CHAPTER 4: PIPE TESTS

4.1 INTRODUCTION

Tests were commissioned by a plastic pipe manufacturer to determine experimentally safe cover heights for trafficking of pipe installations in trenches. A nominal limit of 5% diametric deformation of the pipes was imposed in the tests. Both construction traffic and traffic on a paved surface were to be investigated. Loads and contact areas were equivalent to heavy truck design loadings used in pavement design. The effect of repetitive loadings was investigated. All testing was designed and supervised by the author. The results of the program of tests described in this Chapter are compared later in this thesis with predictions obtained from sophisticated numerical modelling of the buried pipe installations.

In the tests on the pipes, a single backfill material was employed, which was poorly graded sand as described in Chapter 5. Three deliveries of sand from the same quarry were made for the long testing program and some variation was possible between batches. Only one batch was extensively evaluated. The sand was considered to be a low quality backfill. Although potentially more convenient, a uniformly sized sand was deliberately avoided so that the influence of surround and backfill density could be evaluated. All tests in the laboratory were conducted with dry sand.

Loads were applied directly onto the backfill surface, through a rectangular steel plate, representing the area of the backfill surface stressed by the traffic loading.

The flexible pipe was a spirally-wound, ribbed, uPVC pipe, which was produced in a wide range of sizes. The nominal diameters dealt with in this study ranged between 250 and 600 mm, although most of the pipe tests were conducted on diameters of 300, 375 and 450 mm, and so only these pipe diameters are reported in this thesis. A photograph of a typical pipe after a buried pipe field test is provided in Figure 4-1.

In this Chapter, twenty-two buried pipe tests are reported, four of which were conducted in the field. The pipe tests preceded the numerical analysis reported in this thesis, and indeed were the catalyst for further investigation. The tests were conducted at the University of South Australia between 1989 and 1991.

4.2 TESTING MATERIALS AND EQUIPMENT

4.2.1 Testing Facility

Generally, tests were conducted in a soil box of propped, plywood formwork (Figure 4-2). The pipes were tested on a laboratory strong floor in a braced plywood box, 3.0 m long, 0.75 m wide and 1.8 m deep (photographs of the box are provided in Figure 4-2). The pipe was installed along the length of the box, with its ends sleeved over collars, which were fixed on each of the end walls of the box. The width of the box could be varied. In all the tests, the width was kept equal to or greater than the value of the sum of 300 mm and the nominal internal diameter of the pipe.

The soil box was constructed of steel framed plywood panels, which were designed as formwork for concreting. During testing, the sides of the box were supported with a series of beams and a central column support, either side of the box. The column support was bolted to the laboratory's strong floor and strutted at its top against a substantial portal loading frame (see Figure 4-2). Deflection of the trench wall was minimized as far as practical by these supporting beams and props.

The box was designed to facilitate emptying of the sand. After testing, the box was raised onto a pair of large hoppers. Side trap doors were opened and the sand backfill was allowed to rain out (refer photograph in Figure 4-3).

A series of field tests was conducted in trenches in a clay soil profile, to confirm the trends observed in the laboratory testing program (refer photographs of the preparation of the field installations in Figure 4-4). The laboratory soil box was thought to be a stringent test for the buried pipe owing to the relatively low wall friction, δ, developed at the interface between the backfill and plywood (δ ≈ 25°; refer Chapter 5), when compared with an interface with natural soil. The pressure at the pipe crown from the surface load is likely to be more severe owing to the relatively smaller side shear support offered by the plywood walls. However it was also recognised that well-braced sidewalls of the soil box may have been too stiff relative to conditions in the field. A trench in the ground could present less lateral support for the pipe as it deflects, allowing greater lateral deflection of the pipe with surface loading.

Soil samples were taken horizontally from the trench walls (Figure 4-4a) to evaluate lateral soil stiffness using simple unconsolidated undrained testing. Horizontally oriented soil samples were taken near the springlines of the installations, with the depths of samples ranging between 0.9 and 1.4 metres. The samples of red brown silty clay were essentially unsaturated soil with variable calcium carbonate contents. The soil was seasonally dry and its stiffness varied with depth as well as with location across the site.

Nominal 50 mm diameter samples were tested unconsolidated and undrained in the triaxial cell. Cell pressures were kept low (50 to 100 kPa), reflecting the shallow depth of the buried pipe installations. An unloading–reloading loop was introduced in each test after the sample had reached a deviator stress of approximately 50 kPa. Soil modulus was determined as a secant modulus at a deviator stress of 100 kPa.

For the test pit for the 300 mm diameter pipe, the soil moduli determined on two samples were 30 and 40 MPa. The soil moduli were 70 and 95 MPa for the walls of the test pit used for the two 450 mm diameter pipe tests.

4.2.2 Laboratory Loading System

In the laboratory tests, loads were delivered by a hydraulic ram suspended from a portal frame, secured to the strong floor. The ram was driven by a Mohr and Federhoff compression testing machine. Within the range of testing (0 to 100 kN), the accuracy of the force monitoring system was calibrated within ± 2 %. The photograph in Figure 4-5 depicts the ram loading the buried pipe through a large plate, positioned on the surface of the backfill.

4.2.3 Field Loading System

Four stacks or pallets of concrete blocks formed the dead weight system for the steel reaction frame and hydraulic ram (refer photograph in Figure 4-6). The mass of each pallet was approximately 3.5 tonnes, resulting in an average dead load surface pressure of 24 kPa. Consequently, pallets were kept as far as practical from the trench to minimize the influence of the dead load on the pipe-soil system. A minimum distance of approximately 1.2 m was maintained between the edge of each pallet and the wall of the trench. The hydraulic ram for applying load was manually operated.

4.2.4 Measurement of Pipe Deflections

Once the bedding had been formed, the pipe was placed in position and end plates added to fix the pipe to the soil box. The end plates permitted access to the inside of the pipe for monitoring of diametric deflections, both about the circumference and along the length of the pipe. Therefore it was possible to monitor distortions of the pipe during compaction of the backfill, although it was not always done.

Pipe deflections were monitored initially with photogrammetry. Reference targets were fixed to the pipe end steel plates, which fixed the pipe in position. An internal pipe profiler eventually replaced photogrammetry to provide more immediate monitoring data. Displacement transducers were fixed to an axle through the pipe as depicted in the photograph in Figure 4-2. The profiler could be accurately rotated to provide deflections about the pipe circumference and along the length of the pipe. Towards the end of a test, rotation of the transducers was sometimes restricted by excessive pipe deflection.

Pairs of Hewlett-Packard displacement transducers[1] (7DCDT-1000), fixed at 90° to one another, were mounted on a rotating shaft at spacings required for pipe profile measurements. The axle was positioned along the longitudinal axis of the pipe and was

[1] These were later replaced by more robust Duncan displacement transducers

supported at its ends. Rotation of the shaft was performed manually. The rotated position of the shaft was electronically monitored.

The pairs of transducers permitted a check to be made on the repeatability of deflection measurements. Generally, readings were well within 0.5 mm. Occasional problems arose due to interference from sand particles, impeding smooth rotation of the displacement transducers and sometimes leading to damage of the instrumentation.

4.2.5 Measurement of Earth Pressures

Strain gauged earth pressure cells were used in some of the tests (refer Table 4-VI) to measure stresses above and around the pipe, usually within the surround zone between the bedding sand and the backfill cover. The pressure cells were made of aluminium and were designed for the project. Having considered the likely range of Young's modulus of the soil, the cell geometry was chosen, based on the work of Mills, Matthews, and Richards (1974), as follows:

- cell diameter 63.5 mm
- aspect ratio 0.20
- active diameter 36.6 mm
- diaphragm thickness 2.5 mm

Each cell was calibrated twice, firstly under air pressure (active face only) and then loaded uniformly within the sand backfill. The calibration in sand was achieved by placing each cell in a half-filled cylindrical container (315 mm in diameter and 310 mm high) of compacted sand, and then backfilling the remaining volume. A compression testing machine was used to load the sand surface through a 270 mm diameter steel plate, underlain by a 25 mm thickness of rubber discs. To negate wall friction, the cylinder was lined with plastic sheet. Five load-unload cycles were performed before readings were recorded. The maximum calibration pressure was 500 kPa.

The response of the active face of the earth pressure cell to loading depends upon cell geometry and the level of side pressure. Therefore, a difference in calibration was evident between the two calibration techniques. Theoretically, the soil surcharge test should be preferred. However, it seemed to be a less reliable technique with the main difficulty being to ensure that the surcharge pressure loaded the soil mass uniformly. The air pressure calibration gave excellent linear relationships between strain gauge output and applied pressure, whereas the second method provided slightly curved plots of pressure against cell strain.

The difference between the average linear calibration factors obtained from the two techniques was of the order of 10%. The air calibration factor averaged 1.0 kPa/μstrain for the five cells used in the buried pipe tests. The soil calibration factors were higher.

For reduction of pipe test data, it was decided to average the calibration factors obtained from the two calibration procedures. Neither calibration method is completely satisfactory, as previously discussed, however differences between the methods were relatively small.

4.3 SET-UP AND TEST PROCEDURES

4.3.1 Compaction of the Backfill

The bedding, the surround and the first 150mm depth of backfill above the pipe crown were compacted manually. Manual compaction was achieved with a falling weight tamper of mass 15 kg and a tamping foot, 250 mm long by 50 mm wide. The bedding as defined in Figure 2-2 was compacted and shaped to receive the pipe. The bedding angle was generally kept within the range of 60 to 90°.

In a few tests, the surround was placed but not compacted. More commonly, the surround was compacted manually in two lifts. The first lift commenced from approximately the level of the spring line of the pipe. In early tests, a single lift from the crown to the bedding was tried, but it was found to be inadequate as compaction below the pipe spring line could not be guaranteed.

The remaining backfill was compacted by a number of passes of a vibrating-plate tamper over lifts of 150mm depth.

At the end of compaction, the falling-weight, dynamic cone penetration test (AS1289-F3.2) was performed at four locations about the central loading area to ascertain the level and uniformity of compaction achieved. For quality control purposes, the resistance of the dynamic cone was calibrated against the average density of the dry sand in a 44 gallon drum. The sand was prepared to a range of densities. Further details are provided in Chapter 5.

4.3.2 Loading

The A14 standard vehicle loading specified by NAASRA (1976) was chosen as the design live load (refer Chapter 2). To simulate construction traffic, loading from a single tyre footprint area was applied through a relatively rigid steel plate, 200 mm by 500 mm and 25 mm thick, directly on the surface of the backfill above the centre of the pipe. The plate was orientated such that its long side was parallel to the pipe axis (traffic crossing the trench).

To simulate street traffic rather than construction vehicles, the loading plate was enlarged to 900 mm by 600 mm and its thickness was reduced to 12 mm (refer Figure 4-5). The size and stiffness of the plate was judged primarily by layered elastic analysis of settlements using program CIRCLY™ [2] for uniform loading through a circular wheel patch. A 200 mm thick flexible pavement, as commonly used in residential street construction, was modelled in the CIRCLY runs (Mills, *personal communication*, as reported in Cameron 1991). The pavement consisted of granular layers of constant Young's modulus of 500 MPa and a Poisson's ratio of 0.45. The sand was assumed to have a Young's modulus of 60 MPa and a Poisson's ratio of 0.35.

The differential deflection of a uniformly loaded, 12 mm circular steel plate was matched as far as practical to the differential deflection of the subgrade surface from the CIRCLY analysis, by increasing the radius of the plate. An extra 200 mm was found

[2] MINCAD Systems, Australia

necessary to produce a close match. Therefore an extra 200 mm was added to the original plate dimensions of 200 by 500 mm to achieve the “flexible” plate dimensions. In hindsight and outside the scope of this thesis, program AFENA™ (Carter and Balaam 1995) could have been employed to more accurately model the rectangular plate loading through three-dimensional finite element analyses.

Cyclic loading tests were performed with a MTS loading device acting on the large plate to simulate traffic loading on a residential pavement, however only static loading tests are reported herein.

During testing, load was generally applied in maximum increments of 10 kN. Plate settlements were measured using a reference beam and sliding vertical steel rule. The tests commonly took half an hour to one hour to complete, depending chiefly on how the pipe displacements were monitored.

4.4 STRUCTURAL PROPERTIES OF THE PIPE

4.4.1 Introduction

The flexible pipe was a spirally-wound, ribbed, uPVC pipe. The ribs were T-shaped and were spaced at 12.5 mm centres. The uPVC ribbed profile was supplied to the pipe manufacturer by Vinidex (VX) and, prior to forming the pipe, came in strips of widths, 90 to 125 mm (90VX to 125VX profiles). The geometry of the ribs changed with the different profile designations. Table 4-I provides dimensions of the three sections, as reported by the pipe manufacturer. In this same Table, the area and moment of inertia of each cross section is given.

The nominal diameters dealt with by Cameron (1990, 1991) ranged between 250 and 600 mm, although most of the pipe tests were conducted on diameters ranging between 300 and 450 mm. This thesis will focus on pipes of just three diameters, 300, 375 and 450 mm.

The properties of the pipe are needed to conduct the finite element analyses (FEA) of the soil-pipe interaction. In particular, the flexural stiffness of the pipe in ring bending, EI, and the ability of the pipe to take circumferential thrust and shear force, as indicated by the structural stiffnesses, EA and GA, are both needed.

For complex pipe profiles such as a spirally wound, profiled pipe, EI may be calculated from pipe stiffness test data. The "elastic" properties of plastics are well known to be dependent on the rate and duration of loading as well as the ambient temperature (Schluter and Shade, 1999) and so test Standards define the conditions under which E is evaluated.

EA is best derived experimentally in a direct tension test or a hoop extension test on a length of pipe. The latter method requires sealing the pipe length, filling it with water and pressurizing the water to expand the pipe or inflating a membrane within the pipe. This alternative was deemed too onerous and so tensile test coupons were preferred.
The structural properties of the pipe were in part given by the pipe manufacturers, but were later verified with a limited test series on a 375 mm (110VX) pipe from the original soil box test series. The pipes are no longer manufactured in the materials and profiles of the original test specimens.

4.4.2 Pipe Ring Stiffness, PS

Tests to evaluate stiffness had been conducted by the manufacturers in accordance with ASTM D2412 (American Society for Testing Materials, 1996), which is the specification of a parallel plate test. In this test, a short length of pipe is placed on the lower platen of a compression testing machine, with the axis of the pipe being horizontal. The pipe is then loaded by lowering the top platen, such that ring compression occurs. Loading occurs over the full length of the pipe.

The parallel plate test provides an estimate of the pipe stiffness (PS), which is the force in kN per metre length of pipe required to cause a vertical deflection of the pipe of one metre. For the uPVC pipes in the study, PS values from the pipe manufacturer have been summarized in Table 4–II.

4.4.2.1 Verification of pipe stiffness for a 375 mm diameter pipe

A length of 375 mm diameter pipe (110VX) remained from the original testing program. Three short lengths were cut for the pipe stiffness tests, with the average length of pipe being 298 mm (range -2, +1 mm). The requirements of ASTM D2412 were not completely met as room temperature was not controlled and the temperature during testing was lower than the 23 ±2°C required. The temperature was measured at 16°C. A test rate of 10 mm of deflection per minute was adopted rather than the specified 12.5 mm/min, which could not be accommodated with the available testing equipment. However the influence of loading rate was investigated by re-testing the second pipe specimen (Test 2) at even slower rates of 1 mm/min (Test 2b) and 0.1 mm/min (Test 2c).

The results of the tests are given as plots of applied force against diametric pipe strain in Figure 4-7. Figure 4-8 is a re-working of the data, applying the correction in the ASTM method for changes in curvature of the pipe with deflection. The correction is recommended also by AS/NZS 2566.1 (Standards Australia and Standards New Zealand 1998) and it takes the form:

$$PS = \frac{F}{\Delta y} C = \frac{F}{\Delta y}\left(1 + \frac{\Delta y}{2D}\right)^3 \qquad 4\text{-}1$$

where F = applied force per unit length of pipe

Δy = vertical pipe deflection

D = initial inside diameter of pipe

It is clearly evident that the correction for second order effects substantially restores linearity of the force deflection relationship at large deflections. The pipe stiffness results are tabulated in Table 4-III. The column headed "Range" indicates the range of vertical diametric deflections over which the reported values of pipe stiffness are applicable. The average uncorrected pipe stiffness for the three pipe tests, which were tested at a rate of 10 mm/min was 78 kN/m/m, up to a minimum diametric deflection of 7.5%. The average, corrected pipe stiffness for the same pipe tests was 83 kN/m/m, up to a minimum diametric strain of 12%. These pipe stiffness values are indicated by the straight line plots in Figures 4-7 and 4-8.

Similar stiffnesses may be derived from the slower tests but the range of applicability is reduced, indicating less linear response. For the corrected data, it may be stated that pipe stiffness was reduced by only 5% when the test was conducted at $1/100^{th}$ the speed, however the range was reduced from 15 to 11% diametric strain. This reduction in stiffness compares favourably with the 6.5% reduction reported by Schluter and Shade (1999).

As most of the buried pipe tests were limited to about 7% vertical diametric deflection, the reduction in range is not considered to be important. Although small, the loss of stiffness as the rate of deflection becomes slower is important, when it is considered that the buried pipe tests were tested probably slightly slower than 1 mm/min.

The pipe stiffness of 67 kN/m/m reported by the manufacturer for this pipe is conservative, representing 81% of the average corrected value of three tests in this series, run at 10 mm of deflection per minute. For the purpose of finite element analysis of the buried pipe system, PS could be conservatively chosen as 95% of the lowest test result, or 70 kN/m/m. The 95% factor allows for a slower rate of loading and possibly the influence of slightly higher temperatures.

4.4.3 Pipe Section Stiffness, EA

A portion of a 375 mm diameter pipe, formed from 110VX profile, was sampled to make tensile test coupons to evaluate the circumferential stiffness of the pipe section when acted upon by thrust. The samples were cut in the alignment of the pipe's ribbed profile, rather than the pipe circumference, and incorporated a single rib. The tensile test coupons were shaped to concentrate the stresses within the middle third by reducing the width of each coupon at its mid-section to the spacing of the ribs (12.5 mm, as measured).

Tests were conducted on five coupons at the University of Sydney with an MTS 810 Material Testing System device, having a range of 0 to 100 kN force. Each plastic pipe coupon was fitted at each end with a brass clamping system, fixed to the web of the specimen rib by three high tensile bolts. The jaws of the MTS tensile testing device were then clamped onto a brass extension and not the PVC pipe. This brass extension was aligned so that tension without bending could be applied to the centre of the test coupon.

Figures 4-9 and 4-10 depict the test set up for the first specimen. The brass fittings were aligned with the rib rather than the transverse axis of the pipe and permitted the pipe section to be tested without twisting. The distance between the brass clamps was 62 mm.

The plastic pipe specimens were tested at a rate of displacement of 2 mm/min in a constant temperature environment (≈ 25°C). Deflections of the coupon were assumed to be equivalent to the head movement of the tensile testing apparatus. A proportion of the initial deflection could be attributed to straightening of the initially curved test section. By considering the geometry of the test set-up, it was determined that this straightening contributed approximately half of one percent strain in the sample. Each test incorporated an unload-reload cycle partly to overcome this effect. In the first test, unloading occurred at almost 1 kN which was close to the peak load; subsequent tests were unloaded after having reached 0.5 kN.

All specimens failed at the reduced cross-section. Generally failures were gradual. A tear would develop in either the pipe wall or the flange of the rib and progress through the cross section. Examples of failures are given in Figures 4-11 and 4-12. Upon dismantling of the clamping system, it was observed that ovalisation of the first bolt-hole had occurred at one or both of the ends of the specimen.

Load extension curves are given in Figure 4-13 for all five tests, while the early non-linear behaviour of the specimens is indicated in Figure 4-14. Large deformations of the pipe profile are evident in these plots when it is considered that the gauge length was 20 to 21 mm. Peak tensile strength was realised at strains between 10 and 20%, generally.

Full details of the tests are provided in Table 4-IV. Strains have been calculated assuming the unclamped length of test coupon (62 mm) to be the original length of the pipe specimen. The dimensions of the test specimens were measured with vernier calipers to establish the cross sectional area, which was found to be approximately 27 mm^2.

Linear approximations to the load-deflection curves were made for the re-loading curves to a tensile force of 0.5 kN and for loading between 0.5 an 0.9 kN, so that estimates of "elastic" modulus could be made. These estimates are given in Table 4-IV and they demonstrate the non-linear nature of the PVC pipe in tension. Ignoring test 1 in which the unloading was initiated after considerable loading, the average reduction in modulus from the initial load range to the higher load range was 58%.

4.4.3.1 Pipe peak strength

As indicated in Table 4-IV, the average peak stress in direct tension was 33.7 MPa. The flexural strength of uPVC under short-term loading was reported by Schneider (1990) to be much higher at 90 MPa.

4.4.3.2 Elastic Modulus

The average values of E upon re-loading to 0.5 kN for all five tests was 950 MPa. The short term modulus recommended by AS/NZS 2566.1 (1998) for the pipe material is 3200 MPa, over three times the observed value.

The short-term value of modulus should be corrected for the effect of initial winding strain of the spirally wound pipes (according to the pipe manufacturer). The winding strain, WS, is given by:

$$WS = \frac{2(H - y)}{D + 2y} - \frac{(H - y)}{750\,*} \qquad 4\text{-}2$$

** value for a 1.5m diameter spool*

The short-term modulus is reduced by ΔE_{ST} (MPa), which is defined as:

$$\Delta E_{ST} = m(WS) \qquad 4\text{-}3$$

In this equation, m is an empirical modulus reduction factor, arising from the winding strains realized in producing the pipe. Equations 4-2 and 4-3 were provided by the manufacturers of the pipe, as was a modulus reduction factor of 29,000 for this particular series of uPVC pipes.

With this information, the short term moduli, E_{ST}, for the spirally wound pipe with various profiles and wound to different diameters can be deduced and have been provided in Table 4-V. The estimated short-term values of modulus for the pipes in this study ranged between 70 and 80% of the value recommended by AS/NZS 2566.1 for pipes without winding strain. However the modulus from tensile testing of coupons from the 375 mm diameter pipe was only 38.5% of the short-term estimate of 2,470 MPa, which included the winding strain correction.

4.5 BURIED PIPE TEST RESULTS

Table 4-VI provides a summary of the twenty buried pipe tests and the test variations that were chosen. Tests 450/1, 2 and 5 were conducted as part of an undergarduate research project, supervised by the author and subsequently reported by Morris and Mahar (1989). Density indices are reported to the nearest 5% for the surround and the backfill, based usually on falling-weight penetrometer tests conducted at both sides of

the pipe prior to performing the load test. Penetration resistance varied throughout the depth of the installation and so the values are average values.

Summaries of all the tests are given in Tables 4-VII and 4-VIII at levels of vertical diametric strain of 3% and 5% respectively. In these Tables, the surface pressure applied to reach the strain level is reported, along with the percentage of remaining backfill cover height and the ratio of vertical to horizontal pipe diametric strain. If the test did not reach the specified strain level, only the maximum applied stress is reported in the Tables. All reported strain levels in this Chapter exclude any initial deformation due to the pipe installation process.

4.5.1 Simulated Pavement

Only three tests were conducted under monotonic loading, all test installations having only 300 mm of cover below the large, flexible loading plate, which was designed to represent the influence of a 200 mm thick flexible pavement. Cyclic testing was also conducted in another test series, however these tests are outside the scope of this thesis.

For all three monotonic tests, the diametric strain of the pipe, both vertically and horizontally, has been plotted against the applied surface pressure in Figure 4-15. The top half of each diagram contains the positive diametric strains or extensions of the pipe at the level of the springline. The bottom half contains the negative or compressive, vertical diametric strains of the pipe. The pipe response to the applied pressure is almost linear and symmetric, i.e. the horizontal strain is practically the same as the vertical strain, giving rise to elliptical deformation.

There did not appear to be significant difference between the load-deflection response of the 375 mm diameter pipe and the 450 mm pipe in this series of tests, when the soil in the installation was of comparable density. P375/1 deflected more for a given applied pressure than either of the other two pipe-soil systems. However, this buried pipe installation was the least stiff pipe-soil system, as it had the lowest backfill density, which was 60%, compared with 70 and 75% for the other two tests.

The influence of this lower density is again apparent when the plate deflections are considered (Figure 4-16). The central plate deflection during test P375/1 was roughly 50% higher at a given surface pressure than the corresponding deflection for test P375/2. However, as expected, the differential deflections of the loading plate in both tests were the same (centre-edge plots). The differential deflection is the difference between the central deflection and the average movement of the corners of the plate.

Although the measured plate deflections in Figure 4-16 seem high, the plate only penetrated the surface of the backfill by 3 to 4 mm, after taking the vertical strain of the pipe into account.

4.5.2 Unpaved Trench

4.5.2.1 Load-deflection responses of pipe-soil systems

The pipe deformations were quite localised. The greatest reduction in diameter occurred vertically under the centre of the loading plate. A typical distribution of vertical deformation along the pipe is given in Figure 4-17 for test 375/5, in which the initial cover height was 0.7 m. The pipe crown deflected most, directly beneath the centre of the loading plate. The invert of the pipe suffered little movement but tended to rise slightly, well away from the loaded area. The central deflections amounted to a vertical diametric strain of –3.9 % at a surface pressure of 585 kPa (or a crown deflection of -15 mm). It should be noted that the plate had moved almost 150 mm at this same surface pressure.

The diametric strains of the pipes below the centre of the rigid loading plate, both vertically and horizontally, have been plotted against the average applied surface pressure in Figures 4-18 to 4-25. Again, the top half of each diagram contains the positive diametric strains, or extensions, of the pipe at the level of the springline. The bottom half contains the negative, or compressive, vertical diametric strains of the pipe. Generally pipe responses have been grouped according to the nominal internal diameter of the pipe.

The results have also been summarized in Tables 4-VII and 4-VIII, which give the applied surface pressures needed to reach vertical diametric strains of 3 and 5%, respectively. These values have been interpolated where practicable from the load-deflection data. Alongside the pressures, the remaining backfill cover height is given as a percentage of the initial height, at the stipulated pressure level. Finally the ratio of vertical to horizontal diametric strain is provided in each Table.

It can be seen in the plots of pipe strain with applied pressure that the vertical diametric strain was usually significantly higher than the horizontal strain. The average deformation ratios (vertical to horizontal), or deformation ratio, at 3% vertical strain were 1.3, 1.4 and 2.5 for the 300, 375 and 450 mm diameter pipes, respectively (Table 4-VII). The high ratio for the 450 mm pipes indicates relatively deformable pipes. Excessive ratios of vertical to horizontal strain (> 3.5) were recorded towards the end of testing for the two 450 mm diameter pipes, which were associated with the field test series (F450/3 and 4), possibly indicating local buckling failure of the pipe crown.

Generally with greater load and deflection, the deformation ratio increased, for example, it increased from 1.3 to 1.6 on average for the 300 mm diameter pipes, as the vertical diametric strain of the pipe increased from 3 to 5%. So the pipe deformation became less elliptical ("elliptical deformation" corresponding to a strain ratio of unity) as the vertical deformation of the pipe increased.

Backfill cover height was reduced as loading progressed, the extent of settlement seemingly being dependent upon the level of loading achieved, the height of initial backfill cover to the pipe crown, and the degree of backfill compaction. In the majority of these tests, the relatively rigid loading plate was observed to punch into the surface of the sand backfill.

Table 4-IX provides data on interpolated values of surface pressures to cause, firstly, excessive settlement (judged to be 5% of initial cover height) and, secondly, punching shear failure (if applicable). In the four 375 mm diameter pipe tests with 700 mm of

cover, which reached a vertical diametric strain of 5%, the backfill cover[3] was reduced by 165 mm on average. The ratio of the remaining cover to the original cover has been plotted against the applied pressure at the surface of the backfill for each of the tests in which loading plate settlements were observed (Figures 4-26 to 4-29).

Figure 4-30 contains two photographs of the loading plate in a field test, taken at the start of loading and some time later when the plate had punched into the backfill. The settlement of the plate relative to the backfill surface is considerable in the latter photograph.

The deformation response of the pipe-soil system to the external loading was non-linear. Upon unloading, the pipe-soil system was unable to recover the deflection, however the pipes were usually observed to regain their shapes after they were recovered from the buried pipe installation.

In the 300 mm diameter pipe tests, two different pipe profiles were tested. The load-deflection response of the 90VX pipe profile under various levels of backfill cover is given in Figure 4-18. It should be cautioned that the tests are not directly comparable as the installation densities varied between tests. However it is generally evident that increasing the backfill cover afforded greater protection to the pipe. A vertical diametric strain of 5% was reached at a surface pressure of approximately 500 kPa for the shallow covers, but a pressure of 670 kPa was needed to achieve the same deflection for the test with 800 mm cover.

The influence of pipe profile can be observed in Figure 4-19. Three test results are provided, all with 450 mm of cover. Two of the tests were with pipes having a 90VX profile. Test 300/1 on a 110VX profile pipe showed a slightly stiffer response than the better of the 90VX tests, test 300/2, which had similar soil densities after installation. Test 300/4 had the lowest density index in the surround, which was reflected in the weaker pipe installation response than that realized in test 300/2.

[3] Cover is equal to the initial cover less the plate settlement, plus the settlement of the pipe crown.

The influence of pipe profile was more pronounced at greater cover height. Figure 4-20 provides data from a further three tests of buried pipes with an initial backfill cover height of 650 mm. An average applied surface pressure of approximately 615 kPa was required to reach a vertical diametric strain of 3% for the 110 VX profiles, 66% more than the pressure that brought the 90VX profile to the same level of vertical deflection.

Initial validation of the soil box testing is provided in Figure 4-21, wherein the load-deflection response of a field test (F300/3) is compared with that of two soil box tests having the same pipe-soil geometry. The estimated density indices of the sand as placed in both the backfill and the surround were generally 70% or slightly higher, however the more readily deformable pipe-soil system, 300/4, was estimated to have the surround soil placed at a lower density index of between 60 and 65%.

The 375 mm diameter pipes were all 110VX profile and in all but one instance were protected with 700 mm of cover. The exception had only 300 mm of cover (test 375/1). A comparison of load-deflection data for 300 and 700 mm cover is given in Figure 4-22, which verifies that cover height is an important parameter in limiting pipe deflection for a given load. The target vertical diametric strain of 5% was reached at only 225 kPa for the 300 mm cover, but took two to three times this value of pressure when the cover was increased to 700 mm (pressures were estimated to be 560 and 800 kPa for tests 375/4 and 375/6, respectively). It should be noted that the density index of the backfill in test 375/1 with only 300 mm of cover was only 60%, suggesting that this test would best be compared with 375/4.

From Table 4-VIII it would appear that the shallow cover height meant that the pressure applied to the surface of the backfill was transmitted directly to the crown of the pipe, as the loading plate had not penetrated the sand at this small pressure.

The difference in load-deflection behaviour of 375/4 and 375/6 was most likely a consequence of the relatively low density achieved in the backfill in the former test (a density index of 65% compared with approximately 78%), giving rise to an apparently less stiff response. The densities of the surround in the two tests were quite close (75 and 80%).

All soil box tests on 375 mm diameter pipe with 700 mm cover are compared in Figure 4-23. The bounds of load-deflection behaviour were provided by tests 375/4 and 375/6. Despite test 375/8 having the same soil preparation as 375/6 (identical densities within both the backfill and the surround), the load-deflection response was weaker. The pressure required to reach 5% vertical diametric strain in test 375/8 was approximately 10% less than that observed in test 375/6. The difficulty of achieving repeatability in soil box tests of this nature is apparent, as a bearing failure is clearly evident in the plot for test 375/8 (at a surface pressure of 600 kPa), but not for test 375/6.

In addition, test installation 375/5 had even higher soil density indices than 375/6 for both the surround and the backfill, yet was marginally a less stiff pipe-soil system.

In Figure 4-24, the load-vertical deflection responses of soil box tests 375/5 and 6 are compared with the field test, F375/7, all tests having an initial cover height of 700 mm. The field installation was prepared at soil densities approaching those recorded for 375/5, however the response was much stiffer. Importantly, loading in the field test appeared not to affect the pipe until a surface pressure of almost 300 kPa had been reached, suggesting high shear stress was developed between the stiff clay soil and the compacted sand of the installation, helping to take the initial external loading on the backfill surface.

The 450 mm diameter pipe test series consisted of pipes of the one pipe profile, 125VX. Two field tests were among the five tests in the series (F450/3 and 4). Cover heights were 450, 600, 700 and 800 mm. The load-deflection responses observed in the tests are provided in Figure 4-25. Generally as cover height increased, the stiffness of the soil-pipe system increased.

Again there were differences in soil densities of the installations, most noticeably with high compaction levels achieved in field test F450/4 (700 mm of cover). The high surround density index in this test (over 85%) may explain partly why the horizontal deformation of the pipe lagged well behind the vertical deformation as it was loaded. The ratio of vertical to horizontal diametric strain was 3.5 at 5% vertical strain.

Judging by the observed deformation ratios for each of the tests (Tables 4-VII and 4-VIII), it would seem that the pipe profile was inadequate, in terms of its stiffness, for the pipe diameter. At 3% vertical diametric strain, the deformation ratio was observed to vary between 1.7 and 4.3, considerably higher than any other test series. Only one 300 mm diameter, 90VX pipe test exceeded the lower boundary of the deformation ratio in the 450 mm diameter test series, namely test F300/3.

4.5.2.2 Earth pressures

Soil pressure cells were used in eleven of the tests, which included those conducted by Morris and Mahar (1989) (tests 450/1, 2 and 5), two of the field tests (F450/3 and F375/7), and four of the remaining tests (300/4, 5 and 6, and 375/8). Generally, the cells were positioned at a level of 150 mm above the pipe crown to measure vertical pressure, and in the surround at the mid-height of the pipe to record both vertical and horizontal earth pressures. Pressure cell data for each test are provided in graphical form in Appendix A. All pressure cells were re-zeroed on the day of testing, so initial stresses are not included.

Pressure cells located at 150 mm above the pipe crown to measure vertical soil pressure were positioned below the centre of the plate and along the pipe, up to 500 mm away from the centre of the load. The greatest vertical soil pressure increases due to surface loading were recorded immediately below the loading plate and above the pipe crown. Distributions of vertical pressures at 150 mm above the pipe crown and at 150 mm and 300 mm longitudinally from the centre of the_pipe are shown in Figure 4-31 for three 300 mm diameter pipe tests, provided with 450, 650 and 800 mm of cover.

It can be seen from Figure 4-31 that cover height has two effects. Firstly, the proportion of load reaching the pipe below the centre of loading reduces as the cover is increased. Secondly, at the maximum cover height of 800 mm, load spreading along the pipe from the central point was clearly evident. These observations are highlighted in Table 4-X, wherein the proportion of the applied pressure reaching the pipe (as measured at a height of just 150 mm above the crown) is recorded for 450 kPa surface pressure, the maximum recorded for the shallow pipe installation.

As the cover height increased, the pressure 150 mm above the pipe crown, and below the centre of the loading plate reduced from 97% at 450 mm of cover, to 27% at 800 mm cover, of the average pressure applied to the plate. The proportion of the applied pressure measured 300 mm along the pipe from the centreline at the same level within the installation, was 14%, 32% and 23%, for the 450, 650 and 800 mm cover heights, respectively. The extent of load spreading is more readily seen if the pressure 300 mm away from the centre is expressed as a proportion of the central pressure. Then the proportions are 14%, 36% and 84%, for the 450, 650 and 800 mm cover heights, respectively, clearly indicating the value of providing cover to spread the load along the pipe.

In this same Table, proportions of the applied pressure are also given for the two other tests near the maximum applied pressure for each test. Proportions increased as the applied loading increased, most noticeably in test 300/8 in which the pressure above the pipe and below the centre of the loading plate increased from 63 to 95%, when the surface pressure was increased from 450 to 750 kPa.

The effect of backfill height on the maximum pressure increase observed above the pipe crown for 300 mm diameter pipes and 90VX profile is provided in Figure 4-32. The last pressure reading in test 300/5 was strangely low, suggesting unloading near the pipe, although 150 mm either side of this location, measured pressures increased by 26% and 58% from the previous readings. Ignoring this one reading, it can be seen that the

800 mm cover height dramatically reduced the load on the pipe, when compared with either the 650 or 450 mm covers.

Figure 4-33 provides data for the same pipe tests on the lateral (or horizontal) pressures developed in the surround beside the springline of the pipe. Lateral pressures built up quickly in both tests with 450 and 650 mm of cover, but both the rate of increase and the magnitude of lateral pressures were significantly lower for the deepest cover. At 490 to 495 kPa surface pressure, the lateral pressure was only 71 kPa compared with 195 kPa in test 300/5 with 650 mm of cover.

The lateral pressures may have been influenced by the pipe's ability to deform under loading of the crown, as indicated by its pipe stiffness. Therefore the lateral pressures for the three tests with 650 mm of cover have been plotted against applied pressure in Figure 4-34. Each of these tests had similar soil preparations and densities. Comparing the 90VX test data (300/5) with the two 110VX tests (300/7 and 300/8), it can be observed that the less stiff pipe (90VX) shed the load to the surround soil far more readily, after the applied pressure passed 300 kPa. In the other two tests, the lateral pressure measured at a surface pressure of 500 kPa varied from only 35 to 75 kPa, compared with 195 kPa for 300/5 at an applied pressure of 495 kPa.

Only two of the 375 mm diameter pipe series were provided with earth pressure cells. Both had cover heights of 700 mm, however one was a field test (F375/7) while the other was a test, which was conducted in the soil box (375/8). As with the 300 series, pressure cells were located at 150 mm above the pipe crown and were placed at and away from the centre of the loading. As larger spacings were adopted in the field test, the distribution of vertical soil pressure along the pipe has been presented in Figure 4-35 by the ratio of the measured pressure away from the centre, to the pressure at the centre, for the particular pipe test.

Three observations may be made from this Figure. Firstly, the applied loading did not have any significant influence on the soil, 150 mm above the pipe and one metre away from the centre of the 200 mm by 500 mm long loading plate. Indeed the soil pressure increase at this distance from the plate was effectively zero throughout the test. Secondly, the measured pressure was almost inversely related to the distance from the centre of the plate. For example, between applied surface pressures of 400 and 600 kPa, pressure cells placed 150, 300, 500 and 1000 mm from the centre recorded approximately 70, 35, 15 and 0% of the central pressure at the same depth, respectively. The theory of elasticity would tend to suggest that these proportions should be higher, however the soil was overstressed as evidenced by the large settlement of the loading plate. Finally, in the latter stages of testing, the pressure ratios decreased, suggesting localization of pressure closer to the centre of loading.

The lateral pressures recorded at the springline for the two tests are compared in Figure 4-36. The field test was prepared to a higher surround density. The soil box pipe-soil system shed slightly more of the applied surface pressure laterally to the surround, suggesting slightly better arching than was observed in the field test. However a limit was reached at almost 700 kPa, beyond which no further increase in pressure was recorded.

The 450 mm diameter pipe series included four tests with earth pressure measurements 150 mm above the crown below the centre of the applied load, as well as horizontally and vertically in the surround adjacent to the springline of the pipe. In Figure 4-37, the pressure measured above the crown in each of the four tests has been plotted against the applied surface pressure. As these tests installations were prepared with cover heights of 450 (two tests), 600 and 800 mm, the plot provides further evidence of the importance of cover in protecting the flexible pipe. The proportion of the applied pressure measured at 150 mm above the pipe crown varied with the height of cover. The 450 mm covers resulted in 65 to 75% of the 500 kPa applied at the surface of the backfill, while 600 mm cover realised just 54%. The proportion of pressure for the test at 800 mm cover and under the same loading condition was only 17%.

The relationship between pipe deflection and the pressure increase at 150mm above the pipe crown due to loading is illustrated in Figure 4-38 for the three pipe diameters. Vertical diametric strain has been plotted against the pressure measured 150 mm above the crown of the pipe. Deflection appeared to be in most instances directly proportional to this pressure. Generally 1% of diametric strain was realised by applying 80 to 90 kPa of pressure immediately above the crown. However the two field tests (F375/7 and F450/3) gave a much stiffer response, with approximately 140 kPa being required to achieve the same level of strain. So it may indicate that the supported walls of the soil box were not as stiff as the dry clay soil in the field tests, although differences in soil compaction between tests may have contributed to this observation.

One pipe-soil system (test 300/6) was noticeably less stiff. The relevant test was conducted in the soil box on a 300 mm diameter, 90VX pipe, with 800 mm of protective cover. This pipe was the least stiff of all the pipes according to the pipe stiffness tests reported by the manufacturer. However, other soil box tests on the same pipe configuration gave similar responses to that of the 110VX profile, 300 mm diameter pipes.

Figure 4-38 suggests that there is no direct relationship between pipe stiffness and vertical deflection of a pipe, at least for the range of pipe stiffnesses investigated. Rather it would seem that deflection is effectively independent of pipe stiffness, confirming the notion of researchers McGrath, Chambers and Sharff (1990) that the overall stiffness of the pipe-soil system is the key. Indeed, for these very flexible pipes, the overall response is dominated by the stiffness of the soil around the pipe. One exception to this general observation was observed during testing of the 300 mm diameter pipes with 450 mm of cover. Pipe stiffness did appear to influence pipe deflection. Unfortunately, the 110VX pipe test with 450 mm of cover was not installed with earth pressure cells.

4.6 SUMMARY OF THE CHAPTER

4.6.1 Structural Properties of the Pipe

The manufacturer's pipe stiffness test value for 375 mm diameter pipe was shown to be slightly conservative. However tensile testing of coupon specimens from the same pipe revealed that the recommendations given in AS/NZS 2566.1 for Young's modulus of the pipe material grossly exaggerated the capacity of PVC to absorb tensile loading. Corrections from the manufacturer for the effects of spiral winding were unable to explain this discrepancy.

4.6.2 Buried Pipe Tests

Pipe stiffness appeared to be an important factor in limiting deflections of the 300 mm diameter pipes under external loading, judging by the differences in performances of installations with the 90VX and 110VX pipe profiles under the same depth of backfill cover of 450 mm (refer Figure 4-18). The stiffer pipe experienced less deflection.

The 450 mm diameter pipe profile did not have sufficient cross-sectional stiffness, judging from the low degree of ovality of pipe deformations upon loading. The lack of ovality may also have been a function of the ratio of the width of the loaded area to the pipe diameter, and the cover height. At low cover heights and a width of loading much smaller than the diameter, a greater part of the loading will be transmitted to a localised region near the crown of the pipe.

Cover height is essential in protecting the pipe. If the cover is too shallow, surface pressures may be transmitted almost directly to the pipe, without much reduction in the magnitude of the surface pressure. Greater covers will permit greater loading of the near surface soil, before the pipe is adversely affected.

The level of compaction of the backfill soil is important as, the greater the compaction, the higher will be the ultimate bearing capacity under the surface loading. The level of compaction of the surround soil is just as important in ensuring that the pipe is supported laterally. Less well-prepared surrounds will permit greater deflections of a pipe protected by the same cover height and consisting of soil of the same density.

A review of the influence of the measured pressure above the pipe crown and the vertical diametric strains indicated that deflection of the pipe was largely independent of pipe stiffness for the range of pipe stiffness in this test series. In terms of industry standards, the pipes would be considered to be very flexible. Most pipe-soil systems had similar stiffness, regardless of the pipe diameter or profile. However the two field tests, which had pressure cells installed, were noticeably stiffer, suggesting that the walls of the soil box were not as stiff as the clay in the field installations.

There was also evidence that the sand-clay interface in the field tests supported the loading from the backfill surface, until the side interface strength was exceeded, and the load was almost directly transmitted to the pipe. There was little evidence of significant side support from the sand-plywood interface in the soil box tests.

Some variability of trends occurred, which could not be readily explained throughout the buried pipe test series. An aim of the subsequent numerical modelling was to clarify some of these discrepancies. After development of a constitutive model for the backfill soil in the next chapter, a series of finite element analyses are applied to simulate all the tests discussed in this chapter, including the simulated pavement buried pipe tests and the series of "unpaved trench", buried pipe tests, conducted both in the laboratory soil box and in the field. Chapter 7 discusses the two-dimensional FEA (finite element analyses), while Chapter 8 presents the results of the three-dimensional FEA.

The pipe properties determined in this Chapter are applied in these analyses. Verification of the chosen stiffness of the 375 mm diameter pipe was made through 3D FEA of the pipe stiffness test (refer Chapter 8).

4.7 REFERENCES TO THE CHAPTER

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TABLE 4-I. Geometry of Profiled Cross Sections, Prior to Winding

PROPERTY		SECTION		
		90VX	**110VX**	**125VX**
Profile width	(mm)	90	112.2	124.0
Number of ribs per width of profile		9	9	9
Overall height of profile	(mm)	7.55	10.75	11.8
Width of flange	(mm)	4.45	6.3	6.8
Flange thickness	(mm)	0.82	1.24	1.4
Web thickness	(mm)	0.78	1.3	1.1
Web height	(mm)	5.53	8.31	9.0
Wall thickness	(mm)	1.2	1.2	1.4
Rib spacing	(mm)	10	12.47	13.8
Area	(m^2/m)	1.60×10^{-3}	2.69×10^{-3}	3.10×10^{-3}
Moment of inertia	(m^4/m)	1.15×10^{-5}	3.86×10^{-5}	5.70×10^{-5}

TABLE 4-II. Bending Stiffnesses (EI) of Pipes derived from Pipe Stiffness Tests (as reported by the pipe manufacturer)

Profile	D (mm)	PS (kN/m/m)	S = 0.0186PS (kN/m^2)	EI (= SD^3) (kNm^2/m)
90VX	300	41	0.763	0.0206
110VX	300	108	2.01	0.0543
110VX	375	67	1.25	0.0658
125VX	450	55	1.02	0.0933

TABLE 4-III. Results of Pipe Stiffness Tests on 375 mm Diameter Ribbed Pipe

Test	Pipe length L_{av} (mm)	Uncorrected			Corrected		
		PS (kN/m/m)	EI ($kN.m^2/m$)	Range of strain	PS (kN/m/m)	EI ($kN.m^2/m$)	Range of strain
1	299	79.1	0.0777	7.5%	73.8	0.0724	12%
2	295.9	79.9	0.0785	7.5%	87.3	0.0858	15%
2b	as above	79.3	0.0779	6%	82.9	0.0814	15%
2c	as above	79.3	0.0779	6%	82.9	0.0814	11%
3	298.5	75.0	0.0737	9.5%	87.3	0.0858	15%

TABLE 4-IV. Tensile Test Results on Coupons of Ribbed Pipe

TEST	Area (mm^2)	Peak tensile load (kN)	Stress at peak load (MPa)	Strain at peak load (%)	E upon re-loading (MPa)	E for 0.5 - 0.9 kN (MPa)
1	32.1	1.06	33.15	11.9	912	617
2	32.2	1.07	33.4	11.9	934	383
3	32.0	1.09	34.15	13.1	848	336
4	32.6	1.11	34.0	12.0	1011	374
5	32.6	1.11	34.1	10.7	1042	511

TABLE 4-V. Short Term Moduli, E_{ST}, for the Spirally Wound Pipe (based on short-term modulus and correction for winding strain from the pipe manufacturer)

Pipe Diameters, D (mm)	Pipe profile	Distance, y[2], to NA from inside of wall (mm)	Height of profile, H[2] (mm)	WS[2]	E_{ST} (MPa)
300	90VX	2.46	7.55	0.0266	2430
300	110VX	4.29	10.75	0.0332	2240
375	110VX	4.29	10.75	0.0251	2470
450	125VX	4.52	11.80	0.0220	2560

[2] from pipe manufacturer

TABLE 4-VI. Details of the Buried Pipe Tests

Test	Nominal pipe dia. (mm)	Profile	Height of backfill (mm)	Trench width (mm)	Estimated density index (%)[4]		Pressure cells
					Surround	Backfill	
1. Soil Box Tests - simulated pavement/ large semi-rigid plate/static loading							
P375/1	375	110VX	300	750	60	65	N
P375/2	375	110VX	300	750	75	65	N
P450	450	125VX	300	750	70	65	N
2. Soil Box Tests - non-paved tests/ small rigid plate							
300/1	300	110VX	450	620	75	75	N
300/2	300	90VX	450	620	70	70	N
300/4	300	90VX	450	620	75	60 to 65	Y
300/5	300	90VX	650	620	70	75	Y
300/6	300	90VX	800	620	60 to 65	60	Y
300/7	300	110VX	650	620	70	72	Y
300/8	300	110VX	650	620	68	72	Y
375/1	375	110VX	300	750	-	60[5]	N
375/4	375	110VX	700	750	75	65	N
375/5	375	110VX	700	750	80	*80*	N
375/6	375	110VX	700	750	70	75 to 80	N
375/8	375	110VX	700	750	70	75 to 80	Y
450/1	450	125VX	450	750	-	70	Y
450/2	450	125VX	450	750	65	75	Y
450/5	450	125VX	800	750	-	85	Y

[4] From dynamic cone penetration test, estimated to the nearest 5%
[5] By sand replacement test method

TABLE 4-VI, continued. Details of the Buried Pipe Tests

Test	Nominal pipe dia. (mm)	Profile	Height of backfill (mm)	Trench width (mm)	Estimated density index (%)[6]		Pressure cells
					Surround	Backfill	
3. Field Tests - non-paved tests/ small rigid plate							
F300/3	300	90VX	475	625	70	75	N
F375/7	375	110VX	700	760	85	70 to 85	Y
F450/3	450	125VX	600	770	75	80	Y
F450/4	450	125VX	700	770	85 to 90	80	N

[6] From dynamic cone penetration test, estimated to the nearest 5%

TABLE 4-VII. Summary of the Results of the Buried Pipe Tests (3% strain)

Test[7]	Height of backfill (mm)	Average pressure (kPa)	Cover height (%)	Deformation ratio Vert:Horiz
1. Soil Box Tests - simulated pavement/ large semi-rigid plate				
P375/1	300	120	99	1.05
P375/2	300	(185 max.)	-	-
P450	300	(185 max.)	-	-
2. Soil Box Tests - non-paved tests/ small rigid plate				
300/1	450	425	86	1.35
300/2	450	445	98	1.3
300/4	450	365	99	1.25
300/5	650	370	95	1.2
300/6	800	496	91	1.2
300/7	650	600[8]	96	1.2
300/8	650	625	95	1.15
375/1	300	200	100	1.3
375/4	700	475	85	1.4
375/5	700	516	88	1.4
375/6	700	600	79	1.5
375/8	700	600	86	1.2
450/1	450	385	93	2.4
450/2	450	395	-	1.9
450/5	800	795	-	1.7
F300/3	475	455	86	1.78
F375/7	700	930	71	-
F450/3	450	630	71	2.3
F450/4	450	740	70	4.3

[7] Italicised test notations indicate 90VX profile pipes
[8] Backfill surface failed after 600 kPa, prior to reaching 3% strain; plate had to be re-set.

TABLE 4-VIII. Summary of the Results of the Buried Pipe Tests (5% strain)

Test	Height of backfill (mm)	Average pressure (kPa)	Cover height (%)	Deformation ratio Vert:Horiz
Soil Box Tests - non-paved tests				
300/1	450	550	86	1.55
300/2	450	530	97	1.55
300/4	450	435	99	1.55
300/5	650	495	92	1.3
300/6	800	670	86	1.25
300/7	650	(650 max.)	-	-
300/8	650	(696 max.)	-	-
375/1	300	225	100	1.5
375/4	700	560	79	1.4
375/5	700	620	79	1.35
375/6	700	800	70	1.35
375/8	700	735	78	1.2
450/1	450	(490 max.)	-	-
450/2	450	505	-	2.15
450/5	800	(800 max.)	-	-
3. Field Tests - non-paved tests/ small rigid plate				
F300/3	300	525	76	2.4
F375/7	700	(950 max.)	-	-
F450/3	450	(675 max.)	-	-
F450/4	450	860	70	3.55

TABLE 4-IX. Applied Pressure in Unpaved Buried Pipe Tests to Cause Excessive Settlement (5% of initial cover) or Punching Failure

Test[9]	Cover height (mm)	Density index of backfill, $I_{D\ av.}$ (%)	Surface Pressure (kPa)		Comments
			At 5% reduction in cover height	Initiating punching failure	
300/1	450	75	345	NA	
300/2	450	70	600	NA	
300/4	450	62.5	412	NA	
300/5	650	75	385	395	
300/6	800	60	355	395	
300/7	650	72	650	680	Plate was re-set
300/8	650	72	615	730	Plate was re-set
375/1	300	60	-	265	No significant penetration of the sand
375/4	700	65	340	395	Poorly supported side walls
375/5	700	*80*	435	400	
375/6	700	77.5	370	390	
375/8	700	77.5	595	640	
450/1	450	70	355		
450/2	450	75	-	-	Not recorded
450/5	800	85	-	-	Not recorded
F300/3	475	75	410		
F375/7	700	77.5	530		
F450/3	600	80	328		
F450/4	700	80	299		

[9] Italicised test notations indicate 90VX profile pipes

TABLE 4-X. Proportion of Applied Pressure at 150 mm above Pipe Crown

Test	Cover Height (mm)	Applied Pressure (kPa)	Position of Pressure Cell along Pipe (150 mm above crown)		
			Below centre	+ 150 mm	+ 300 mm
300/4	450	450	97%	66%	14%
300/8	650	450*	63%	39%	32%
300/6	800	450*	27%	27%	23%
** interpolated results*					
300/8	650	750	95%	52%	39%
300/6	800	685	37%	34%	24%

Figure 4-1. A typical spirally wound uPVC pipe

Figure 4-2. The soil box with rotating displacement transducers for measuring internal pipe displacements

Figure 4-3. Emptying the soil box

Fig 4-4a. Excavation and sampling of the natural soil

Fig 4-4b. Pipe in position ready for backfilling

Fig 4-4c. Compaction of backfill with vibrating plate compactor

Fig 4-4d. End of pipe for monitoring of internal pipe displacements

Figure 4-4. Preparation of the field buried pipe test series

Figure 4-5. Large plate loading
(600 x 900 mm, simulating trafficked light pavement)

Figure 4-6. Reaction beam and dead weight system for loading the backfill surface of the buried pipes

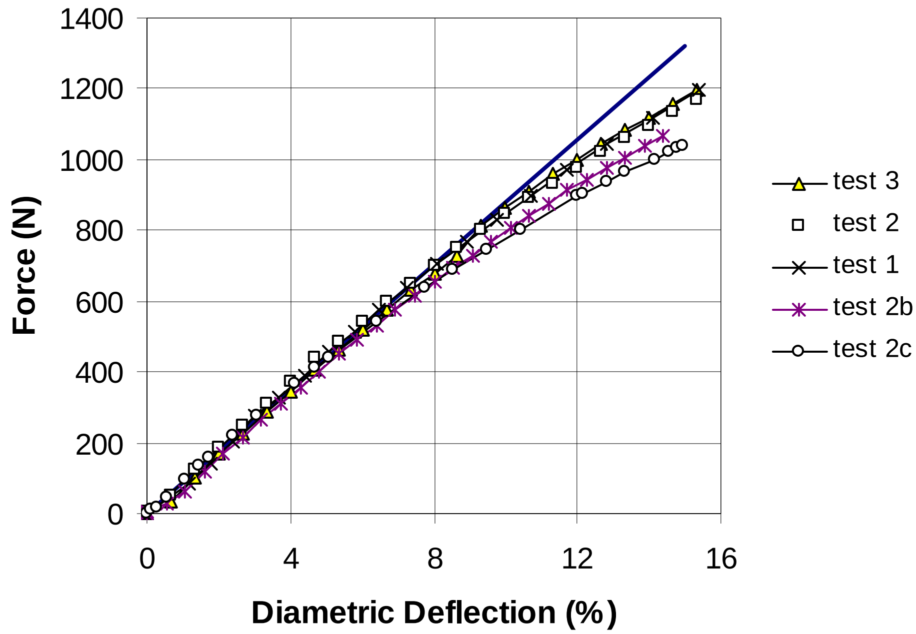


Figure 4-7. Pipe stiffness test data for 375 mm diameter, uPVC pipe (110VX)

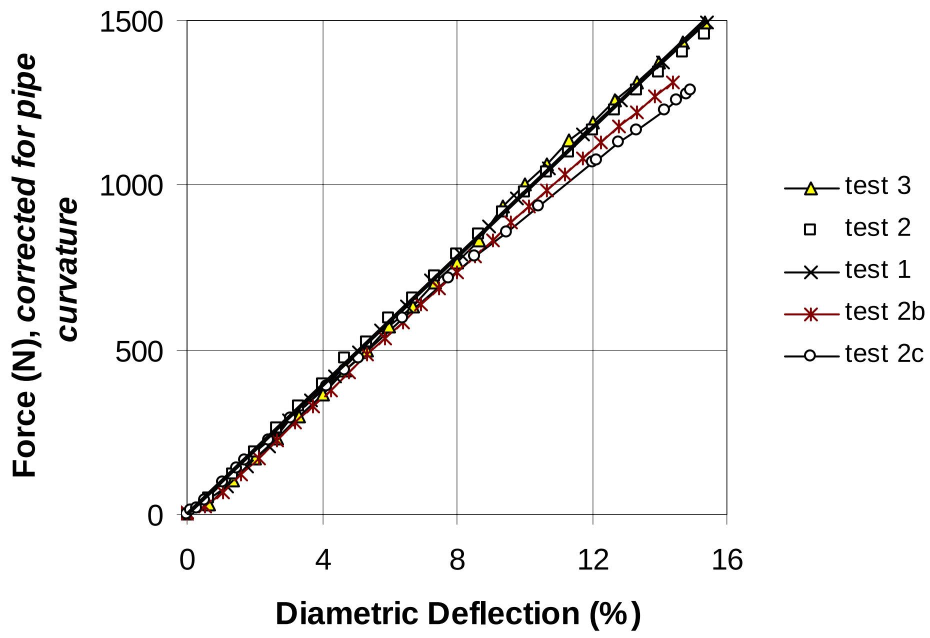
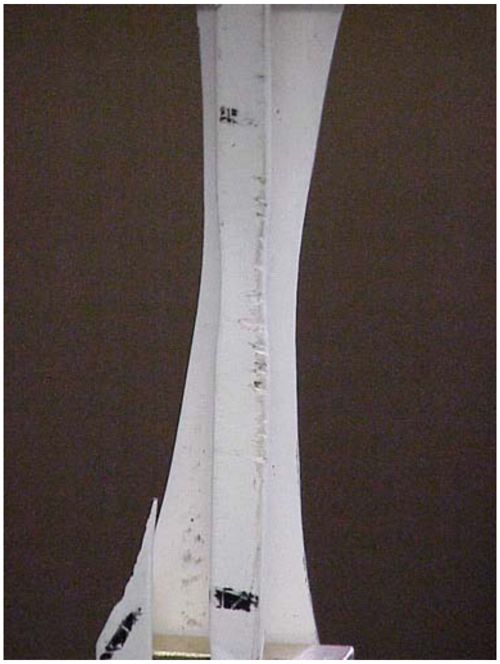


Figure 4-8. Corrected pipe stiffness test data for 375 mm diameter pipe

Figure 4-9. Set up of tensile coupon test 1: side view

Figure 4-10. Set up of tensile coupon test 1: front view



Front view of specimen 1 showing necking of flange

Side view of specimen 1

Fig 4-11. Stretching of coupon test specimen 1

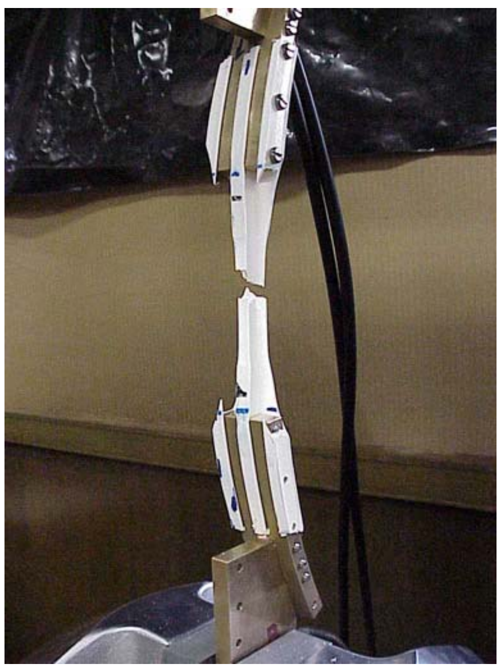


Figure 4-12. Failure of specimen 5

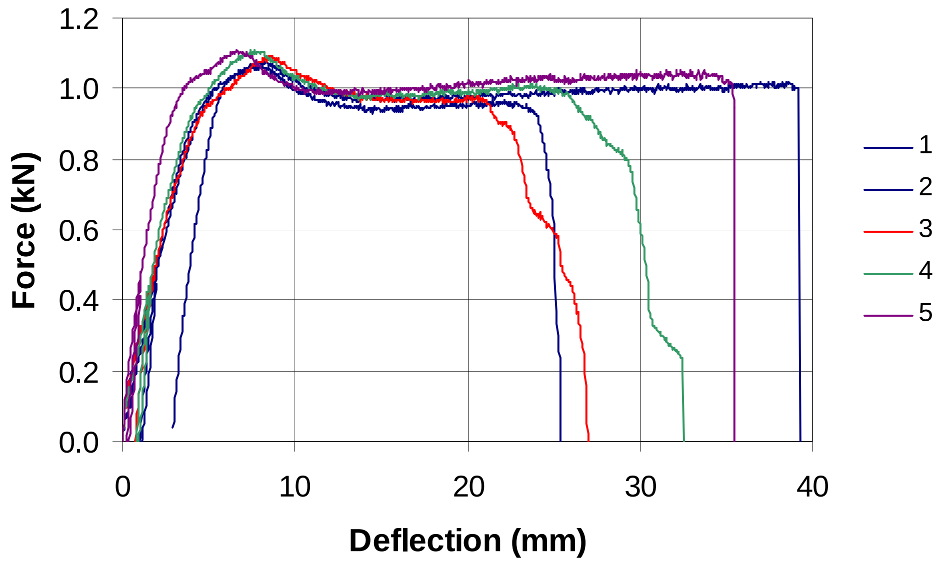


Figure 4-13. Load extension curves for the tensile coupon tests

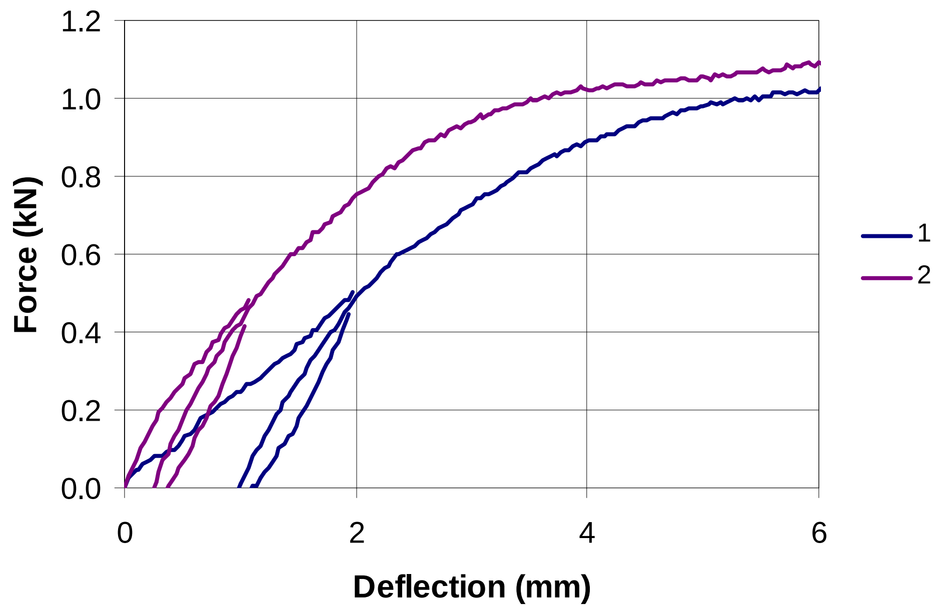


Figure 4-14. Examples of non-linear behaviour to peak force for tensile coupon tests 2 and 5

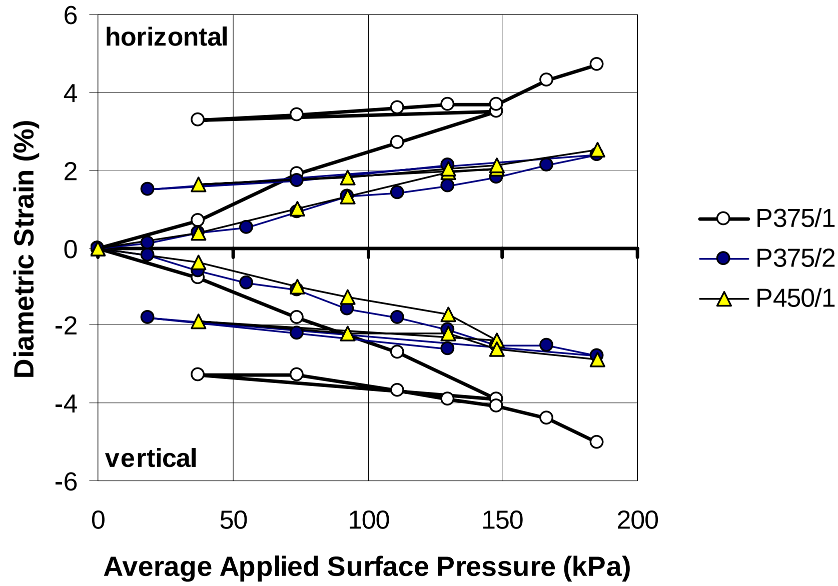


Figure 4-15. Deflection response to loading of 375 and 450 mm diameter pipe, simulated pavement, 300 mm of backfill cover

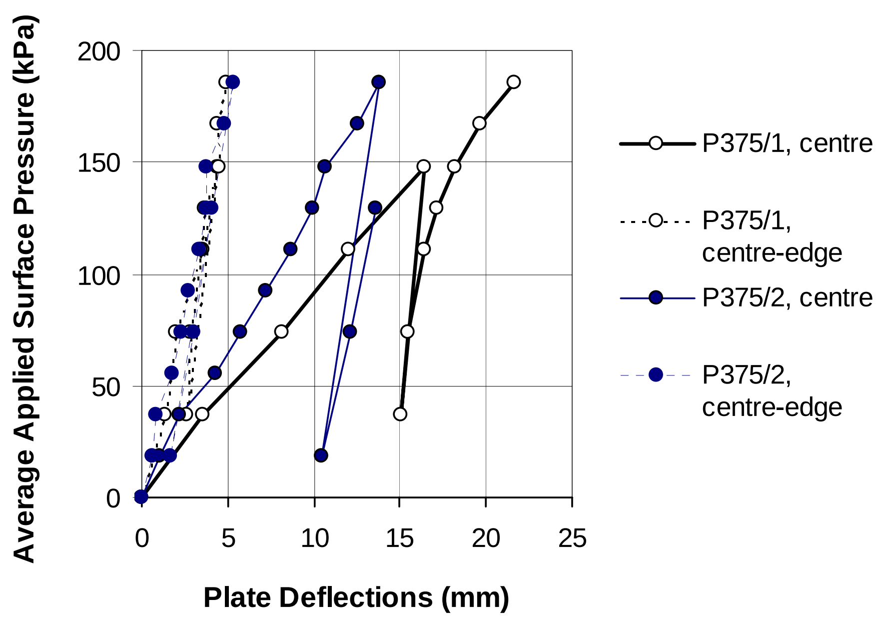


Figure 4-16. Defection of large plate, 600 x 900 mm, with loading

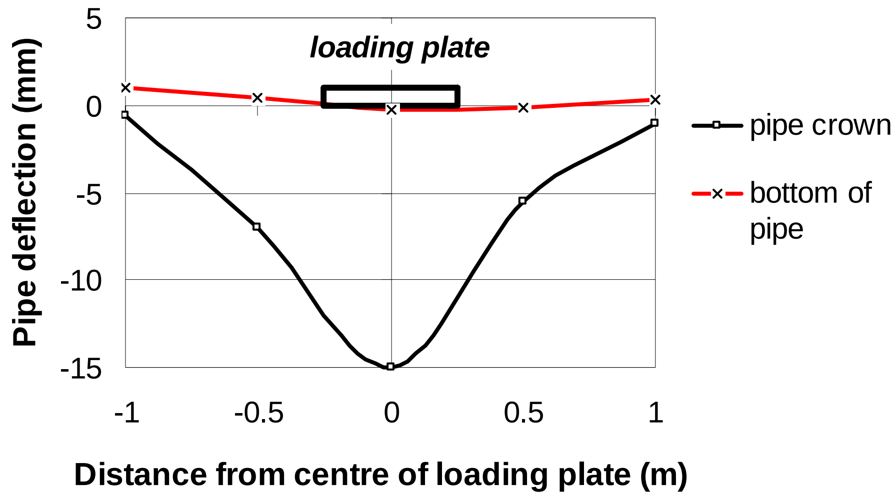


Figure 4-17. Longitudinal deflection of pipe 375/5 (700 mm initial cover) at a surface pressure of 585 kPa.

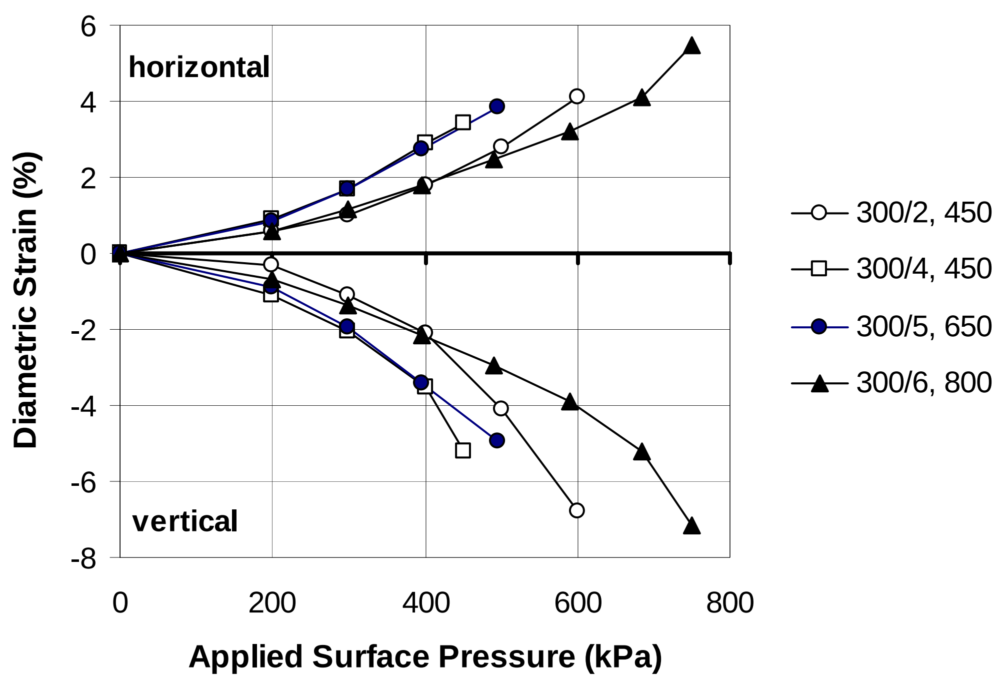


Figure 4-18. Deflection response to loading of 300 mm diameter, 90VX pipe, with varying backfill cover

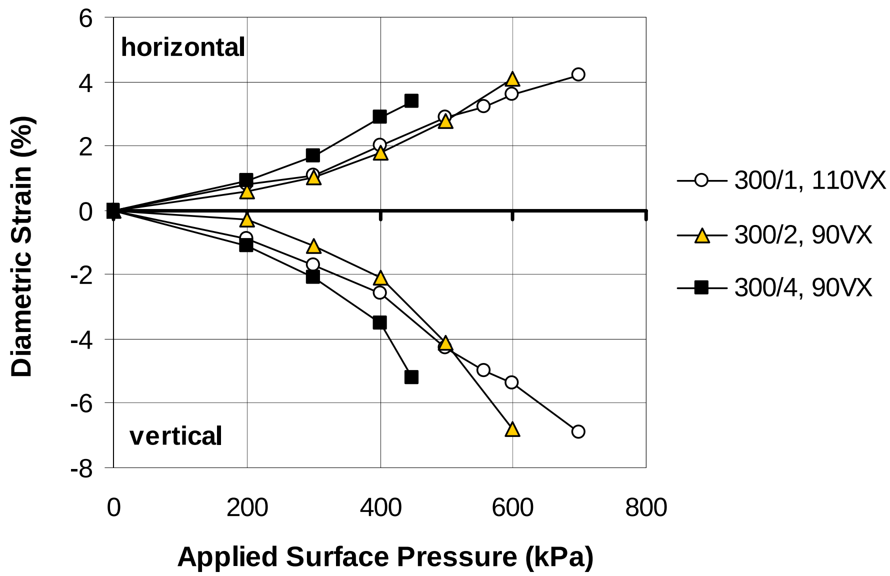


Figure 4-19. Influence of pipe section on deflection of 300 mm diameter pipe (450 mm of backfill cover)

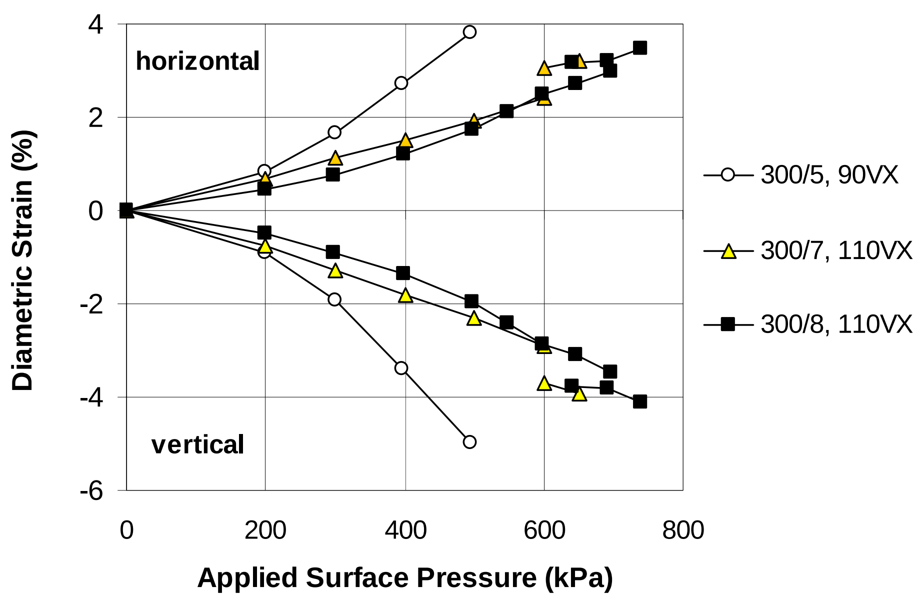


Figure 4-20. Influence of pipe section on deflection of 300 mm diameter pipe (650 mm of backfill cover)

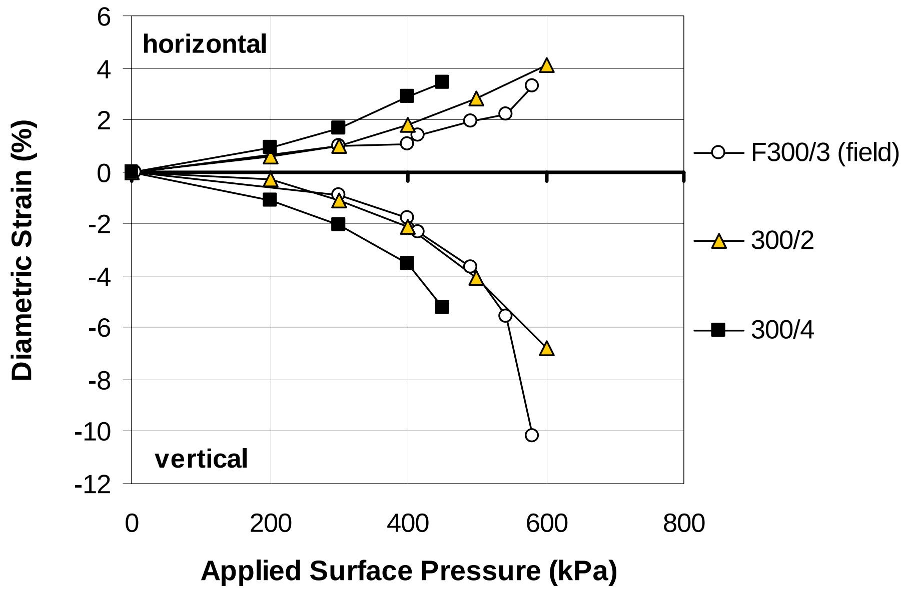


Figure 4-21. Field and soil box deflection response of 300 mm diameter pipe (90VX, 450 mm of backfill cover)

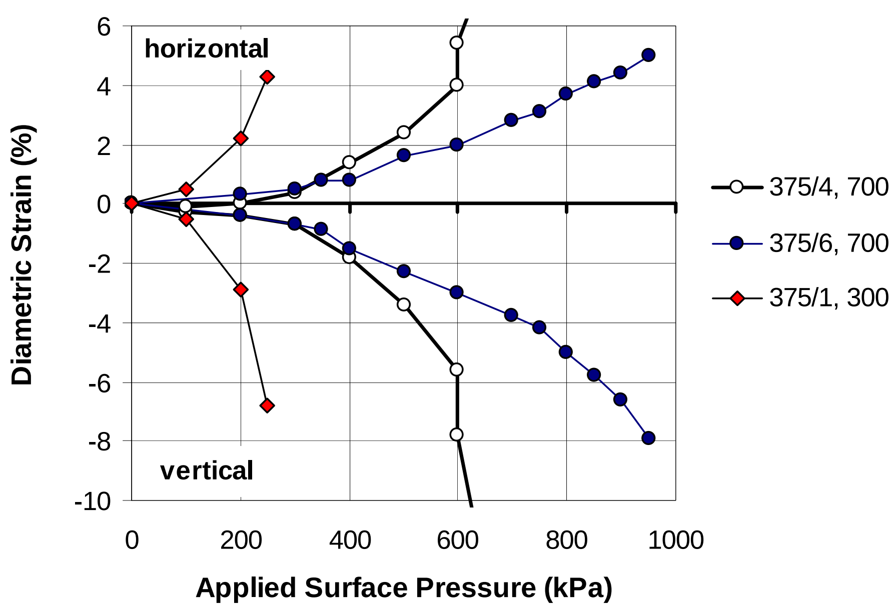


Figure 4-22. Deflection response to loading of 375 mm diameter, 110VX pipe, with 300 and 700 mm backfill cover

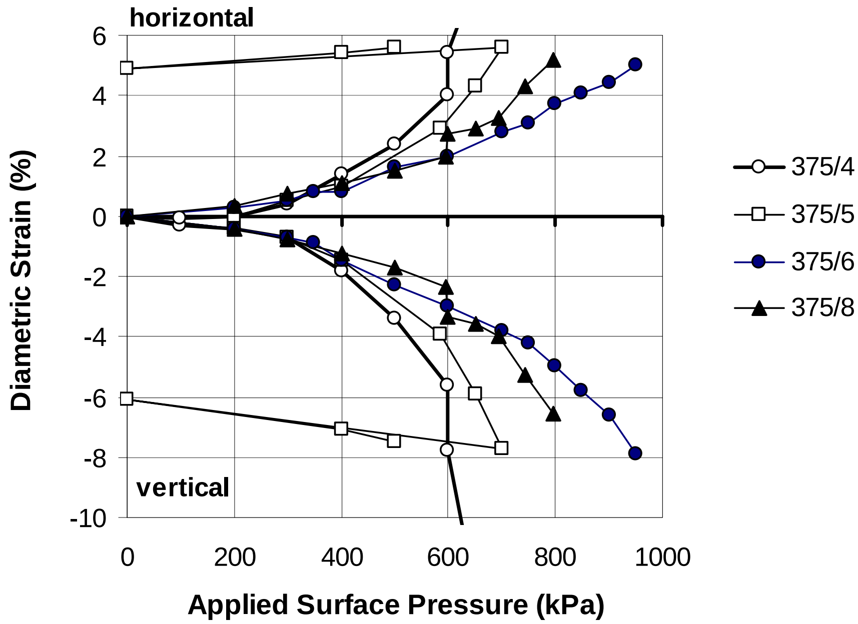


Figure 4-23. Deflection response of 375 mm diameter pipe (soil box, 700 mm of backfill cover)

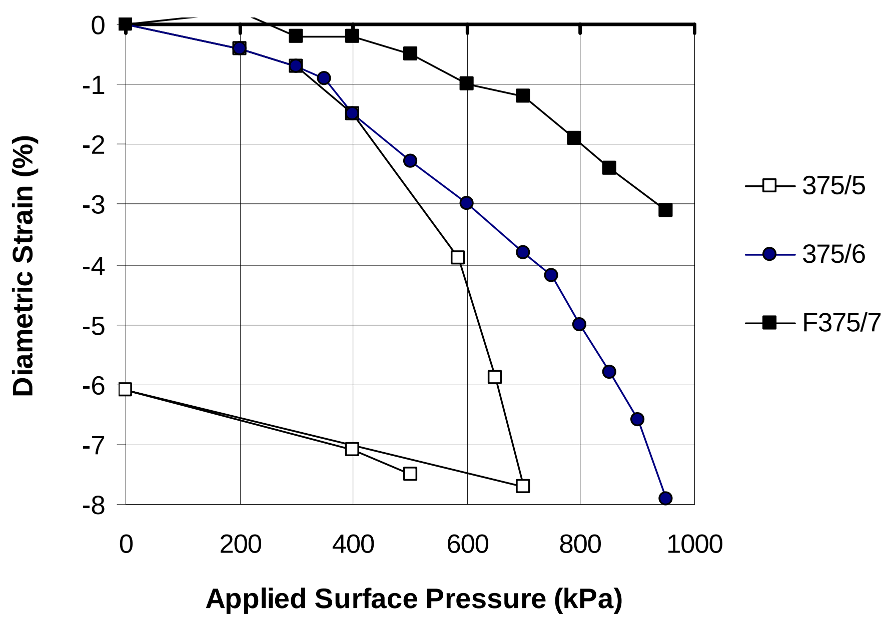


Figure 4-24. Vertical deflection response of 375 mm diameter pipe in field installation and in the soil box (700 mm of backfill cover)

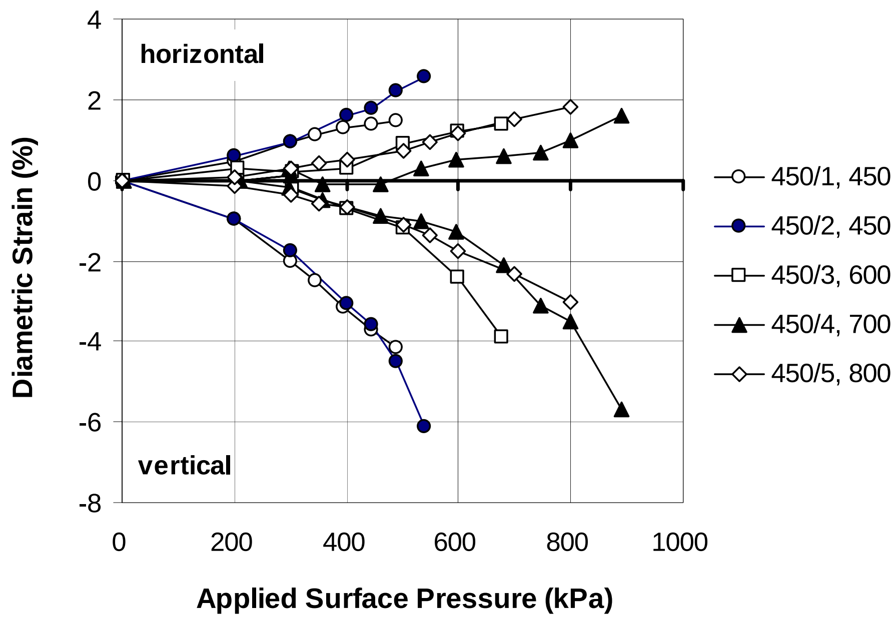


Figure 4-25. Deflection response to loading of 450 mm diameter, 125VX pipe, with varying backfill cover (Note: 450/3 and 4 were field tests)

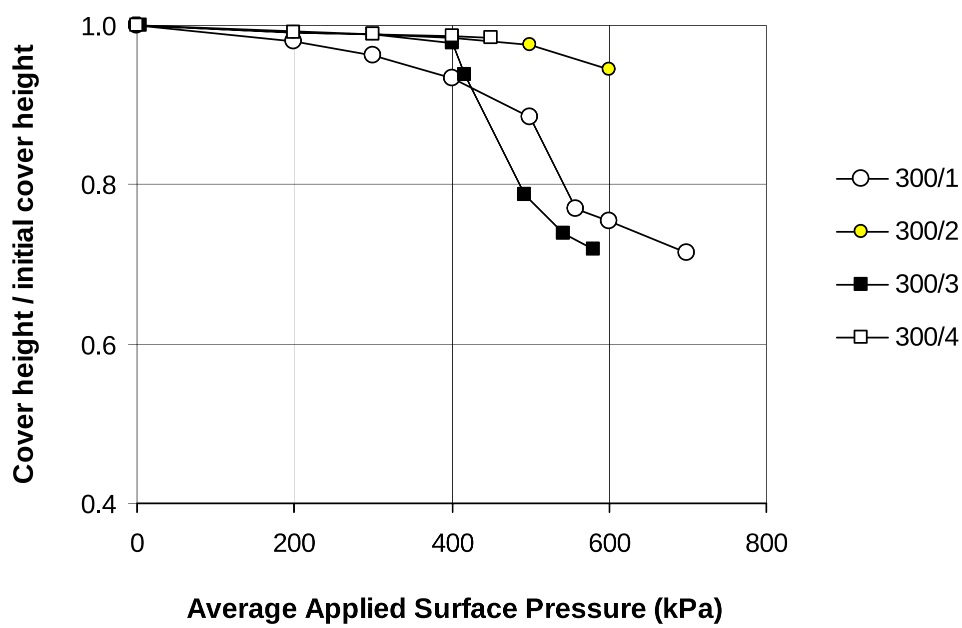


Figure 4-26. Relative settlement of rigid plate during loading of 300 mm diameter pipe (450 mm initial cover)

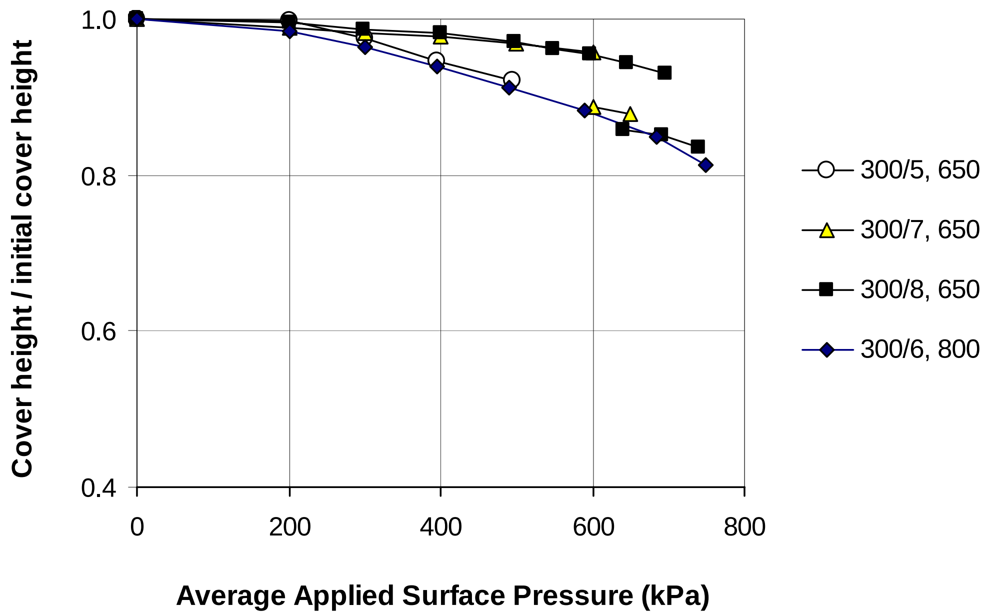


Figure 4-27. Relative settlement of rigid plate during loading of 300 mm diameter pipe (> 450 mm initial cover)

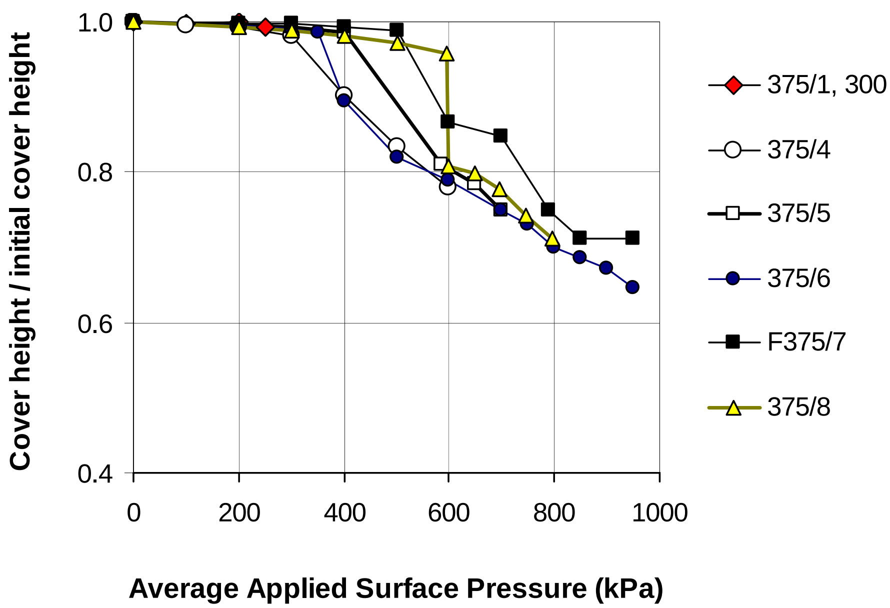


Figure 4-28. Relative settlement of rigid plate during loading of 375 mm diameter pipe (300 and 700 mm initial cover)

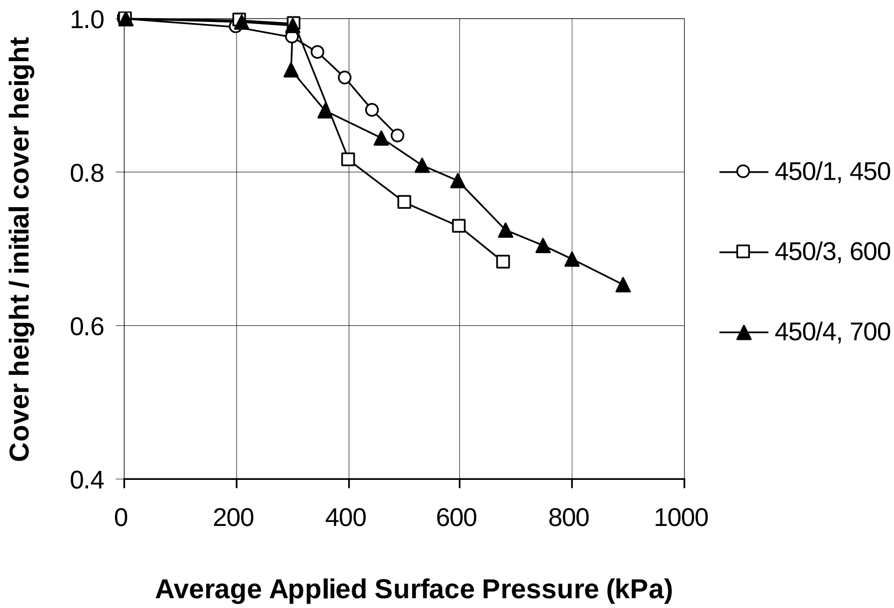


Figure 4-29. Relative settlement of rigid plate during loading of 450 mm diameter pipe (450, 600 and 700 mm initial cover)

Plate position at set-up

Punching shear failure of sand upon loading

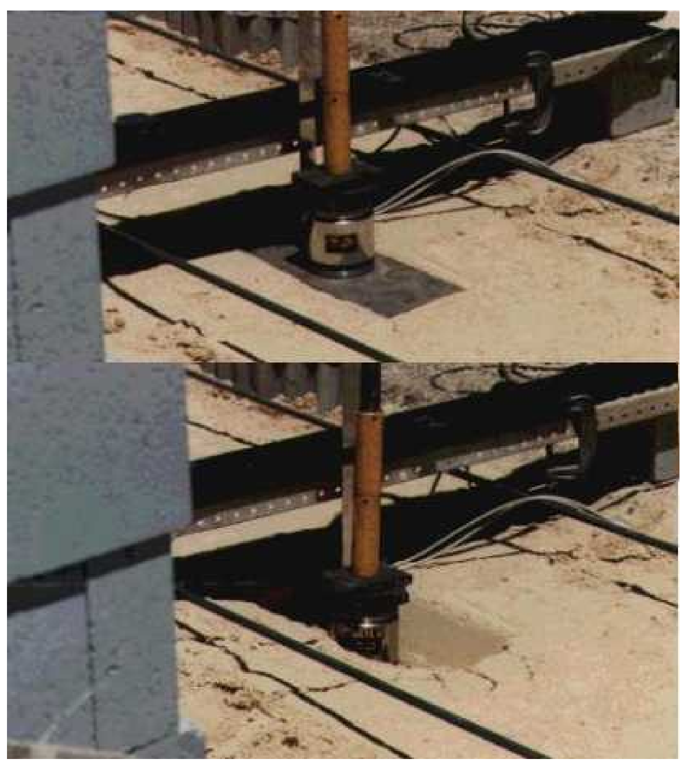


Figure 4-30. Failure of sand upon loading in a field test (0.2 x 0.5 m rigid plate)

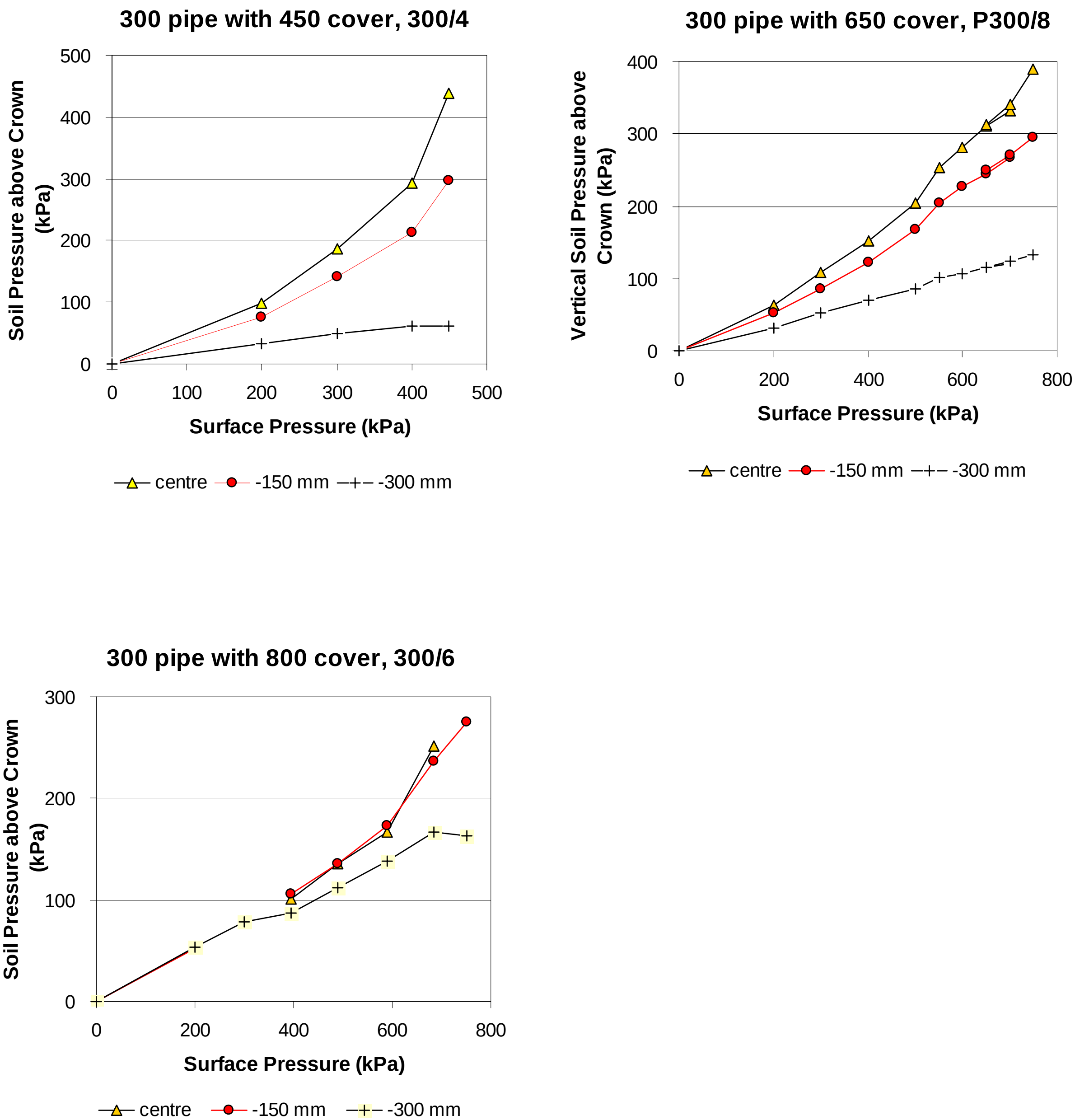


Figure 4-31. Distributions of vertical soil pressure at 150 mm above the pipe crown along the pipe, for three 300 mm diameter pipes

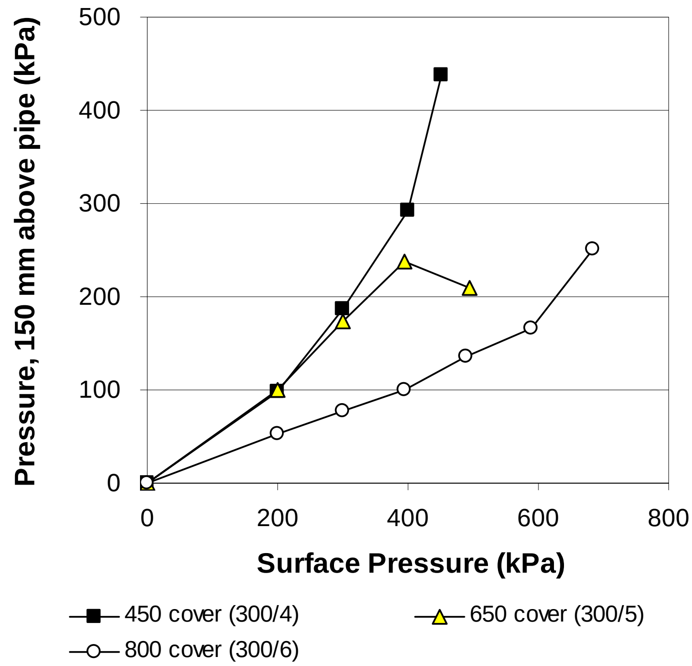


Figure 4-32. The influence of backfill height on the vertical soil pressure 150 mm above the pipe crown (centre of pipe), 300 mm diameter 90VX pipes

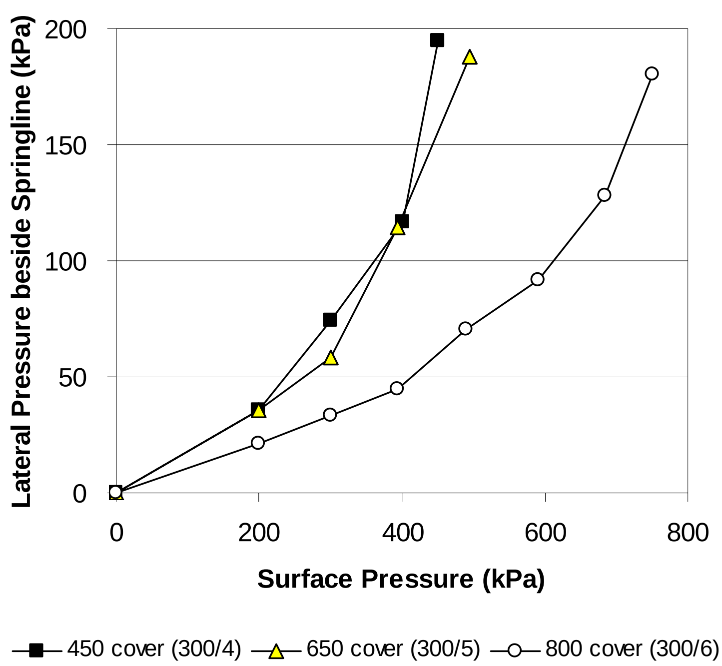


Figure 4-33. Lateral pressures in the surround, 300 mm diameter 90VX pipes

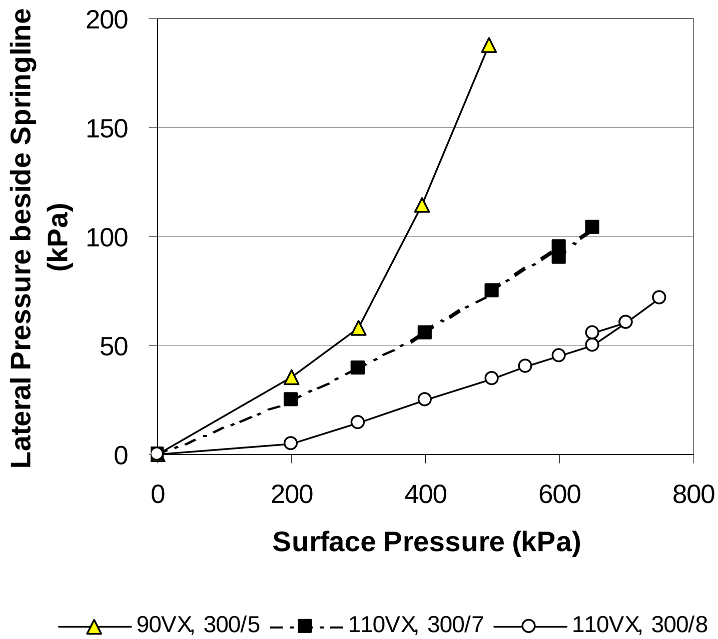


Figure 4-34. The influence of pipe profile on lateral pressures developed in the surround, 300 mm diameter pipes, 90VX and 110VX

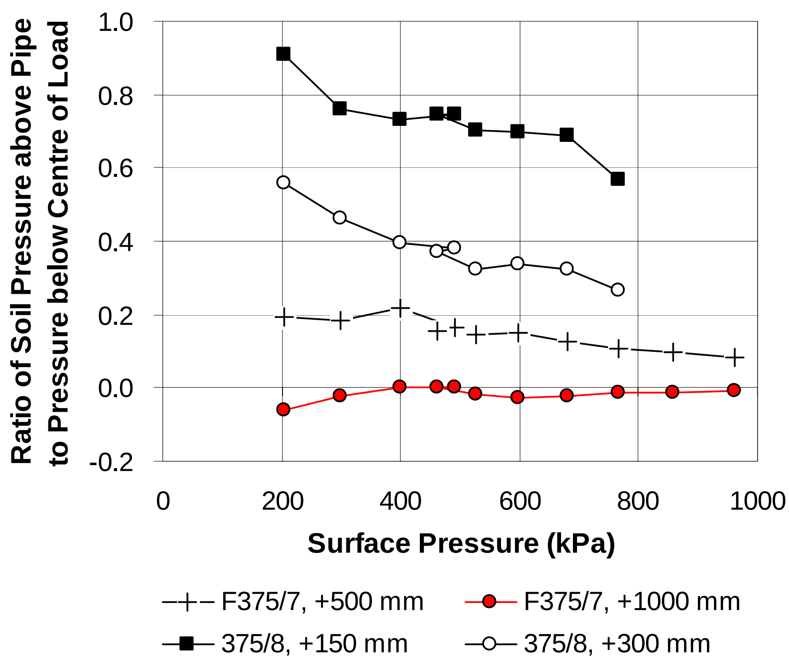


Figure 4-35. Distributions of vertical soil pressure at 150 mm above the pipe crown along the pipe, 375 mm diameter pipe, with 700 mm of cover (F375/7 & P375/8)

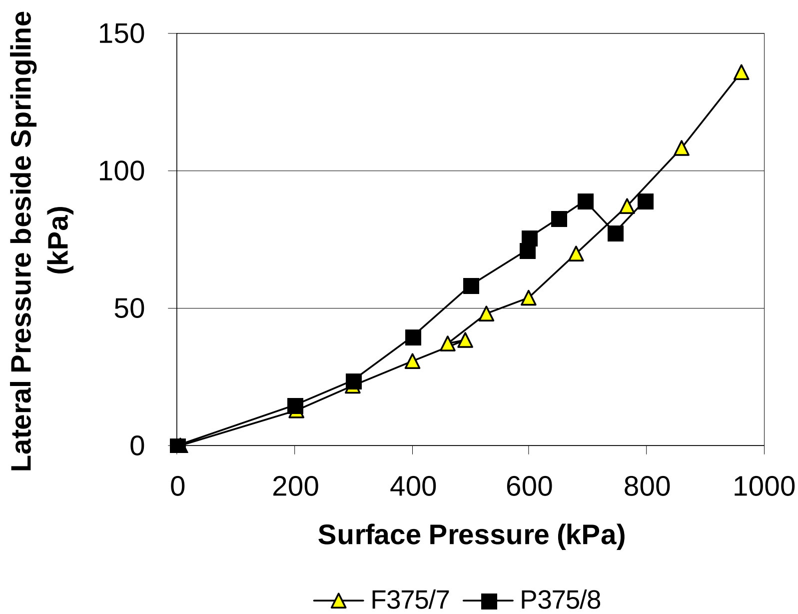


Figure 4-36. Lateral pressures in the surround, 375 mm diameter pipes.

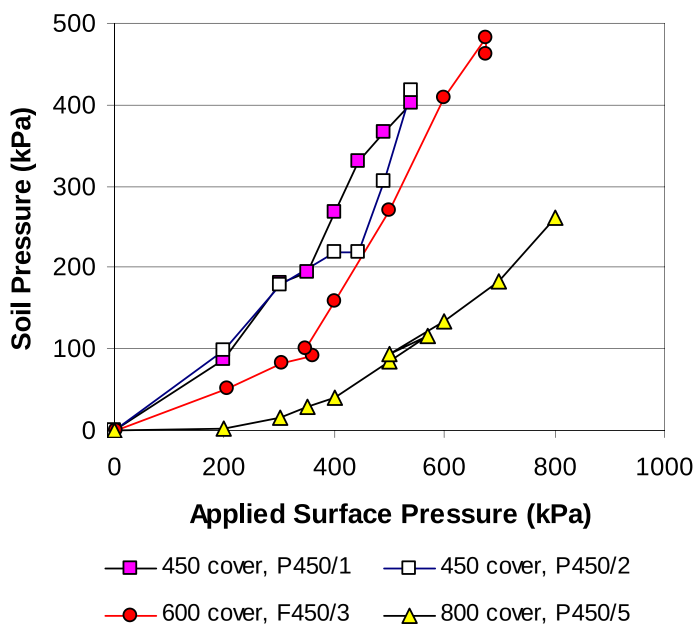


Figure 4-37. The influence of backfill height on the vertical soil pressure 150 mm above the pipe crown (centre of pipe), 450 mm diameter pipes

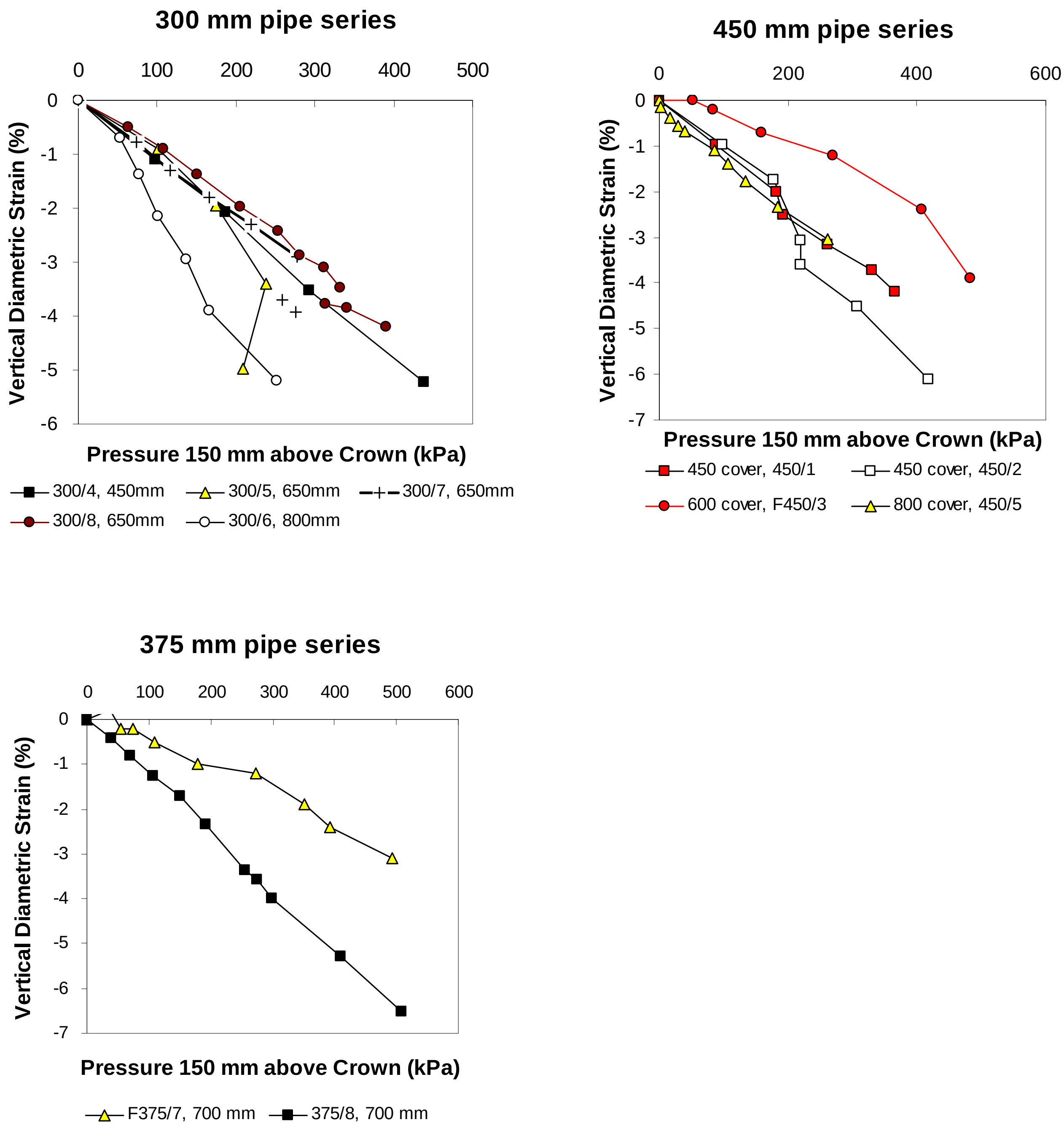


Figure 4-38. Vertical pipe deflection and the vertical soil pressure at 150mm above the pipe crown