Some Observations on Flexible Pipe Response to Load

C. D. F. Rogers

The response of 160-mm-diameter shallow-buried unplasticized polyvinylchloride pipes to surface loading has been investigated in full-scale experiments in a reinforced box. Standard installation and loading conditions were adopted. Measurements of pipe-wall strain and pipe deformation were taken to determine the influence of the surrounding soil on the mode of pipe deformation. The shape of the pipes when deformed varied with the stiffness of the soil at each level within the trench. Pipe deformation in soils offering little support was roughly elliptical, whereas in stiffer soil configurations the deformation deviated markedly from elliptical. In addition, the deviation from an ellipse was far more pronounced under static loading, subsequent cyclic loading causing an additive component of elliptical deformation. Four deformation modes have been isolated and data from other researchers have been included to confirm the observations. A clear relationship between pipe-wall strain and vertical diametral strain was found, indicating that inference of deformation from strain gauge measurements is possible if care is used. The assumption of elliptical pipe deformation in both theoretical and experimental work on flexible pipes should be avoided and allowance for significant deviations from an ellipse should be made in predictions of deformation measurement.

Pipelines are currently used for transportation, communications, and the supply and removal of fluids on a vast scale. A large quantity of new pipeline is being installed and, perhaps more pertinently, a considerable amount of existing pipeline is being replaced annually, thus emphasizing the need to understand fully the behavior of such pipelines in use. This in turn provides the information required to successfully design and construct a suitable infrastructure for future generations.

The fundamental engineering requirement of a pipeline is that it should retain a suitable size, shape, direction, and degree of integrity for as long as it is in use. This requirement can be met by relatively rigid pipes that have inherent strength and require only a suitable bedding layer, or by relatively flexible pipes that deform under load and thereby derive support by composite action with the surrounding soil. The distinction between rigid and flexible pipes has become less important with the advent of pipes of intermediate flexibility and greater attention is being paid to the fill materials used to surround pipes. Pipeline design therefore requires an appreciation of the composite response of the pipe and soil, and various design methods of varying sophistication have been proposed to account for this.

Prediction of flexible pipe performance has presented a challenge ever since Spangler (*1*) presented his classic work on deformation prediction. In the development of his theory, Spangler assumed the deformed shape of a flexible pipe to be elliptical, based on observations of large-diameter corrugated steel culverts. This assumption has recurred in many subsequent theories of behavior, either explicitly or implicitly, and has resulted in vertical deformation, or vertical diametral strain (VDS), being the critical performance parameter to be measured in experimental work. A number of researchers have recorded a deviation from elliptical behavior under certain circumstances, notably Howard (*2*), who refers to rectangular deformation.

A program of full-scale experiments was conducted at the University of Nottingham on 160-mm-diameter shallow-buried unplasticized polyvinylchloride (uPVC) pipe under conditions simulative of building drainage. As part of this program, instigated and sponsored by the British Plastics Federation, a series of experiments was conducted in a reinforced box to determine the influence of the surrounding soil on the magnitude and mode of pipe deformation. In particular, measurements were taken of pipe-wall strain and the deformation profile of the pipe under load. The aim of this paper is to examine the cause of deviation of the deformed profiles from an ellipse, based on the findings of these experiments and confirmed by research data published in the literature.

The terminology shown in Figure 1 is used when discussing the experimental results. Diametral strain is defined as the change in the diametral measurement divided by the original diameter.

PREVIOUS OBSERVATIONS OF SHAPE OF DEFORMATION

Howard (*2*) reports the results of experiments in a 2-m cubic box in which unlined steel pipes of various diameter and wall thickness were buried in clay at different densities and were subject to uniform surface pressures. Elliptical deformation, characterized by plastic hinges developing at 90 and 270 degrees (the pipe springings), tended to occur in the stiffer pipes, whereas more flexible pipes deformed rectangularly with plastic hinges developing at 45, 135, 225, and 315 degrees. The ratio of horizontal to VDS (diametral strain ratio) for elliptical pipe deformation was in the range 0.8 to 0.9 (a perfect ellipse would give 0.91) and for rectangular deflection was between 0.6 and 0.8. The deflected form was predicted from strain gauge readings, which showed high compressive strains on the internal surface at the critical points.

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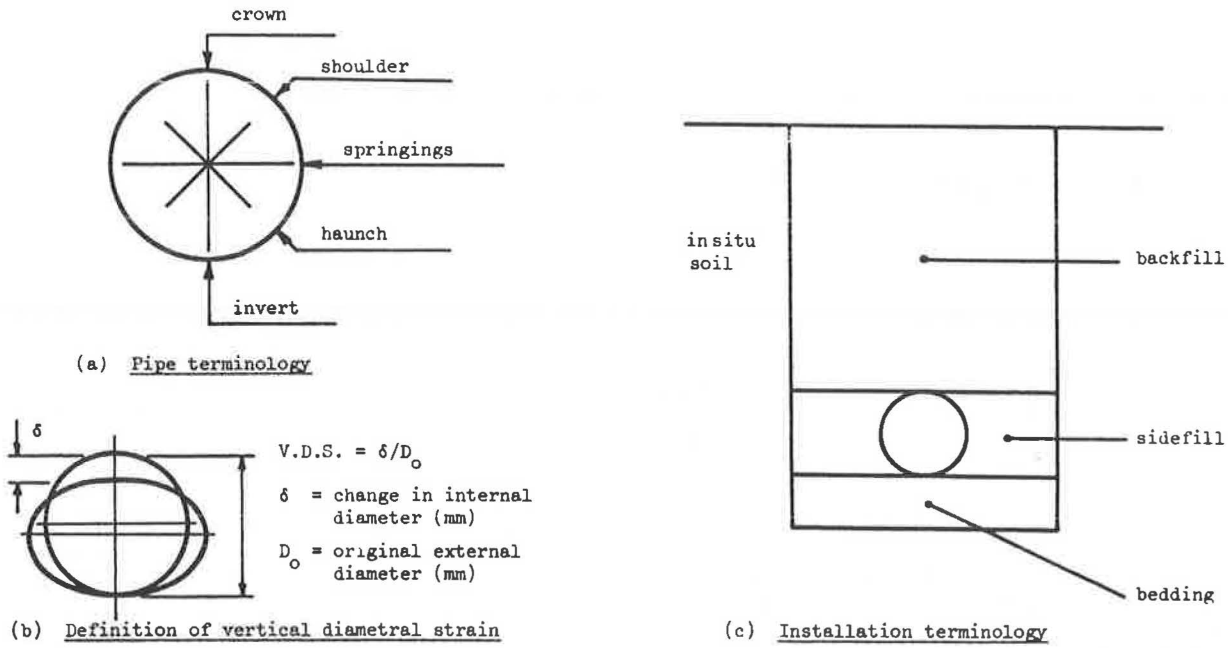

FIGURE 1 Terminology and definitions.

This series of tests was extended to include plastic pipes and is reported by Howard (*3*). For uPVC pipe, the diametral strain ratio implied a departure from purely elliptical deformation at an early stage of the test. This was verified by the internal pipe-wall strain profiles, from which Howard describes the deformation as semielliptical.

In a later paper, Howard (*4*) reiterates the variation in deformed shape and associates rectangular deformation with large ratios of soil to pipe stiffness. When pipes have deformed rectangularly, the horizontal diametral strain is found to be much less than the VDS. Howard considers that elliptical deformations may be expected for dumped and lightly compacted sidefills, but that the deformed shape of pipes in moderate or highly compacted sidefill will depend on the stiffness of the pipe.

Broere (*5*) reports experiments on uPVC pressure pipes in practice. Eight 500-mm-diameter uPVC pipes were buried under distinctly different conditions and deformation was measured using 36 strain gauges equidistantly spaced around the external circumference of the pipe. Broere describes the deformation of the pipe in uncompacted sand as being elliptical in the upper half of the pipe and that corresponding to deformation between two flat plates in the lower half. He ascribes this behavior to the hard trench bottom's providing a linear support to the pipe, which produces an exaggerated peak stress at the invert. The pipe deformed more in the lower half than the upper half of the pipe. Little deformation occurred in compacted sand. In compacted clay, the strain gauge pattern is described as elliptical in both the upper and lower halves, though with more deformation above the springings. In uncompacted clay, deformation is described as elliptical in the upper half and somewhere between elliptical and flat plate deformation in the lower half (the trench bottom was relatively soft). Greater deformation occurred below the springings because the soil was considered to be looser around the haunches than the shoulders.

Soini (*6*) describes field measurements of plastic pipes using a pipe cruiser to describe the deformed profile. In order to calculate the tangential strain in the pipe wall from the measured ring deformation, a factor (k) is applied to account for the shape of the deformed pipe. Where deformation is elliptical the value of k will be 3.0, and values for pipes in general use have been thought by Scandinavian researchers to range from 3.0 to 6.0 because of variations in deformed shape. Results obtained by the Pipe-Cruiser indicate that this variation in shape is considerably greater than supposed, with values of k ranging from 2.85 to more than 10. However, no description of the variation in shape is given.

EXPERIMENTAL PROGRAM

The aim of the experimental program was to investigate the performance of small-diameter uPVC pipes when buried at shallow depth in a 500-mm-wide trench. Surface load was applied to simulate the passage of site construction traffic. The main series of experiments was conducted in a large pit and these have been described by Rogers (*7*). A further test was conducted in which a line load was applied across the pipe. A second series of experiments was conducted in a reinforced box, having constant boundary conditions, in order to gain comparative data, and these are reported herein.

The box was 750 mm long, 500 mm wide, and 550 mm deep, with a depth of cover to the pipe of 250 mm. Load was applied to the surface of the backfill through a 480-mm-diameter rigid platen, which represented the load caused by the rear wheel arrangement of a construction truck passing approximately 500 mm above the pipe crown. This loading condition was more severe than that of the main program of tests and was adopted to produce significant deformations in the pipes. Over the surface of the clay not covered by the platen, a dead load was applied to simulate 500 mm of soil

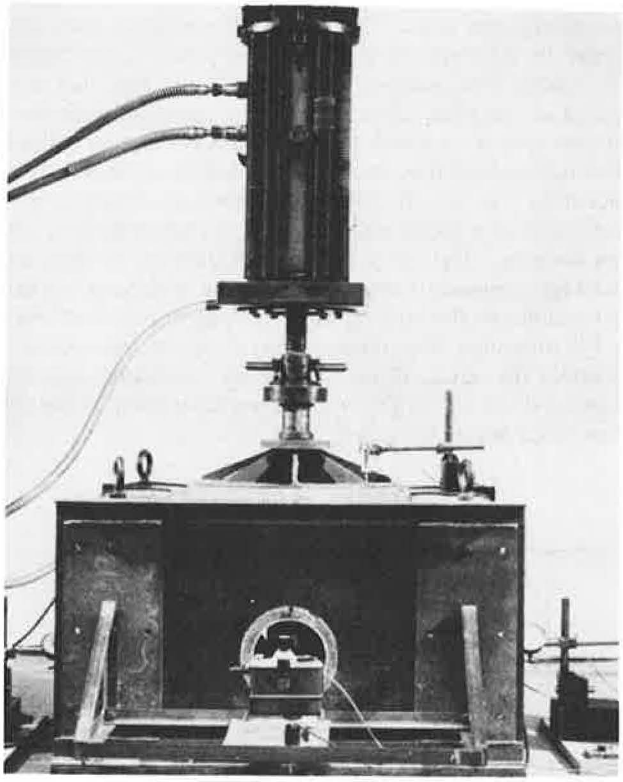

FIGURE 2 The test box.

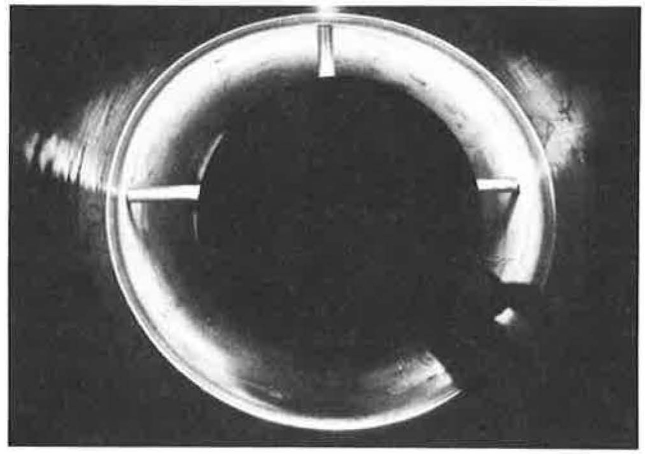

FIGURE 3 A ring flash photograph.

cover. This equipment is shown in Figure 2 with the dead load removed for clarity.

Howard (*2*) showed that where a trench-width-to-pipe-diameter ratio of 4.67 was used for his experiments, the pressure cell readings on the box wall on the horizontal axis of the pipe were the same as those 600 mm above the horizontal axis. This implied that the box walls had no influence on the behavior of the pipe. When a ratio of 3.50 was used, the lower pressure cell consistently recorded higher stresses on the horizontal axis, indicating an external influence. Dezsenyi (*8*) quotes a limiting ratio of 5.0 beyond which the container walls have no influence. In the experiments quoted herein, the ratio was 3.2, which implies that the box walls do influence pipe behavior. This should be taken into consideration when attempting to measure absolute, as opposed to comparative, performance from the results.

The deformed shape of the pipe was recorded throughout each test using a ring flash camera developed at the Transport and Road Research Laboratory. The ring flash head was mounted on a boom and inserted into the pipe below the load platen. The head, which appears as a silhouette to provide a datum measurement, produced a thin band of light, which was recorded photographically (Figure 3). Diametral change and shape of deformation were measured from the sequence of photographs. Vertical diametral change was also recorded by a linear potentiometer mounted on a sledge. Internal pipe-

TABLE 1 DETAILS OF EXPERIMENTAL INSTALLATIONS IN THE BOX

Reference	Bedding Type	Bedding Thickness (mm)	Sidefill Type	Sidefill Compaction	Comments
1	Pea gravel	100	Pea gravel	None	Standard practice
2	Pea gravel	50	Pea gravel	None	
3	None	0	Pea gravel	None	
4	Pea gravel	50	Pea gravel to springings, silty clay above	None None	Support to mid-height of pipe only
5	None	0	Pea gravel to springings, silty clay above	None; thorough	Split sidefill
6	None	0	Silty clay to springings, pea gravel above	Thorough; none	Split sidefill
7	None	0	Silty clay to crown, pea gravel 50 mm above	Thorough; none	Arching layer over 9
8A and 8B	None	0	Silty clay to springings, pea gravel to 50 mm above pipe crown	Thorough; none	Arching layer over 6; 8*A* had low water content, 8*B* high
9	None	0	Silty clay	Thorough	
10	None	0	Silty clay	Thorough	Compacted in 2 layers
11	None	0	Silty clay	Light	
12	Pea gravel	100	Silty clay	Thorough	
13	None	0	Concrete ballast	Light	
14	None	0	Concrete ballast	None	
15	None	0	Reject sand	Light	
16	None	0	Reject sand	None	

wall strains were measured in the circumferential direction by eight equally spaced single active strain gauges glued directly to the wall of the pipes.

Keuper marl (a silty clay having a liquid limit of 32 percent and a plastic limit of 19 percent) was used as backfill, the side fill and bedding consisting of distinctly different soils (Table 1). In addition to standard installation configurations, relatively good (pea gravel) and poor (silty clay) soils were juxtaposed around the pipe in order to isolate the critical areas of soil support. Pea gravel is a uniform rounded 10-mm gravel, concrete ballast is a well-graded aggregate of medium sand to medium gravel, and reject sand is a well-graded silty sand. Grading curves for these soils are given by Rogers (*7*). The pipes were 160-mm diameter with a standard dimension ratio (diameter-wall thickness) of 41 and were manufactured to the British Standard.

Silty clay was compacted to form a flat trench bottom at the appropriate level. The bedding layer, when used, was spread to the required depth and the pipe was positioned. The sidefill was carefully placed beside the pipe and compacted as specified. Three levels of compaction were used: no compaction, in which the material was dumped and leveled; light compaction, in which the sidefill was carefully compacted by foot after leveling; and thorough compaction by two passes of a pneumatic tamper with a single head of 125-mm diameter. The box was then backfilled in one layer and thorough compaction was applied to the surface of the clay 250 mm above the pipe crown. Readings of pipe-wall strain and deformation were taken at every stage of installation to ascertain the effects of the installation procedure, including negative diametral strain, or diametral elongation, as soil was compacted beside the pipe.

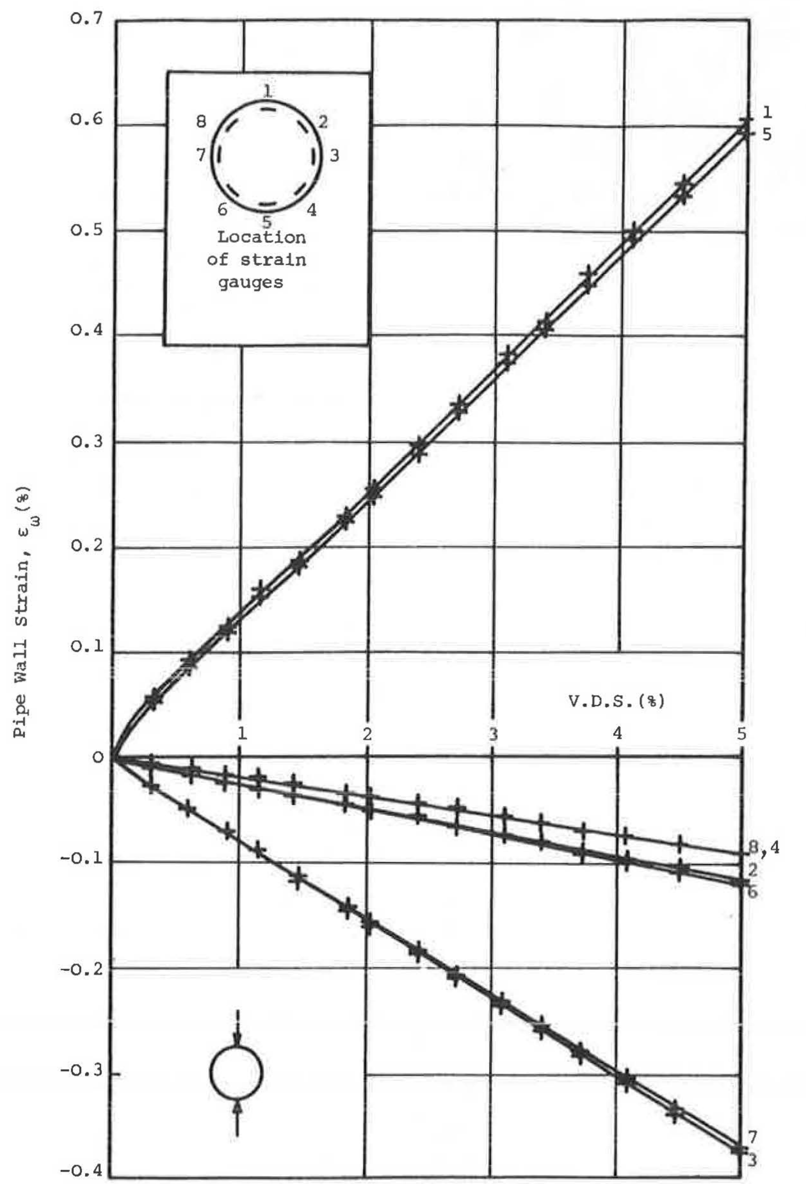

FIGURE 4 Graph of pipe-wall strain against VDS for unconfined line load test.

Surface loads of 5.5 and 7.0 tonnes were applied both statically and cyclically to each experimental installation. The lower load was applied statically for 30 min, was removed for 45 min, and was then cycled 150 times at approximately 12 cycles/min. After 150 cycles of load, the pipe deformation was found to have stabilized. The installation was allowed to recover for 2 hr before the process was repeated with the higher load, the final recovery period being at least 18 hr. Readings were taken throughout the loading sequences and recovery periods. In cases where excessive deformation occurred during the loading sequence, the test was prematurely terminated to avoid equipment damage.

EXPERIMENTAL RESULTS

Although many readings were taken during the test program, only those relating to pipe-wall strain and deformation will be presented herein. Further information is given in Rogers (*7*) and Rogers et al. (*9*). Circumferential strain was measured at 45-degree intervals around the internal surface of the pipe. These data have been presented in either linear or circular plots of the strain profile. Where comparisons have been made between installations, the data have been extrapolated to those that would occur at 5 percent VDS, assuming a linear relationship, and an average strain was taken for linear plots, assuming symmetry about the vertical axis. The sign convention adopted throughout this paper is that tensile strains are positive and compressive strains are negative.

The relationship between pipe-wall strain and vertical diametric strain (VDS) in the unconfined line load test (Figure 4) was linear for each gauge up to 5 percent VDS. Pipe-wall strain profiles at integer percentages of VDS during this test are plotted on a circular axis in Figure 5, from which their elliptical nature can clearly be seen. When the same data were averaged and plotted on a linear axis (Figure 6), a clearer description of the relative magnitudes of strain was apparent. It may be concluded, therefore, that the deformed shape of the pipe was an ellipse, as expected. In addition, the deformed shape of the pipe could be predicted from the strain profiles.

The influence of surrounding the pipe in various soils and applying surface load (Tests 3, 10, 13, and 15) is shown in Figure 7, in which the permanent strains at the end of the test have had the somewhat variable installation effects removed before extrapolation to those that would occur at 5 percent VDS. The tests using the clay and sand sidefills were terminated after the 70 kN static load and the 55 kN cyclic load sequences, respectively. In general, compaction of the sidefill caused diametral elongation of an approximately elliptical nature, the precise shape depending on the level at which the compaction was applied. The effects of diametral elongation on deformation are discussed by Rogers (*7*).

All four curves conformed to the same approximate pattern, with high tensile strain in the pipe crown and equal and opposite strains at the springings (compressive) and invert. The curve for pea gravel exhibited the greatest deviation from the V-shaped pattern, with the highest pipe crown and shoulder strains and the lowest strain at the haunches. Howard (*3*) demonstrated that elliptical deformation is associated with a V-shaped, rather than elliptical, pipe-wall strain profile when the pipe is buried because of the resistance to movement of the side of the pipe. It can be concluded from these data, therefore, that the deformation of the pipes at the end of the tests was approximately elliptical, with the pipe in pea gravel showing a tendency to flatten at the crown and bulge slightly at the shoulders. It should be noted at this point that the amount of deformation of the pipe associated with these profiles is between 5 and 11 percent and the deviations from an

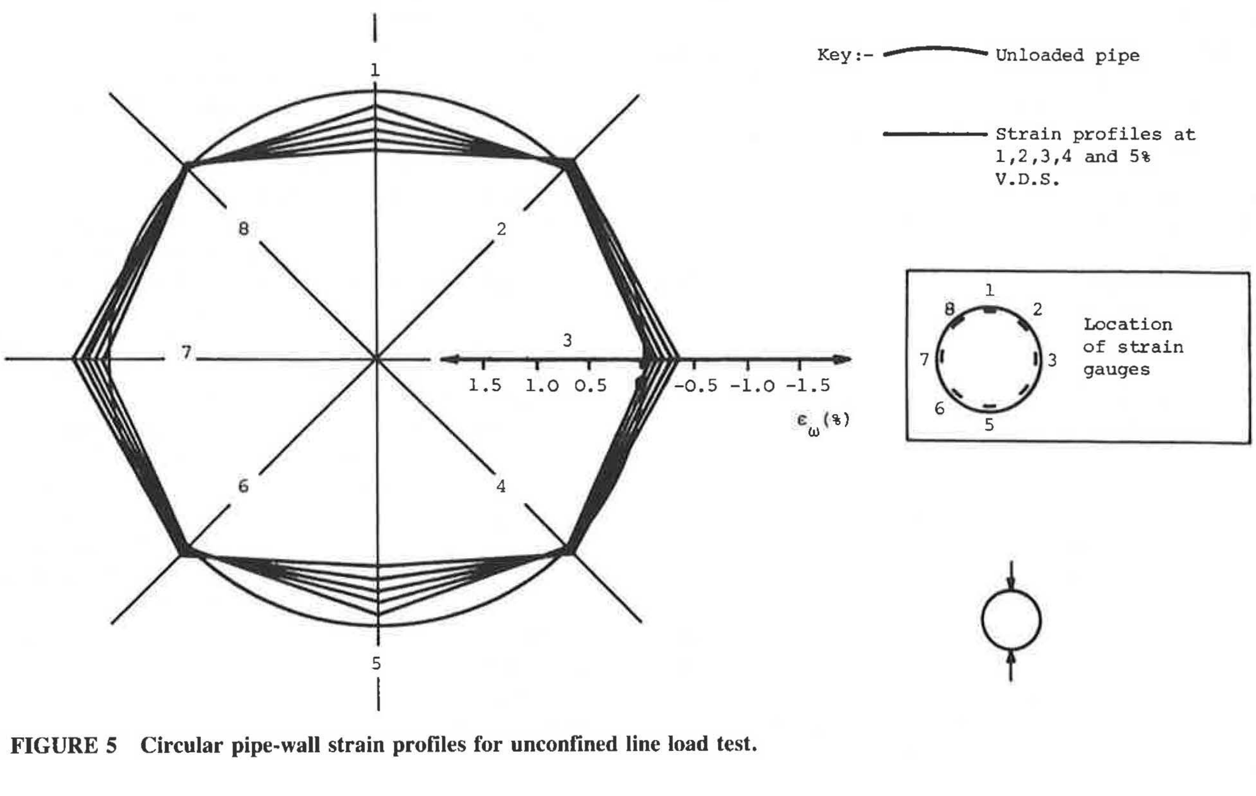

FIGURE 5 Circular pipe-wall strain profiles for unconfined line load test.

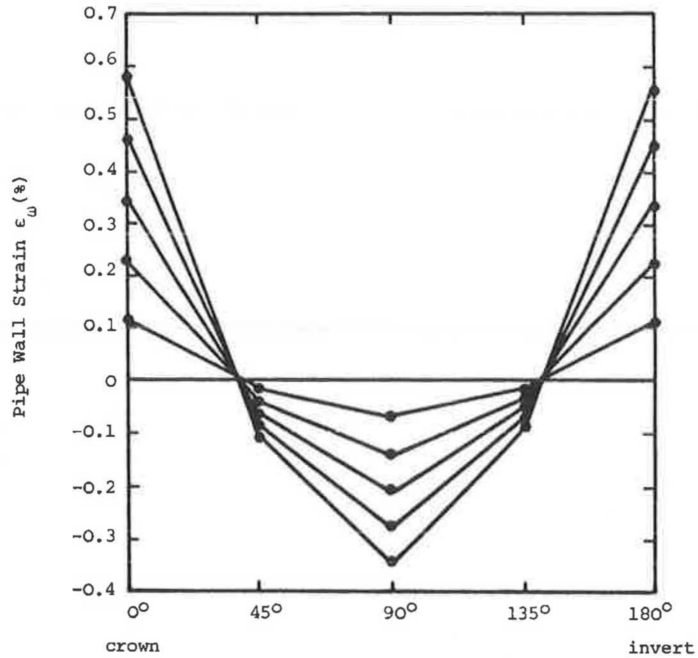

FIGURE 6 Linear pipe-wall strain profiles for unconfined line load test.

ellipse are hardly discernible from the ring flash photographs. The descriptions of flattened crowns and bulging shoulders are, therefore, greatly exaggerated and are solely used to distinguish marginal changes in shape.

In contrast, the extrapolated pipe-wall strain profiles for the same tests after the 55 kN static load had been applied for 30 min (Figure 8) show a considerable difference in behavior. The curve for pea gravel was indicative of considerable action to relieve pressure in the top section of the pipe and consistently good support around the pipe. Similar, though less exaggerated, behavior was apparent in the concrete ballast installation, with greater movement at the haunches and invert reflecting a lack of compaction at these points. The strain profile for the silty clay installation is of a near perfect V form indicating purely elliptical behavior under load, the more competent reject sand conforming to approximately elliptical behavior.

These two figures show that the pipe deformed in an elliptical manner under load when surrounded by a poor material and application of further loads, whether static or cyclic, did not change this pattern. When surrounded by a material that provided good support, however, deformation under load was considerably different from an ellipse and totally dependent on the character of the surrounding soil. Application of the remaining load sequences caused the distortions from an ellipse to become so much less evident that the curves for distinctly different materials took the same form.

Corresponding curves for the four tests using uncompacted pea gravel (UCPG) and well-compacted silty clay (WCSC) in different configurations around the pipe (Tests 3, 5, 6, and 7) are shown in Figures 9 and 10. All four soil configurations provided good support to the pipe. As before, the greatest difference in pipe-wall strain profiles occurred under static load (Figure 10). The profile under load for full depth UCPG exhibited flattening of the crown and bulging of the shoulders, with little movement around the haunches and invert. The curve for WCSC over UCPG showed similar behavior, although with negligible strain at the springings. In this case the relief of pressure concentrations above the pipe was largely affected in the WCSC, though with flattening occurring at both the crown and the invert and bulging at both the shoulders and haunches. The arching layer diverted the area of most action to the lower section of the pipe, resulting in the lowest crown and shoulder strains and highest strains at the haunches (bulging) and invert (flattening). Similar, though less pronounced, behavior occurred where a split sidefill of UCPG overlying WCSC was used.

These tests indicated that most deformation occurred where the support was poorest. The curves at the end of the tests retained the characteristics of those when under load while reverting to a more uniform pattern consistent with elliptical deformation (Figure 9). Retention of strains developed under load was greatest in areas associated with clay surrounds, which indicated a lower degree of elastic recovery and was consistent with the soil properties. A detailed study of recovery on removal of the static load confirmed this observation.

In order to illustrate the behavior under static and cyclic loads, the strain profiles at various stages of the test using a full-depth UCPG sidefill (Test 3) is shown in Figure 11. The effects of installation were small. The profile under the 55 kN static load exhibited large crown and shoulder strains, which increased marginally as the load was held for 30 min. On removal of the load, significant elastic recovery occurred. Application of the cyclic load caused large increases in strain at the crown, springings, and invert, but had a negligible influence on behavior at the shoulders and haunches. Application of the 70 kN static load caused similar large strain increments to those of the lower static load, the pipe exhib-

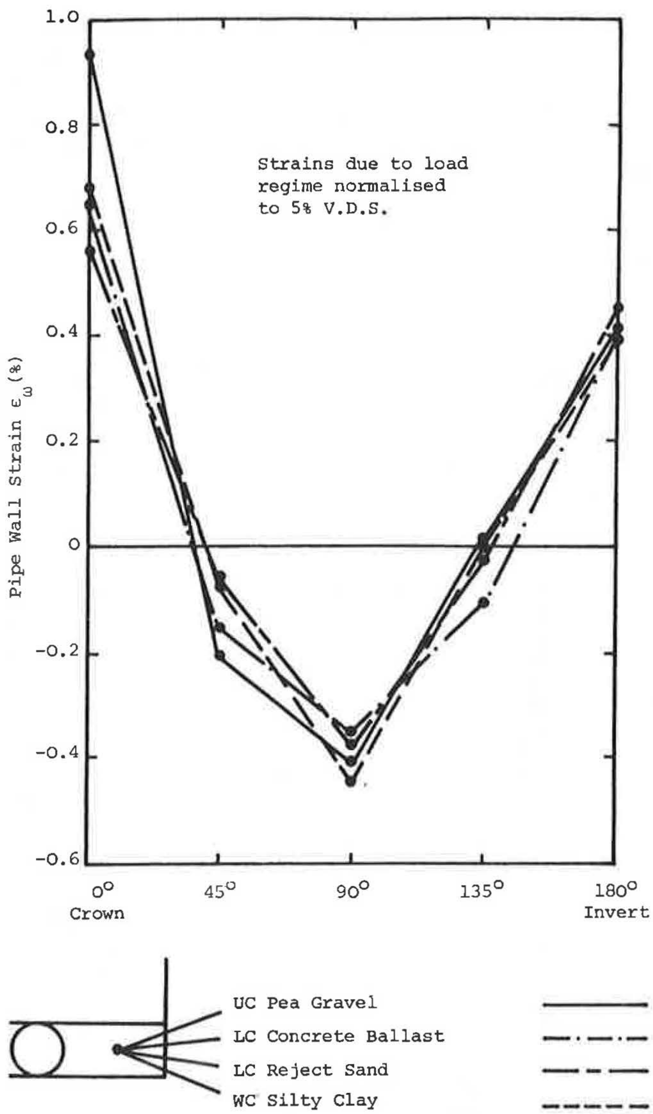

FIGURE 7 Pipe-wall strain profiles at end of tests using four sidefill materials.

iting little creep behavior. On removal of this load, nearly all of the additional strain was lost. The higher cyclic load produced the same results as the lower one.

It is clear from this analysis that, when buried in a competent sidefill, the pipe exhibited distortional behavior under load, with little creep movement and considerable elastic recovery. Application of the cyclic loads produced almost perfect elliptical behavior, thus reducing the distortional influence on the final strain profile.

It has been stated in the literature by Broere (*5*) and others that the deformed shape of a flexible pipe can be obtained when the circumferential pipe-wall strain distribution is known. This was shown to be true for uPVC pipes in the case of unconfined line load test. When the pipe was confined in a good sidefill, the shape of the strain profile differed significantly from an ellipse, and a component of hoop compression would have been expected.

These phenomena are illustrated in Figure 12, which shows a graph of pipe-wall strain against VDS for a full-depth UCPG sidefill (Test 3), in which distortional profiles were produced. At each point around the circumference except the invert, the pipe-wall strain measurements under the static load show higher compressive, or lower tensile, strain than the corresponding values after the cyclic load had been applied, indicating that a compressive component of hoop strain was induced under load. The gauges on the horizontal and vertical axes exhibited a discernible linear relationship through the origin despite this effect. The cyclic load sequences produced a slightly curved relationship for the pipe crown strain. Strain in the gauges on the springings was remarkably similar and also slightly curved. The relationships for the gauges at the shoulders and haunches were of similar type, with large compressive components under static and a slightly curved, though approximately horizontal, line under cyclic load. This reflected distortional behavior under load followed by elliptical behav-

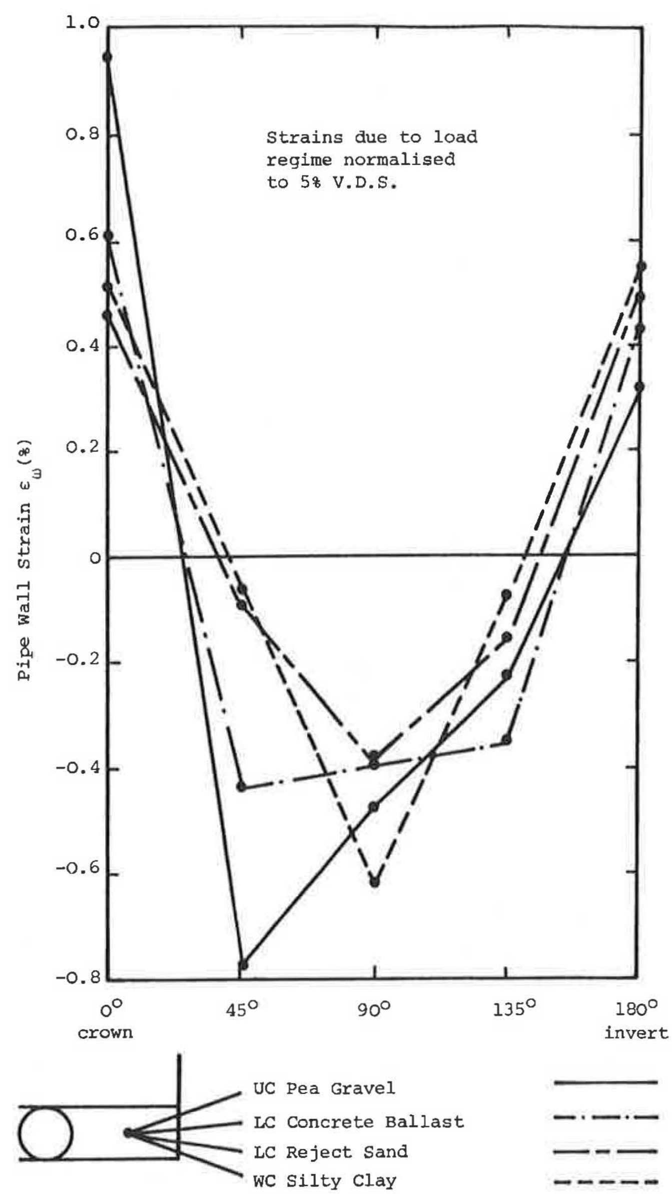

FIGURE 8 Pipe-wall strain profiles under 55 kN static load using four sidefill materials.

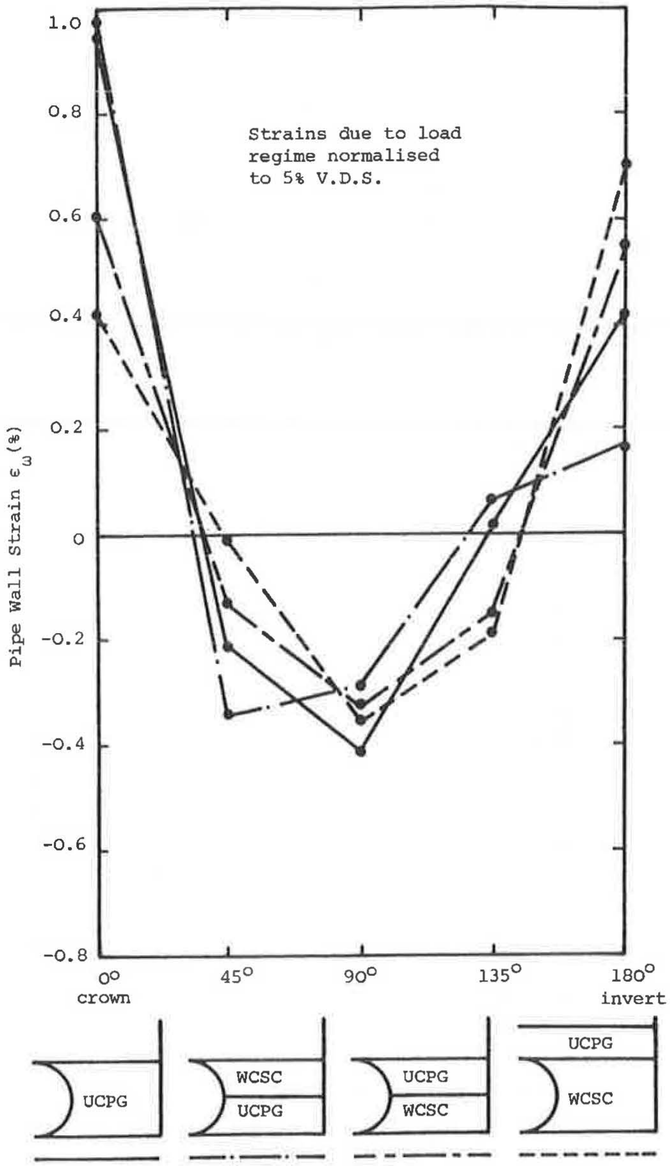

FIGURE 9 Pipe-wall strain profiles at the end of tests using four combinations of gravel and clay.

ior, in which little change in strain was experienced at these points, when the load was cycled.

Considering Figure 12, it can be concluded that the shape of deformation can be deduced from the strain profiles if care is used. When analyzing such data, it should be remembered that the correlation sought ought to have been that between pipe-wall strain and the change in curvature of the wall, or relative movement of the point toward (or away from) the center of the pipe. The good correlation of strain with VDS on both horizontal and vertical axes was encouraging, therefore, and the behavior at the shoulders and haunches was explicable.

The results previously quoted lead to the following working hypotheses of pipe behavior. When a circular pipe is subjected to a line load across its vertical axis but is otherwise unloaded, it will deform elliptically. The pipe-wall strain profile will be elliptical also. When surrounded by a relatively poor soil and load is applied to the soil, the pipe will again deform approximately elliptically, but the pipe-wall strain profile will tend to a V shape (Figure 13*a*). This is caused by the lateral restraint of the soil, or passive pressure developed therein, which induces a greater compressive strain in the pipe springings. Where a buried pipe is bedded in a good quality stiff soil up to at least its horizontal axis and a vertical load is applied to the soil surface, the pipe will tend to deform to a heart shape, in which the pipe crown flattens and the shoulders become relatively more curved with a roughly even change in curvature below this (Figure 13*b*). Such a deformation is accompanied by high tensile wall strain at the pipe crown and high compressive strains at the shoulders. Diametrically opposite behavior can occur in cases where the soil around the haunches is poor and that above it is of good quality (Figure 13*c*). In cases in which exceptionally good lateral restraint is provided at the pipe springings, deformation will tend to be square shaped, in which the pipe and invert flatten and the

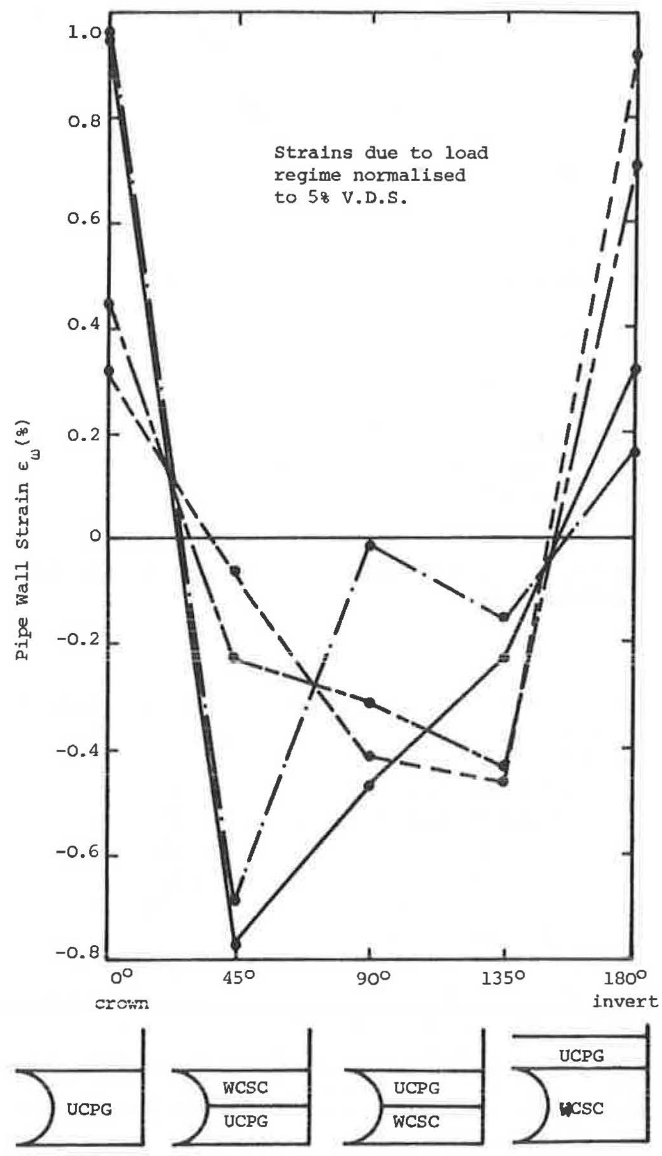

FIGURE 10 Pipe-wall strain profiles under 55 kN static load using four combinations of gravel and clay.

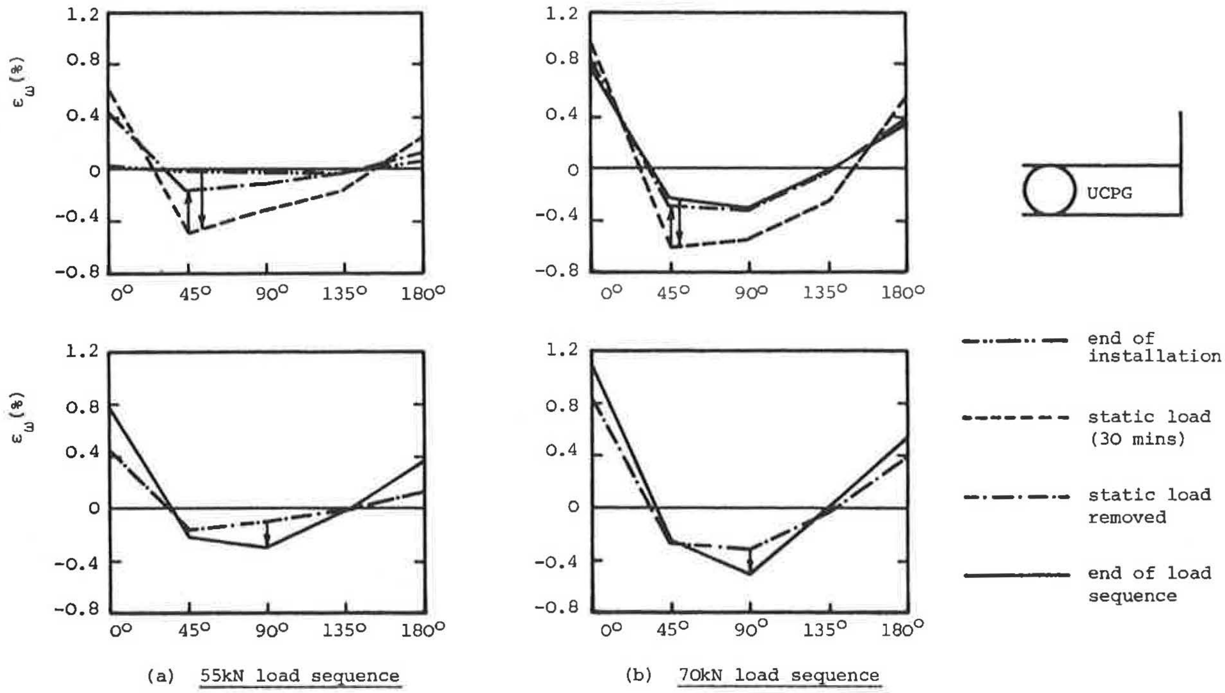

FIGURE 11 Development of pipe-wall strains in pea gravel.

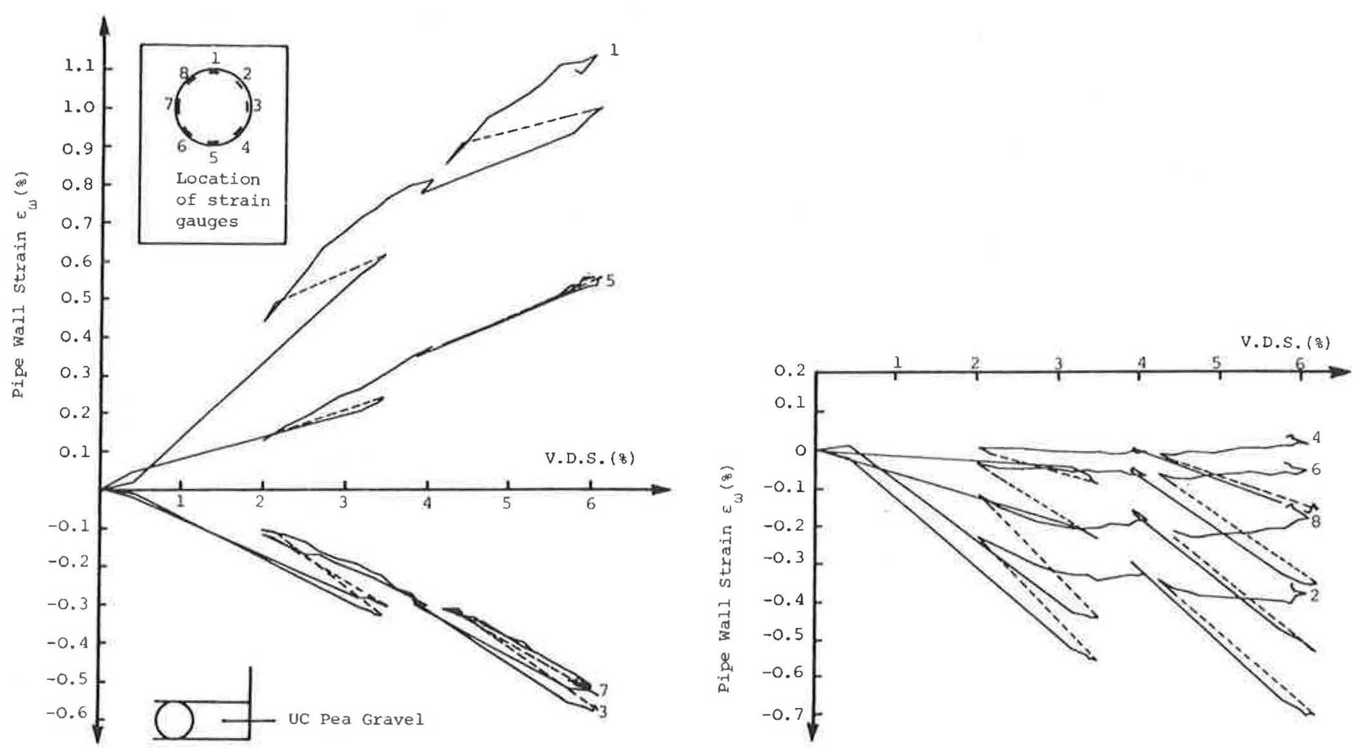

FIGURE 12 Graph of pipe-wall strain against VDS for a pea-gravel installation.

shoulders and haunches take up a smaller radius of curvature, the springings remaining largely unstrained (Figure 13*d*). This behavior typically occurs only in cases in which thorough compaction is applied to the sidefill at the level of the pipe springings, thereby creating a locally stiff medium.

The behavior described as semielliptical by Howard (*3*) is consistent with the inverted-heart-shaped profiles already described, although in a less exaggerated form. The description by Howard (*2*) of rectangular deflection is consistent with the square-shaped deflection referred to previously. In this respect, rectangular is perhaps a better description because the pipe undergoes flattening at the crown and invert, with

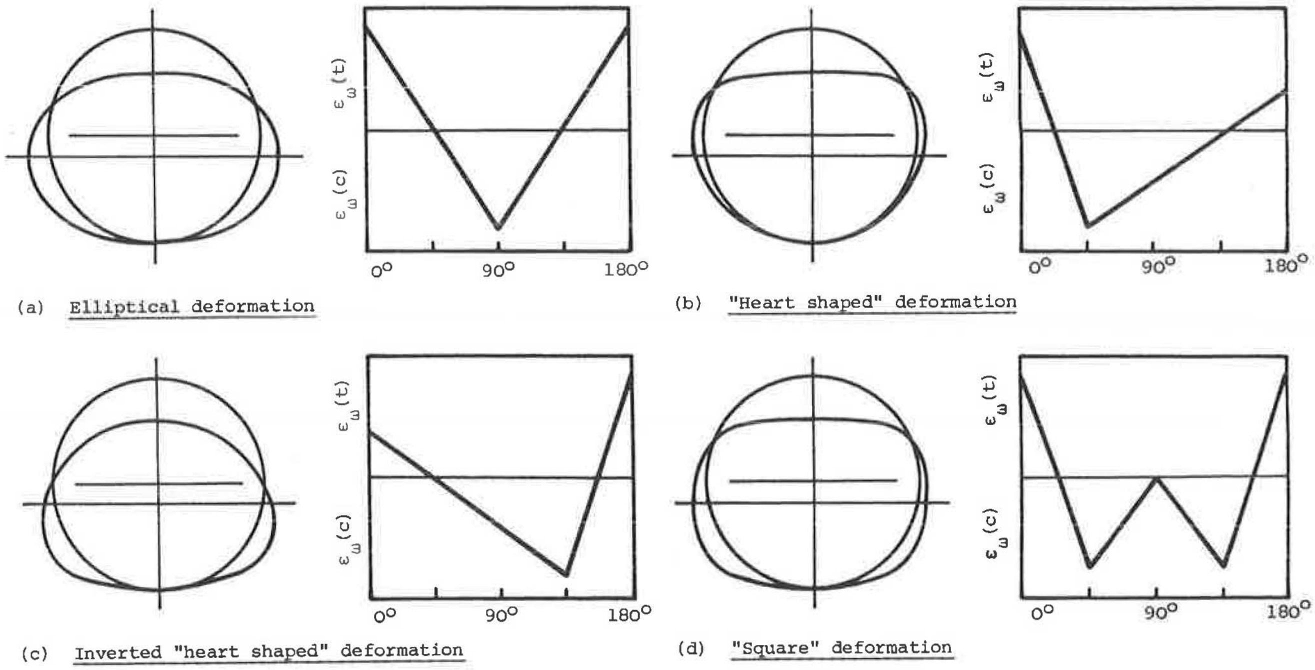

FIGURE 13 Types of deformation and associated strain profiles.

no change in curvature (i.e., negligible strain) at the springings. The V-shaped strain profile associated with elliptical deformation was confirmed by the experimental results.

Where Broere (*5*) refers to flattening, as between two plates, in the lower half of the pipe buried in uncompacted sand, he is referring to the tendency of the pipe to adopt an inverted-heart shape. He confirms this by stating that the pipe deformed more in the lower half of the pipe than in the upper half. The pipe in compacted clay also showed a tendency to an inverted-heart shape.

CONCLUSION

An unconfined pipe produced an elliptical pipe-wall strain profile when loaded, the strains being proportional to VDS at each point around the circumference. This was consistent with the expected elliptical deformation of the pipe. When buried, elliptical deformation was accompanied by a V-shaped pipe-wall strain profile and such behavior was only found with poor sidefills such as silty clay and reject sand. Distortional behavior, consistent with the character of the sidefill, occurred under static load in pipes that were given good support, behavior being essentially elliptical under cyclic loads. Elastic recovery of static load deformation was greatest in soils of highest elasticity and in cases in which pipe support was best. The arching behavior of granular soils was important. The deformed shape of a buried pipe was deduced from the pipe-wall strain profiles, the relationship of the latter being consistent with VDS measurements.

The assumption of elliptical deformation in methods of prediction of pipe deformation is likely to be valid in cases where the pipe is subject to predominantly cyclic load or where the surrounding soil is not relatively stiff. Where applied load is predominantly static, the assumption could prove to be greatly in error. The assumption of elliptical deformation in experimental work should be avoided and measurement of pipe-wall strain or wall movement, or both, should be made all around the circumference rather than solely across the vertical and horizontal axes.

ACKNOWLEDGMENTS

The research described herein was carried out in the Civil Engineering Department of the University of Nottingham under a contract with the British Plastics Federation, whose help and guidance is gratefully acknowledged. The author is grateful to P. S. Pell, head of the Civil Engineering Department, for providing the necessary facilities and particularly to S. F. Brown, who both supervised and contributed greatly to the work. The author also wishes to acknowledge the help of M. P. O'Reilly and his colleagues at the Transport and Road Research Laboratory.

REFERENCES

1. M. G. Spangler. *The Structural Design of Flexible Pipe Culverts.* Bulletin 153, Engineering Experiment Station, Iowa State College (now the University of Northern Iowa), Cedar Falls, 1941.
2. A. K. Howard. Laboratory Load Tests on Buried Flexible Pipe. *Journal of American Water Works Association*, Vol. 64, Oct. 1972.
3. A. K. Howard. *Laboratory Load Tests on Buried Flexible Pipe.* Progress Report No. 5: GRP, PE, and PVC. USBR Report No. REC-ERC-73-16, Bureau of Reclamation (now Water and Power Resources Service), Denver, Colo., July 1973.
4. A. K. Howard. Diametral Elongation of Buried Flexible Pipe. In *Proc., International Conference on Underground Plastic Pipe*, New Orleans, La., March 30–April 1, 1981.
5. J. J. Broere. *The Behavior of PVC Water Mains under Practical Conditions.* (In Dutch.) H2O, Vol. 17, No. 9, The Netherlands, Sept. 1984.

6. R. Soini. Interaction Between Thermoplastic Pipes and Soft Soil. In *Proc., Europipe '82 Conference,* Basle, Switzerland, Jan. 1982.
7. C. D. F. Rogers. *Influence of Surrounding Soil on Flexible Pipe Performance.* Paper presented at 66th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1987.
8. I. Dezsenyi. *Plastic Sewers—Calculating Deformation.* Building Research and Practice, Leyden Publishing Co., Ltd., London, England, Sept. 1975, pp. 278–288.
9. C. D. F. Rogers, S. F. Brown, and G. Boyle. The Influence of Bedding and Sidefill on the Response of uPVC Pipes to Surface Loading. In *Proc., 6th International Plastics Pipe Conference,* University of York, England, March 1985.

Publication of this paper sponsored by Committee on Subsurface Soil-Structure Interaction