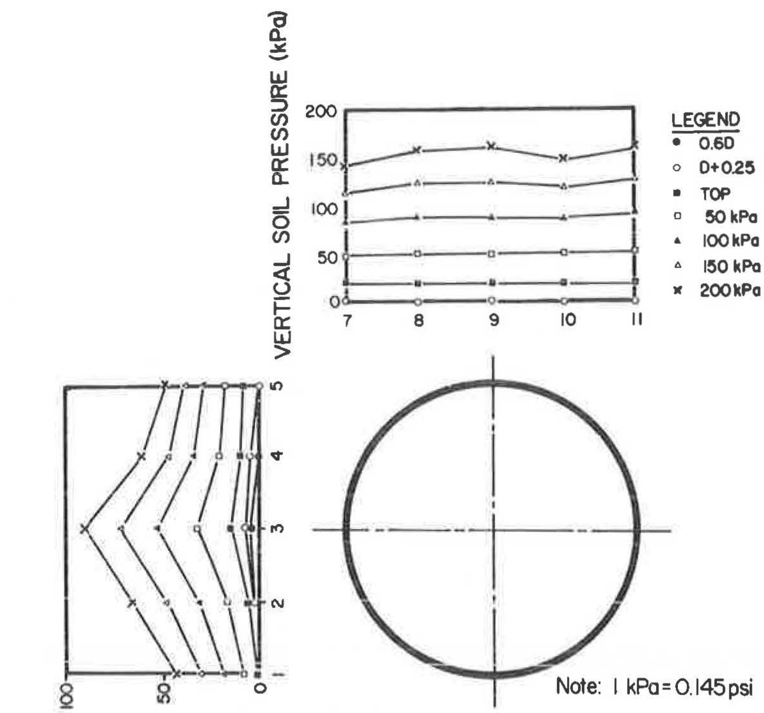


**FIGURE 6 Vertical and horizontal soil pressure in the soil box, 1.27-kPa pipe in clay, Code A/ch installation design.**

Code C than in sand and in higher-class installations. It can be seen in the figure that large initial deflections occurred in the more flexible pipe during installation (0.6*D*, Figure 8*a*). When soil construction is completed and surcharge pressure is applied, the installation deflections disappear and opposite deflections occur. When more rigid pipe and less compaction effort were applied, the initial deflections were negligible and the final deflections were relatively large (Figure 8*b*). This demonstrates that soil modulus or compaction degree affects pipe deflection more than pipe stiffness does over the tested range of relative soil and pipe stiffnesses. Proper soil compaction during installation also results in initial deflections, which are normally not accounted for in design. These

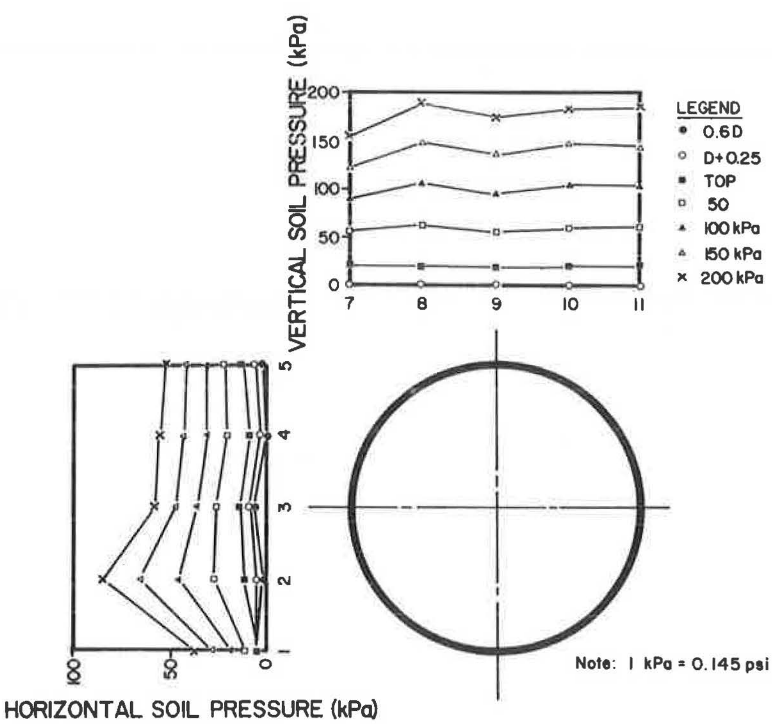


**FIGURE 7 Vertical and horizontal soil pressure in the soil box, 4.62-kPa pipe in clay, Code B/ch installation design.**

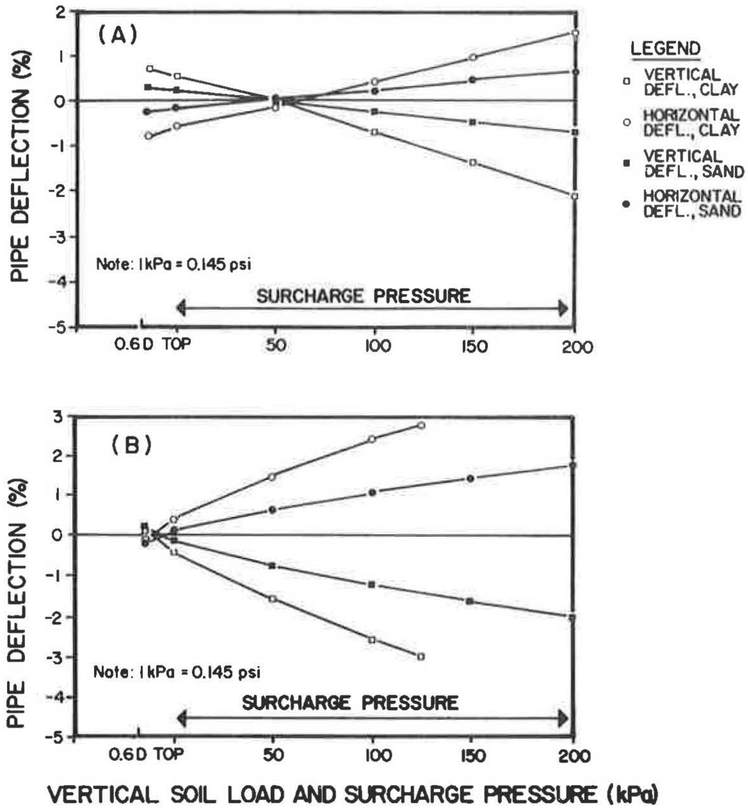


**FIGURE 8 Vertical and horizontal pipe deflections in sand and clay: (A) 5.28-kPa pipe, Code B/ch installation design; (B) 10.84-kPa pipe, Code C/dh installation design.**

installation deflections and the associated strains may contribute to better performance of the flexible pipe under full load.

### Hoop Strains in the Pipe Wall

The measured hoop strains at the inner and outer surfaces of the pipe wall are shown in Figures 9 and 10. The distribution of strains expected in relatively rigid pipes (i.e., with extreme values at crown and spring line) was found only in the more rigid pipe placed in dumped clay (Figure 9). In all of the other tests (Figure 10) strain distributions were irregular at both the inside and the outside surfaces of the pipe. This phenomenon of irregular strain distribution, including the presence of a local minimum at the pipe invert and several zero points around the pipe, was also reported in an earlier study of flexible and semirigid pipes (*4, 5*).

Another typical result of soil loading of nonpressure flexible pipes was the magnitude of the compression hoop strains induced by the surrounding soil. In all tests the compression (negative) hoop strains at any radial cross section of the pipe wall were much greater than the tensile (positive) strains at the same cross section (Figures 9 and 10). This was not found in a soil-pipe interaction study of relatively rigid asbestos-cement pipes (*5*).

### Thrust and Bending Hoop Strains

The contribution of soil loading and backfill design to hoop strains in the pipe wall is better demonstrated by the induced bending

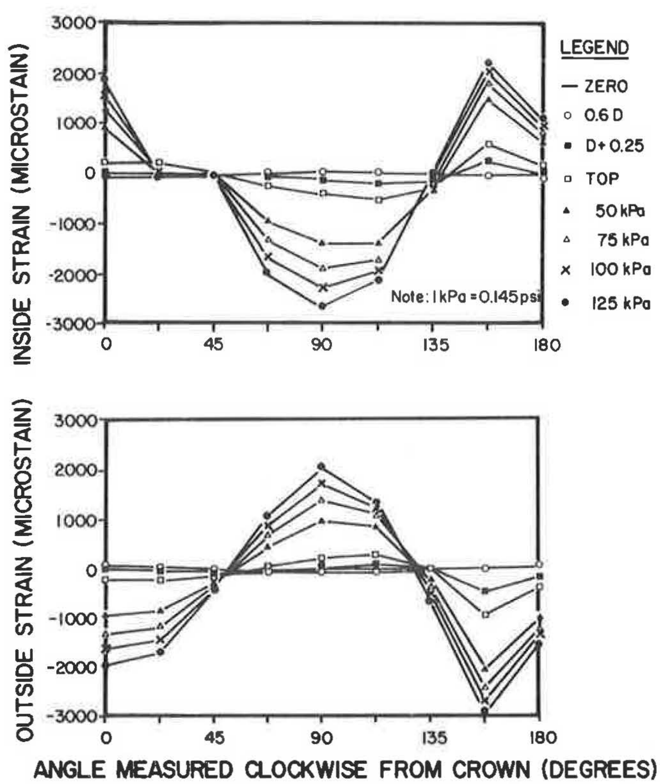


**FIGURE 9 Inside and outside strains in 10.84-kPa pipe in clay, Code C/dh installation design.**

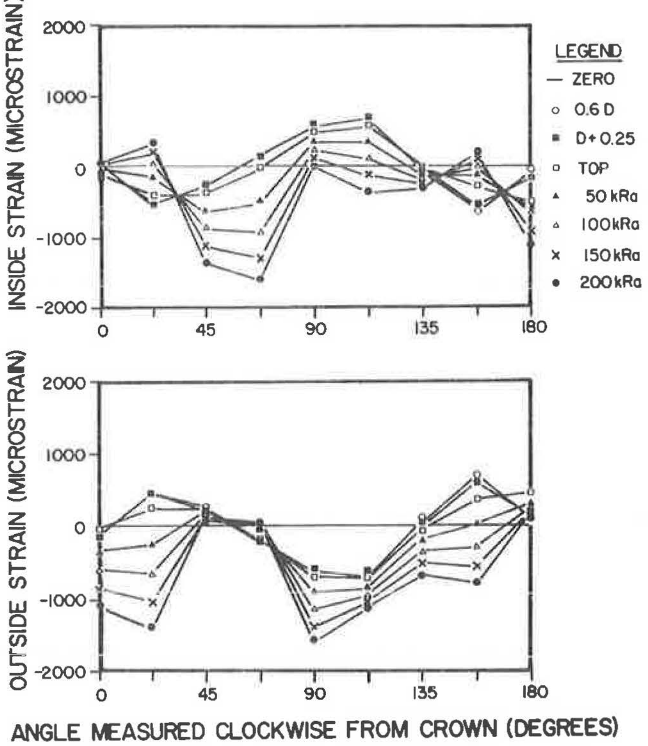


**FIGURE 10 Inside and outside strains in 1.27-kPa pipe in sand, Code B/dh installation design.**

moments. The strains ($e_{in}$ and $e_{out}$), measured at the inner and outer surfaces of the pipe, give the sum of both those due to bending moments and those due to normal thrust in the wall of the pipe. Their separation into "thrust strains" and "bending strains" was calculated from the following expressions:

$$e_{thrust} = (e_{in} + e_{out})/2 \quad (1)$$

$$e_{bending} = (e_{in} - e_{out})/2 \quad (2)$$

Two illustrative examples of these equations are shown in Figures 11 and 12, in which the inside and outside strains are separated into thrust and bending strains. The magnitude of the thrust strains in flexible pipes and the irregular distribution of the bending strains can be clearly seen. In general, thrust strains and the ratio of thrust strains to bending strains increased with decreasing pipe stiffnesses. It can be shown (*1*) that irregular distribution is caused mainly by installation strains that reduce the final opposite strains under full load. The thrust strains, which reached a level of only a few microstrains in the case of asbestos-cement pipes (*5*), are of a significant magnitude in the flexible FRP pipes.

## Installation Quality

The influence of installation quality is shown in Figure 13. As expected, better installation quality considerably reduces the hoop strains in the pipe wall. With well-compacted haunches (Figure 13*a*), maximum strains were recorded in the upper part of the pipe. The dumped haunches caused increasing strains in the lower part of the pipe (Figure 12*b*), and the maximum strains were shifted to the bedding area. However, the effect of poor haunches (or the difference between the extreme hoop stresses in the lower and the upper part of the pipe) was found to be less important in the higher stiffness ranges of the FRP pipes.

## Split Backfill

Split backfill design was investigated in three test series. The first one was performed with a pipe of 4.62 kPa (0.67 lb/in.$^2$) stiffness, and compacted sand was filled up to 0.6 of the pipe diameter (Code B) and the rest of the soil box was filled with dumped clay. The strains in the lower part of the pipe were similar to those shown in Figure 14*a*, which shows the same pipe laid in sand of Code-B backfill design. In the upper part of the pipe, the strains of the split backfill test were as much as 50 percent larger than those obtained in sand. However, the maximum strains under full surcharge load of 200 kPa (29 lb/in.$^2$) were less than 1800 microstrains.

The split backfill design of compacted sand and dumped clay was repeated in a second test (Figure 14), but with a very flexible pipe (1.27 kPa). As a result, high strains occurred at a relatively low surcharge pressure (Figure 14*a*), and the upper part of the pipe lost its circular shape. In a third test, the dumped clay above the sand level of 0.6*D* was replaced by compacted clay, up to the *D* + 0.25*M* (10 in.) level as in the Code-A backfill design. The results were impressive: the surcharge pressure was increased to its maximum value without reaching excessive strains (Figure 14*b*).

## Radius of Curvature of the Deflected Pipes

The radii of curvature, measured by the RCM, give quantitative information about the shape of the deflected pipe at any tested point. Its changes from the state of "zero load" also indicate the magnitude of the bending strain or bending moment at a specific

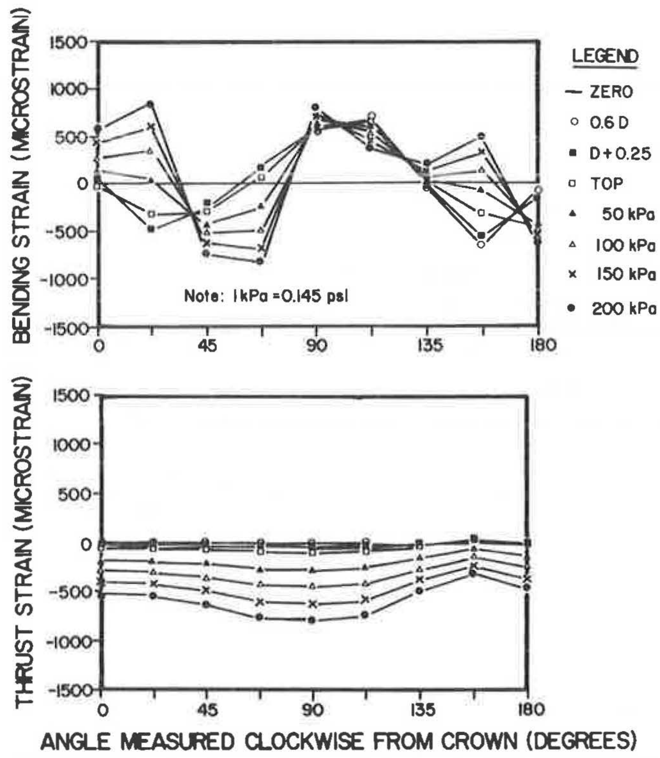


**FIGURE 11 Bending and thrust strains in 1.27-kPa pipe in sand, Code B/dh installation design.**

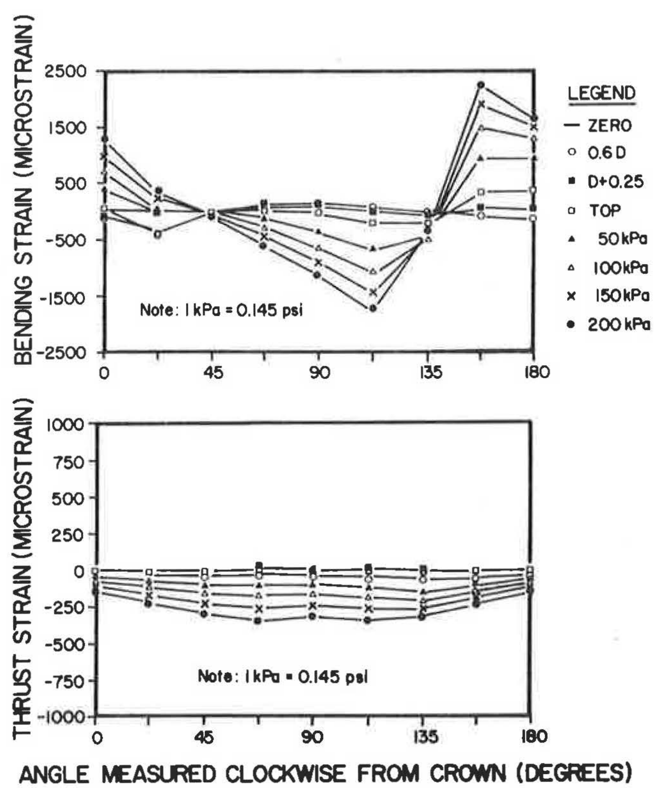


**FIGURE 12 Bending and thrust strains in 10.84-kPa pipe in sand, Code C/dh installation design.**

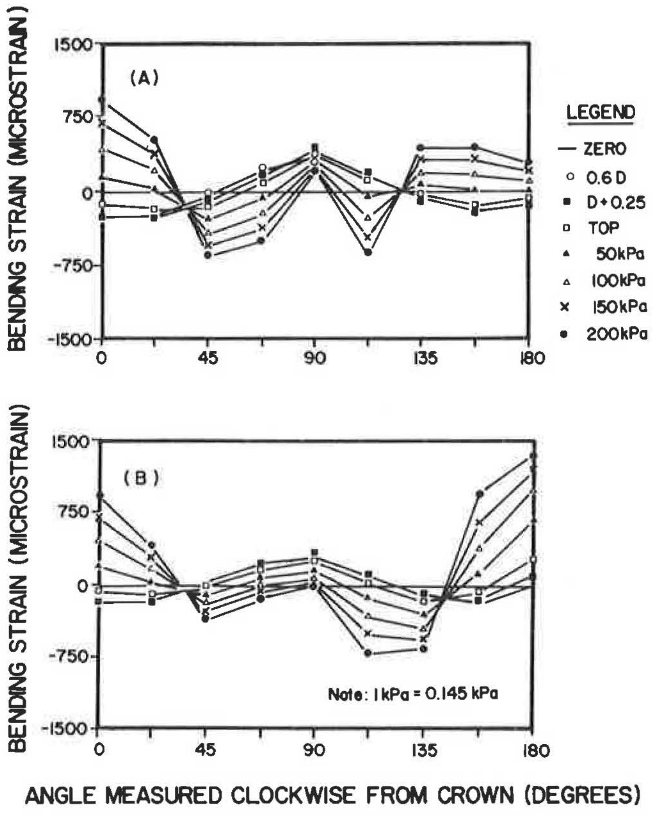


**FIGURE 13 Bending strains in 4.62-kPa pipe in sand, Code B installation design: (A) compacted haunches and (B) dumped haunches.**

point. Relatively large changes of the radius of curvature were measured during installation (0.6*D* backfill height) at the pipe spring line and invert. When backfilling was completed, the shape of the pipe was slightly rerounded. The RCM measurements also indicated whether dumped haunches were applied: the changes in the lower part of the pipe in this case were much greater than those that occurred when compacted haunches were applied. Thus the RCM served as a quick inspection tool during installation. An additional application of the RCM in cross checking strain measurements is shown in Figure 15.

### Bending Strains Calculated from Radius of Curvature

The bending strains were calculated from strain measurements by Equation 2. Bending strains were also calculated from the measured radii of curvature and their alterations due to the various loads according to the following equation:

$$e_{bending} = (1/r - 1/r_0)t/2 \quad (3)$$

where

$r$ = midwall radius of curvature of the deflected pipe,
$r_0$ = midwall radius of curvature of the undeflected pipe ("zero load"), and
$t$ = wall thickness.

The bending strains based on (*a*) the strain gauge and (*b*) the RCM measurements are illustrated in Figures 15*a* and 15*b*, respectively. Fairly good compatibility is shown between the bending strains measured by the strain gauges and by the RCM. This

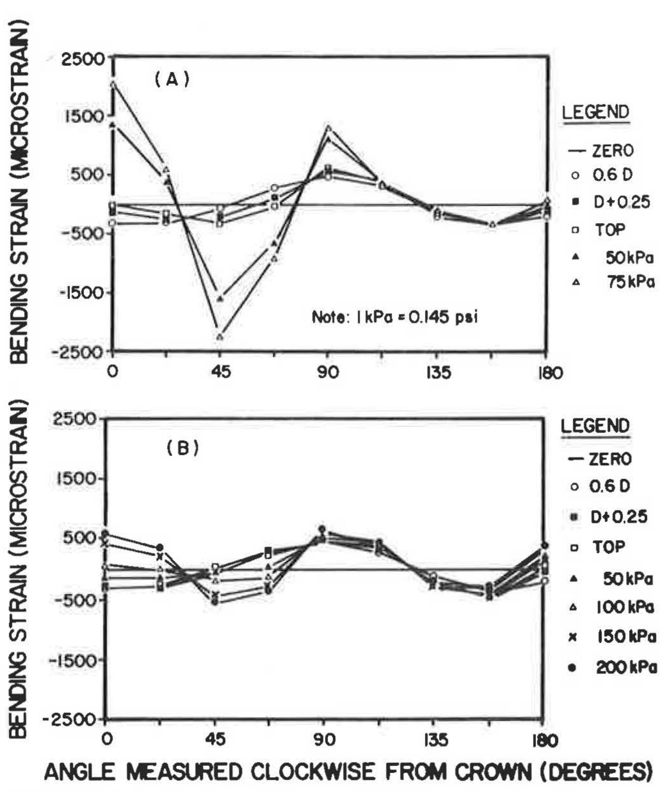


**FIGURE 14 Bending strains in 1.27-kPa pipe in split backfill of sand and clay: (A) Code B/ch installation design and (B) Code A/ch installation design.**

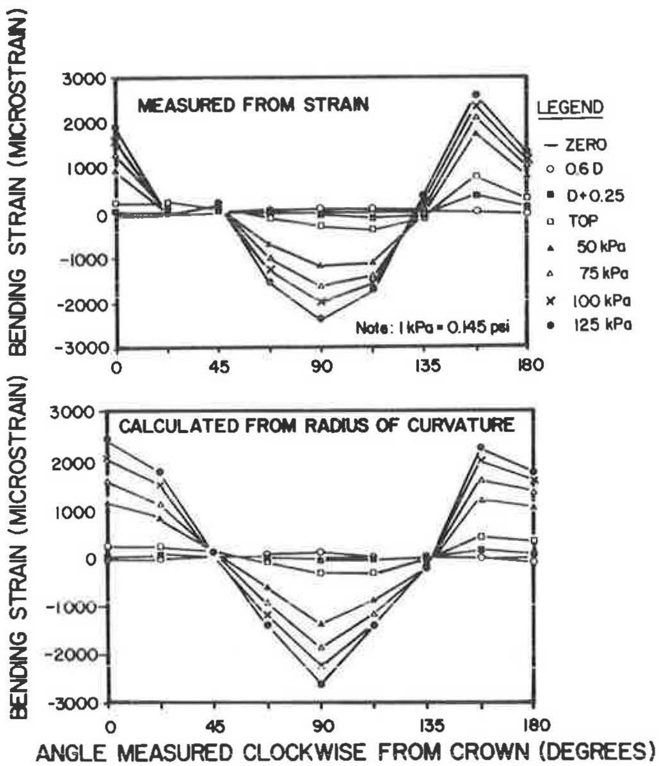


**FIGURE 15 Bending strains in 10.84-kPa pipe in clay, Code C/dh installation design, measured from strains and calculated from radius of curvature.**

compatibility, which was also found in the other tests, is of great importance as proof of the reliability of the test results. Some discrepancies between the two may be due to the fact that the two sets of measurements were taken around two different cross sections of the flexible pipe. An exception is observed in Figure 15 at an angle of 22.5 degrees from the crown. Here the discrepancy between the two measurements is due to malfunction of a strain gauge at the inner face of the pipe (see also Figure 9).

## CONCLUSIONS

The main conclusions of the study can be summarized as follows:

- For the same installation design and surcharge pressure, soil stresses at the pipe-soil interface increase with pipe stiffness and are smaller in sand than in clay. The lateral soil pressure increases and the vertical soil pressure decreases when more flexible pipe and a higher degree of compaction are applied.
- Pipe deflections are reduced considerably with increasing soil modulus or degree of compaction. Proper soil compaction during installation is also associated with initial deflections that contribute to better performance of the flexible pipe under full load.
- Strain distribution around flexible pipes in well-compacted backfill is mostly irregular and the maximum strains do not always occur at the crown of the pipe or at its invert, as would be expected from a more rigid pipe. However, proper soil compaction considerably reduces maximum strains and deformations, in spite of the irregularities.
- The thrust strains in these pipes are of a significant magnitude. In the case of the more flexible pipes, they may reach the same order of magnitude as those due to bending. As a result, the extreme hoop strains in the wall of the nonpressure pipe are compressive (negative).
- Poorly compacted haunches result in higher strains, mainly in the lower part of the pipe. This effect of poor haunches appeared to be less important in the higher stiffness ranges of the FRP pipes.
- Split backfill of sand and clay, both well compacted, was quite successful. Such a backfill might safely be applied and recommended if results of prolonged tests were available.

The experience gained during the application of the radius of curvature meter (RCM) in this study suggests that the calculation of bending strains from the RCM measurements is simple and reliable. The RCM was utilized successfully for cross-checking the data obtained from strain gauge measurements. Additional potential use of the RCM is as a quick inspection tool for proper installation.

## ACKNOWLEDGMENTS

This study was supported by the Israel Asbestos-Cement Corporation. The authors would like to acknowledge Shaul Bar-Shlomo, consultant to the pipe industry, for his assistance and fruitful contributions.

## REFERENCES

1. N. Galili and I. Shmulevich. Testing of Buried Fiberglass-Reinforced Plastic Pipes. *Composite Materials Testing and Design*. STP 787. ASTM, 1982, pp. 559–578.
2. A. P. Moser, R. R. Bishop, O. K. Shupe, and D. R. Bair. "Deflection and Strain in Buried FRP Pipes Subjected to Various Installation Conditions." In *Transportation Research Record 1008*, TRB, National Research Council, Washington, D.C., 1985, pp. 109–116.
3. I. Shmulevich, N. Galili, and A. Foux. Soil Stress Distribution Around Buried Pipes. *Journal of the Pipeline Division*, ASCE, forthcoming.
4. N. Galili, I. Shmulevich, S. Bar-Shlomo, and A. Foux. *Soil-Pipe Interaction, Stages I and II, Final Report*. Publication 291. Agricultural Engineering, Technion City, Haifa, Israel, Nov. 1978.
5. I. Shmulevich and N. Galili. Deflections and Bending Moments in Buried Pipes. *Journal of the Pipeline Division*, ASCE, forthcoming.

*Publication of this paper sponsored by Committee on Culverts and Hydraulic Structures.*