B.H. Kjartanson, R.A. Lohnes, and S. Yang

Reuse of Waste Truck Tires as Drainage Culverts

August 1998

Sponsored by the
Recycling and Reuse Technology Transfer Center
University of Northern Iowa

Grant Contract File: RRTTC 96/97-003

Final

REPORT

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Department of Civil and Construction Engineering

This report was prepared with a grant from the Recycling and Reuse Technology Transfer Center (RRTTC). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the view of the RRTTC.

B.H. Kjartanson, R.A. Lohnes, and S. Yang

Reuse of Waste Truck Tires as Drainage Culverts

August 1998

Sponsored by the
Recycling and Reuse Technology Transfer Center
University of Northern Iowa

Grant Contract File: RRTTC 96/97-003

Final

REPORT

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Department of Civil and Construction Engineering

TABLE OF CONTENTS

1. Introduction

1.1 Background

It is estimated that, in the United States, about 2,000,000,000 waste tires clutter the countryside, and that this form of refuse is growing at the rate of about one waste tire per capita per year (i.e. about 260,000,000 tires per year) (EPA, 1991; Chalmers, 1995). In the state of Iowa, used tires are accumulating at the rate of about 3,000,000 per year. About 10%, or 300,000 of these tires are truck tires. In 1991, the Iowa legislature banned the disposal of whole tires in landfills. The ban was not coupled with the formulation of a definitive plan to find alternative uses for the waste tires. As a result, numerous companies responded to the ban by attempting to find ways to reuse or recycle the materials. Since 1989, various Iowa companies have tried to develop uses and markets for the waste tires such as crumb rubber filler for asphalt, processed chips for fuel or as a component of railroad ties. Relatively high production costs coupled with poor markets have led to the demise of these applications. No other management options that can reuse significant quantities of waste tires have come to the forefront. As a result, the waste tire stockpiles in Iowa continue to grow; according to the Iowa Department of Natural Resources (IDNR), there are approximately 6,000,000 waste tires currently being stored in legal and illegal stockpiles in Iowa.

In recent years, more than thirty other states besides Iowa banned landfill disposal of scrap tires. Several of these states, including Minnesota, Wisconsin, Florida, North Carolina, Virginia, South Carolina, Washington and Maine have sought to develop civil and environmental engineering applications for the tires.

Whole tires have been used as retaining walls and for slope stabilization (Keller, 1988; Ahmed and Lovell, 1992; Poh and Broms, 1995). These projects have demonstrated the potential for recycling used tires and describe in general terms the design of the structures; little data, however, are given regarding important engineering characteristics or behavior.

The use of shredded tires in highway embankments has been reported where more complete engineering data are given (Anonymous, 1990; Ahmed and Lovell, 1992; Bosscher et al, 1992). The second study was limited to chips from 0.6 to 5 cm in size (Ahmed and Lovell, 1992). In this application, one objective is to reduce the weight of the highway embankment and thus reduce settlements by replacing soils with a typical dry unit weight of 17.3 kN/m^3 with shredded rubber having unit weights of 3 to 7.1 kN/m^3. Ahmed and Lovell (1992) suggest that fill consisting of rubber chips alone is more likely to settle than a fill composed of a mixture of rubber chips and soil; however no data on the settlement behavior of the materials are given. The third study utilized chips in the 5 to 7.6 cm size range in a full scale test embankment; it was demonstrated that the chips can be put in place with standard construction equipment.

A number of studies have concentrated on tire chips in the 5 to 7.6 cm size range mixed with various types of soils. Shear strength tests show that the addition of tire chips to a soil can significantly increase its shear strength (Benson, 1995). Compression tests on these small chips alone indicate as much as 37% strain at stresses of 700 kN/m^2; the compressibility, however, decreases as sand content of the mixture is increased. These studies indicate that the permeability of tire chips without soil is about 0.6 cm/s at zero consolidating pressure and decreases only to about 0.4 cm/s at a consolidation stress of 97 kPa (Edil and Bosscher, 1994).

The Army Corps of Engineers and University of Maine were studying the use of shredded tires as insulating material beneath highways to inhibit frost heave and boils (Chalmers, 1995). Here the size of the rubber pieces ranged from 15 to 30 cm. This study emphasized the thermal effects of the material in combating frost action; but it is also possible that ice lens formation was inhibited due to benefits from improved drainage and obstructed capillary rise of ground water.

There are several distinct advantages to using whole truck tires for subsurface drainage structures. The internal steel belts will not be directly exposed to the leaching action of water and the costs of grinding or shredding are eliminated. Truck tires, in particular, are difficult to grind and process because of the heavy bead wire. Recognizing this problem with the recycling of truck tires, Dodger Enterprises of Fort Dodge, Iowa, constructed an innovative 330 m long culvert system using whole truck tires on previously undisturbed land near Fort Dodge. The culvert system was constructed to reduce the groundwater level and to divert surface water runoff away from its buildings during the summer of 1995. While the Dodger Enterprises culvert drainage structure has performed satisfactorily and has demonstrated an innovative reuse of scrap truck tires, the key engineering properties of the whole truck tires and the design and performance aspects of this type of structure have not been quantified to allow use by other parties.

1.2 Research Project Objectives and Organization of the Report

The specific objectives of this research are:

1) Characterize and quantify the key engineering properties of whole truck tires as drainage culverts.

2) Quantify the performance of whole truck tire culvert sections when installed in a trench under various bedding conditions.

3) Develop recommendations for design and construction of culverts with scrap truck tires.

4) Disseminate the design recommendations to the public through publication of the results, open houses, workshops, seminars and/or short courses.

The design of a truck tire culvert involves both hydraulic and structural performance considerations. Following a discussion of relevant truck tire geometric parameters in section 2, the hydraulic analysis of truck tire culverts is presented in section 3. The structural performance of a truck tire culvert will depend on the strength and stiffness of the truck tires as well as their interaction with the surrounding backfill soil. The strength and stiffness properties of single truck tires and three truck tire banded sections were determined by parallel plate testing. The methodologies used and the results of these tests are presented in section 4. Buried conduit field tests were conducted to evaluate the soil-structure interaction between a truck tire culvert and the surrounding backfill soil. Truck tire culvert performance under a range of soil backfill and loading conditions is presented in section 5. The expected load response of a truck tire culvert with a variety of soils at various degrees of compaction was analyzed using the Culvert Analysis and Design (CANDE) program. The results of the parallel plate laboratory testing and the buried conduit field testing played an integral role in the development, calibration and application of the CANDE model for this task. The results of these analyses are presented in section 6. Finally, drawing on both the hydraulic and structural analyses, design guidelines were developed for a whole truck tire culvert drainage structure. These design guidelines, along with an illustrative example, are presented in section 7.

2. Description of Materials

Sixty scrap truck tires were used in the various tests in this research program. Table 2.1 gives an assigned number, the brand/type, and the tire outside diameter, inside diameter, tread width and tread depth for 37 tires used in parallel plate testing, described in section 4. Perusal of Table 2.1 indicates that 21 different brands/types of tires were used in the program.

Measurements of these 37 tires indicate that the inside diameter for conducting water ranges from 0.53 m to 0.60 m, with an average of 0.55 m. The smallest diameter (0.53 m) is used as the pipe diameter in the hydraulic calculations described in section 3. The outside diameter of the tires ranged from 0.99 m to 1.07 m with the most common value being 1.02 m. Actual tire outside diameters are used in calculations for the parallel plate tests, as described in section 4. The value of 1.02 m, however, is used in calculations associated with the buried conduit tests, reported in section 5, and the CANDE analyses, reported in section 6, where this dimension is required.

The widths of the truck tire tread range from 0.18 m to 0.24 m with an average value of 0.21 m. The actual tread width is used as the load bearing width of a truck tire in the parallel plate tests, described in section 4. Note that the gross width of the tire is larger than the tread width by about 0.05 m. Also note that the tread depth varies from zero to 0.013 m; "no tread" is given for the tread depth for tires 11, 12 and 13. The tread has been totally removed from these tires; we refer to these as "bald tires" in later sections of the report.

The most convenient way to place truck tires in the trench is using sections of three tires banded together with steel strapping. Experience has shown that the tires are more stable in the trench and can be installed faster when banded. Sections of four or more banded tires are difficult to handle and are not recommended.

Table 2.1 Tires used in research program

Tire No.	Brand/type	Outside diameter	Inside diameter	Tread width	Tread depth
		(m)	(m)	(m)	(m)
1	GY G114	1.020	0.552	0.206	0.00762
2	sumitomo	1.013	0.556	0.197	0.004318
3	GY G259	1.021	0.556	0.210	0.01016
4	marshal	1.069	0.552	0.222	0.00254
5	MC X	1.063	0.551	0.214	0.003302
6	GY uni II	1.069	0.548	0.229	0.00508
7	MC pilot	1.043	0.598	0.203	0.007112
8	GY uni II	1.051	0.508	0.203	0.006858
9	GY G132	1.038	0.605	0.200	0.00254
11	MC pilot	0.988	0.546	0.230	no tread
12	BS R299	0.994	0.554	0.225	no tread
13	GY G159	0.995	0.554	0.244	no tread
14	kelly	1.017	0.552	0.210	0.008382
15	kumho	0.999	0.552	0.216	0
16	BSR94	1.013	0.554	0.203	0.005588
17	BS R299	1.021	0.549	0.219	0.012954
18	GY uni TD	1.007	0.508	0.184	0.004318
19	GY G259	1.008	0.552	0.229	0.004826
21	GY G259	1.002	0.554	0.235	0.001524
22	GY G259	0.997	0.552	0.230	0.003048
23	MC 11R	1.039	0.551	0.205	0.001524
24	GY G259	0.999	0.554	0.235	0.002032
25	GY uni II	1.050	0.554	0.195	0.007366
26	BS R194	1.030	0.602	0.214	0.00635
27	GY G314	1.007	0.549	0.221	0.007366
28	GY G259	1.007	0.549	0.232	0.005588
29	GY G159	1.007	0.554	0.233	0.005588
31	MC pilot	1.003	0.548	0.211	0.00508
32	BS MLX	1.048	0.554	0.200	0.007874
33	MC pilot	0.996	0.546	0.216	0.002794
34	GY uni II	1.070	0.546	0.229	0.004572
35	GY G188	1.051	0.554	0.189	0.010414
36	CT C455	1.055	0.600	0.203	0.010922
37	GY uni TD	1.021	0.559	0.175	0.009906
38	MC pilot X	1.019	0.546	0.213	0.007112
39	GY uni TD	1.020	0.552	0.175	0.00635
30	GY G259	1.015	0.552	0.238	0.005842
Average		1.023	0.555	0.213	0.0057897

3. Hydraulic Analysis of Truck Tire Culvert

3.1 Assumptions and Limitations

Truck tire culverts are intended to be a very low cost alternative to conventional drainage pipe. The size and shape of scrap truck tires limits their hydraulic capacity and they are not considered as a substitute for concrete, metal and plastic pipe used in extensive projects where design flows are large. It will be shown in this section that the maximum area that can be drained for this type of structure is on the order of several hectares.

The hydraulic capacity of any culvert depends upon the diameter, slope, length, and hydraulic roughness of the structure. In the case of truck tire culverts, the diameter is limited by the inside diameter of the tire. Based upon measurements of 37 scrap tires, the smallest diameter of 0.53 m is used in the calculations.

To the knowledge of the authors, no tests were done to measure the Manning's roughness coefficient of scrap tire culvert, so the Manning's coefficient was estimated by empirical equations.

The friction head loss of a culvert flow is often expressed by the Darcy-Weisbach equation

$$h_f = f\frac{L}{d}\frac{V^2}{2g} \qquad (1)$$

where L is the length of the culvert, d is the pipe diameter, V is the average flow velocity, g is the gravitational acceleration, and f is called the friction factor and is related to the roughness of the pipe.

For the flow in a truck tire culvert, apply the Manning's equation

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{2}$$

where n is the Manning's roughness coefficient, R is the hydraulic radius or the flow area divided by the wetted perimeter, and S is the hydraulic gradient of the flow.

The friction factor f can then be expressed in terms of Manning's roughness coefficient, n by comparing equation (1) and equation (2):

$$f = 78.5 \frac{n^2}{R^{\frac{1}{3}}} \tag{3}$$

Generally, the friction factor f is a function of the Reynolds number of the flow and the pipe roughness. When pipe roughness predominates, such as in a tire culvert, the flow tends to be turbulent and the friction factor does not vary with the Reynolds number as indicated in the Moody diagram. This is expressed by the Nikuradse equation (Straub and Morris, 1950):

$$f = \frac{1}{(1.14 - 2\log\frac{k_s}{d})^2} \tag{4}$$

where k_s is the diameter of uniform sand grains which could be coated on a smooth pipe of the same diameter as the pipe under consideration and would cause the same friction head loss as the actual pipe. k_s /d is called the relative roughness of the pipe.

From equations (3) and (4), the roughness coefficient of a truck tire culvert, n can be calculated after k_s is estimated. An accurate estimation of k_s needs laboratory tests and experience.

Assuming that k_s = 0.3-m for truck tire culverts, f is calculated from equation (4) to be 0.374. Since R is a function of the flow depth, and from equation (3) a larger R would give a larger n when the f value is fixed, the maximum R for a circular pipe, which is 0.304d, was used to calculate n. Substitute f and the maximum R into equation (3) and n is calculated to be 0.05. This value, as it turns out, is two times the roughness coefficient of corrugated metal pipes.

The method proposed herein is an approximate estimation of the Manning's coefficient for scrap tire culverts. The eddy effect, which is caused by the turbulence of the flow in the tires, was not considered. This suggests that n might be underestimated. However, as sand ballast has been recommended for truck tire culverts to reduce the amount of water stagnating in the tires and mitigate buoyancy effects, the inside roughness and eddy effect are also reduced. Therefore, n = 0.05 is recommended for truck tire culverts with sand ballast.

Because of the uncertainty associated with the roughness coefficient, a truck tire culvert is designed to flow partly full with the maximum flow depth limited to less than 75% of the pipe diameter, or 0.4-m. This constraint also helps to avoid buoyancy effects by air trapped in the tops of the tires. The project site will control the length and slope of the culvert.

3.2 Method of Analysis

3.2.1 Design discharge

The design discharge or the storm runoff for a given frequency is a function of the topography, land use and drainage area. A number of methods are available for estimating this flow, however the Iowa DOT method is used here. The discharge for the frequency of fifty years and very hilly land with mixed cover can be determined from Figure 3.1 or from the equation:

$$Q_{50} = 0.446A^{0.74}$$

where Q_{50} is in m^3/sec, and A is the drainage area in hectares and $1<A<400$ hectares. The design flow is then calculated for different frequency factors, FF, and land use factors, LF, from

$$Q = (LF)(FF)Q_{50}$$

Values of FF and LF are in Table 3.1 and Table 3.2 respectively.

3.2.2 Estimating flow capacity

Although the discharge is constant, the depth of flow and the energy in a culvert varies along the length of pipe. Calculation of various flow depths is important in determining the pipe capacity. For a given discharge and assuming uniform depth along the culvert length, the depth of flow is defined as normal depth, d_n. The critical depth, d_c, is the depth at a given section and given discharge where the energy is minimum.

The conditions of flow through a pipe are classified as inlet control and outlet control (AASHTO, 1992). If the critical depth is greater than the normal depth, d_n, the flow is inlet control and the water can flow through the pipe at a greater rate than it can enter. For this type of flow, the pipe capacity is not affected by any hydraulic factors beyond the culvert entrance. If the critical depth is at the outlet and water enters the pipe at a greater rate than water can flow through it, the flow is said to be outlet controlled. For outlet control, factors such as slope, length and roughness affect the flow rate.

The hydraulic capacity of a culvert is calculated by the following procedures (Gupta, 1995). The critical section factor, Z_c can be defined by

$$Z_c = \frac{Q}{\sqrt{g}}$$

where Q is the design discharge. In terms of pipe cross sectional geometry, the critical section factor is:

$$Z_c = A\sqrt{D} = A\sqrt{\frac{A}{T}} = \frac{1}{\sqrt{2}} A^{\frac{3}{2}} [d_c(d - d_c)]^{-\frac{1}{4}}$$

where A is the flow area, T is the top width of the flow area, and D is the hydraulic depth and D=A/T.

The functional relationship based on geometry exists between the flow area and the depth and these data are tabulated in hydraulic manuals. The two previous equations can be solved in a trial and error method to determine the critical depth, d_c. The critical depth must be less than 75% of the truck tire inner diameter or 0.4-m

The next step is to calculate the normal depth using the section factor for uniform flow, Z_n:

$$Z_n = AR^{\frac{3}{2}}$$

where R is the hydraulic radius or the flow area divided by the wetted perimeter. From the Manning's Formula, the section factor for normal flow can also be expressed as a function of the discharge, Q:

$$Z_n = \frac{Qn}{S^{\frac{1}{2}}}$$

where S is the hydraulic gradient of the flow and is equal to the slope of the culvert S_0 for normal flow. The two equations for normal flow section factor can be solved by trial and error to calculate the R that corresponds to the normal flow depth.

After normal depth, d_n and critical depth, d_c are calculated, the flow type can be defined by comparing d_n and d_c. If $d_c > d_n$, the flow is inlet controlled and the highest water depth in the culvert is the critical depth. The capacity of the truck tire culvert can be obtained by setting $d_c < 0.75d$. If $d_c < d_n$, the flow is outlet controlled. The water depth at the entrance needs to be calculated.

To calculate the water depth at the entrance to the culvert, d_e for outlet controlled flow, use the Bernoulli equation that describes the energy difference between the inlet and the outlet

$$d_e + z + \frac{V_e^2}{2g} = d_c + \frac{V_c^2}{2g} + h_e + h_f$$

where d_c is the water depth at the outlet (equal to the critical depth), V_e is the velocity at the entrance, V_c is the velocity at the outlet, z is the elevation difference between the inlet and outlet and $z=S_0L$, and h_e is the entrance head loss.

The previous equation can be combined with the continuity equation

$$Q = A_e V_e = A_c V_c$$

where A_e and A_c are the flow areas at the entrance and outlet respectively. The entrance head loss can be calculated from

$$h_e = K_e \frac{V_e^2}{2g}$$

where K_e is the entrance loss coefficient and a value of 0.5 for a flush inlet appears appropriate for the tires.

The friction head loss, h_f, is calculated from equation (1) by assuming $V_2=V_eV_c$.

The equations for entrance head loss and friction head loss can be substituted into the Bernoulli equation to give

$$d_e + \frac{V_e^2}{2g}(1-K_e) - \frac{fLV_eV_c}{d2g} = d_c + \frac{V_c^2}{2g} - S_oL$$

From the continuity equation and with all other parameters known, the right hand side of the previous equation can be calculated. To complete the analysis, use different values of the entrance depth, d_e, with trial and error until the left-hand side of the equation equals the right hand side. If the entrance depth is less than 0.4 m, the truck tire culvert has adequate capacity.

3.3 Results Applied to Truck Tire Culverts

From this analysis using the estimated value of roughness (0.05) and the measured value of d (0.53 m), and assuming a tail water less than critical depth, the design chart shown in Fig 3.2 was developed for truck tire culverts. The chart shows that for slopes greater than 0.11, the flow through the tires is inlet controlled and the limiting discharge is 0.35 m^3/sec. Comparing this value with Fig 3.1 suggests that the maximum drainage area for truck tire culverts may be up to several hectares, depending on the frequency and land use factors. For slopes less than 0.11 the flow is outlet controlled and culvert capacity increases with culvert slope. At slopes less than 0.07, increasing pipe length decreases the flow capacity of the tire culverts. Fig 3.2 can be used to estimate the hydraulic capacity of truck tire culverts and is incorporated into the design method.

To evaluate the practical application of truck tire culverts it is useful to compare their hydraulic capacity with the capacity of conventional pipes. For this exercise, it was assumed that the conventional pipes would be flowing at full capacity whereas the truck tire culvert is flowing at a depth of only 75% of its diameter. The principles described in section 3.2.2 were used in this analysis with published values of roughness coefficients for concrete and corrugated metal pipes.

Fig 3.3 shows the equivalent concrete pipe and corrugated metal pipe sizes that would conduct the same amount of water as a truck tire culvert at a specific length and slope. For example, a 300-m long truck tire culvert with a slope of 0.025 conducts a flow that is equivalent to a 0.29-m concrete pipe or a 0.35-m corrugated metal pipe. Fig 3.3 also indicates that at slopes in excess of 0.11, the required size for all conventional pipes is 0.49-m. Because the inside diameter of a truck tire culvert is 0.53-m, this analysis suggests that in situations where the slope of the pipe is steep, the hydraulic efficiency of the truck tire culvert approaches that of conventional pipes.

Table 3.1 Frequency Factor (FF)

Frequency, Years	5	10	25	50	100
Factor, FF	0.5	0.7	0.8	1.0	1.2

Table 3.2 Land Use and Slope Description (LF)

Land Use	Slope Description				
	Very Hilly	Hilly	Rolling	Flat	Very Flat (no ponds)
Mixed Cover	1.0	0.8	0.6	0.4	0.2
Permanent Pasture	0.6	0.5	0.4	0.2	0.1
Permanent Woods	0.3	0.25	0.2	0.1	0.05

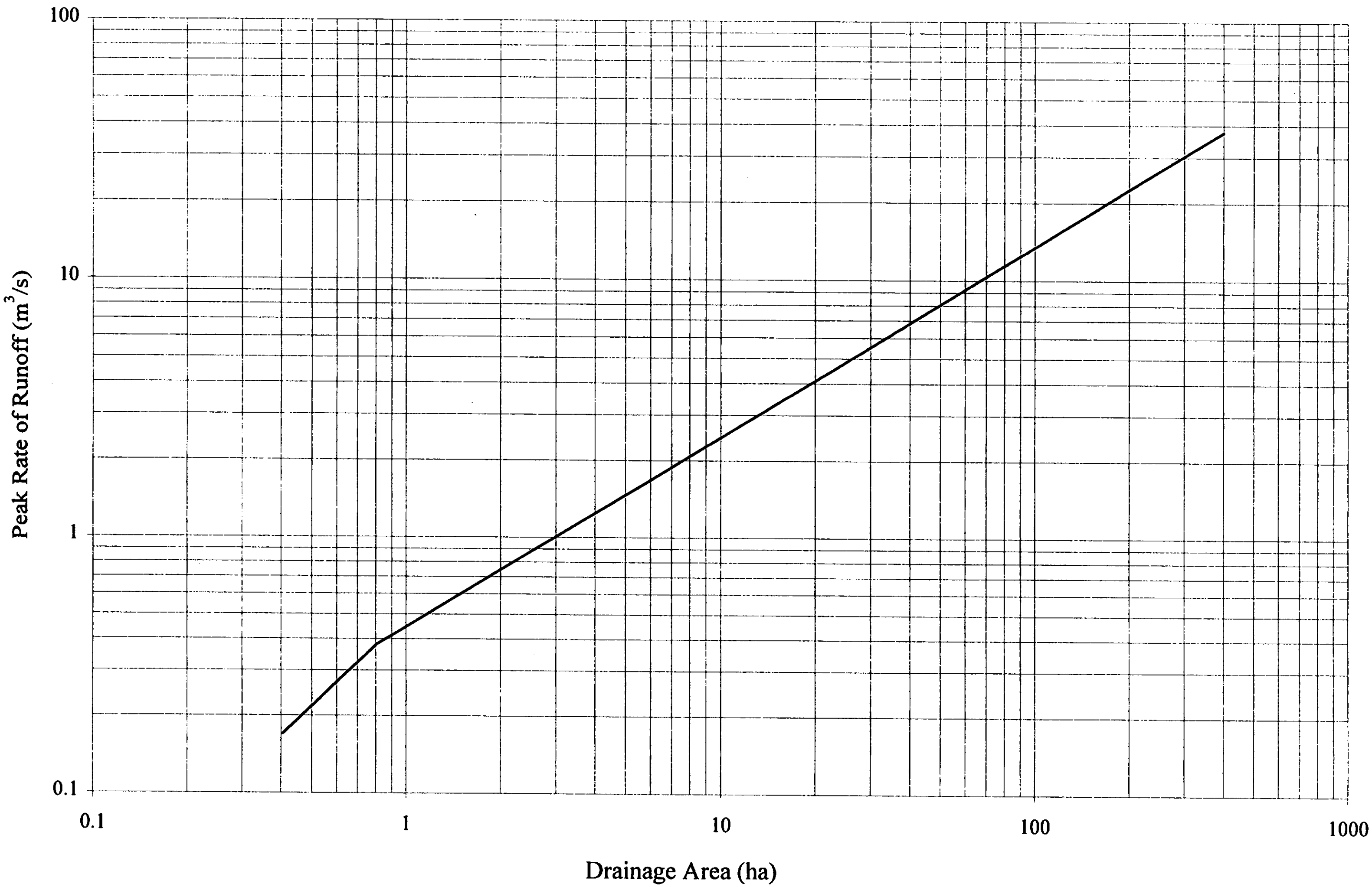


Figure 3.1 Iowa Runoff Chart (Frequency of 50 years, mixed cover on very hilly slope).

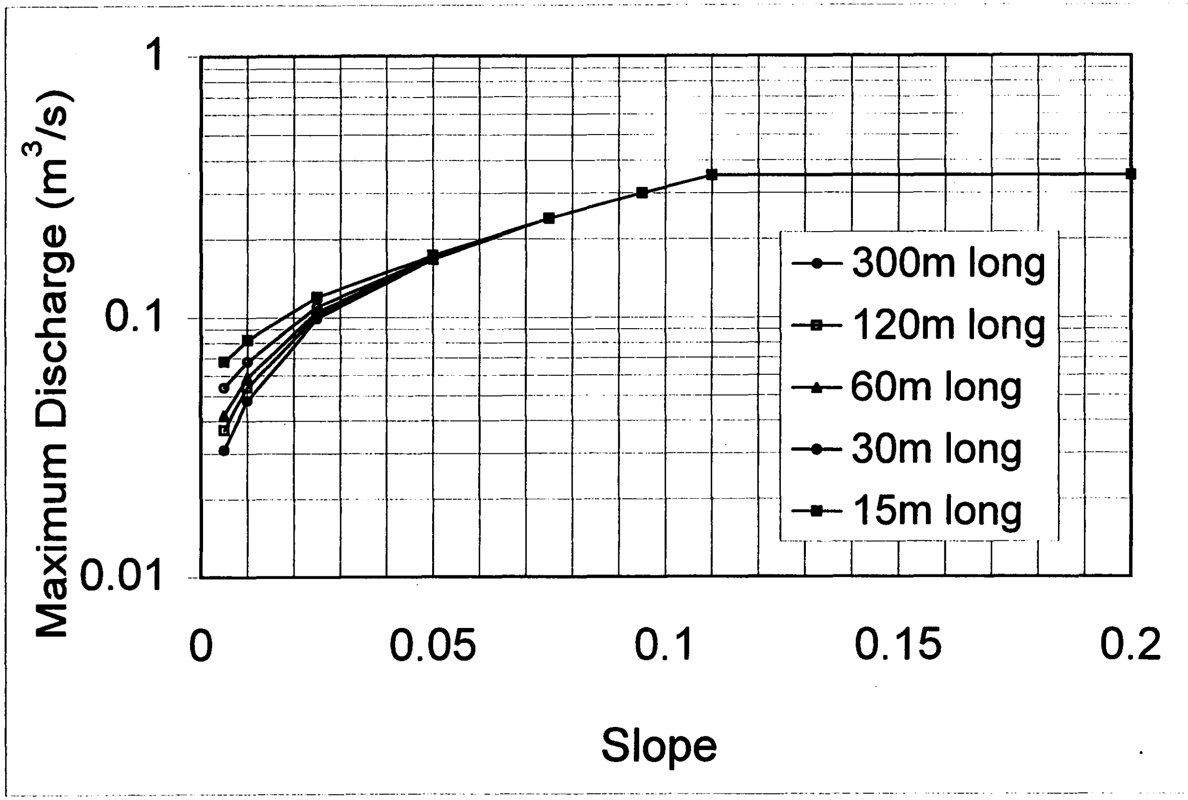


Figure 3.2 Hydraulic capacity of truck tire culvert (tailwater depth less than 0.2d).

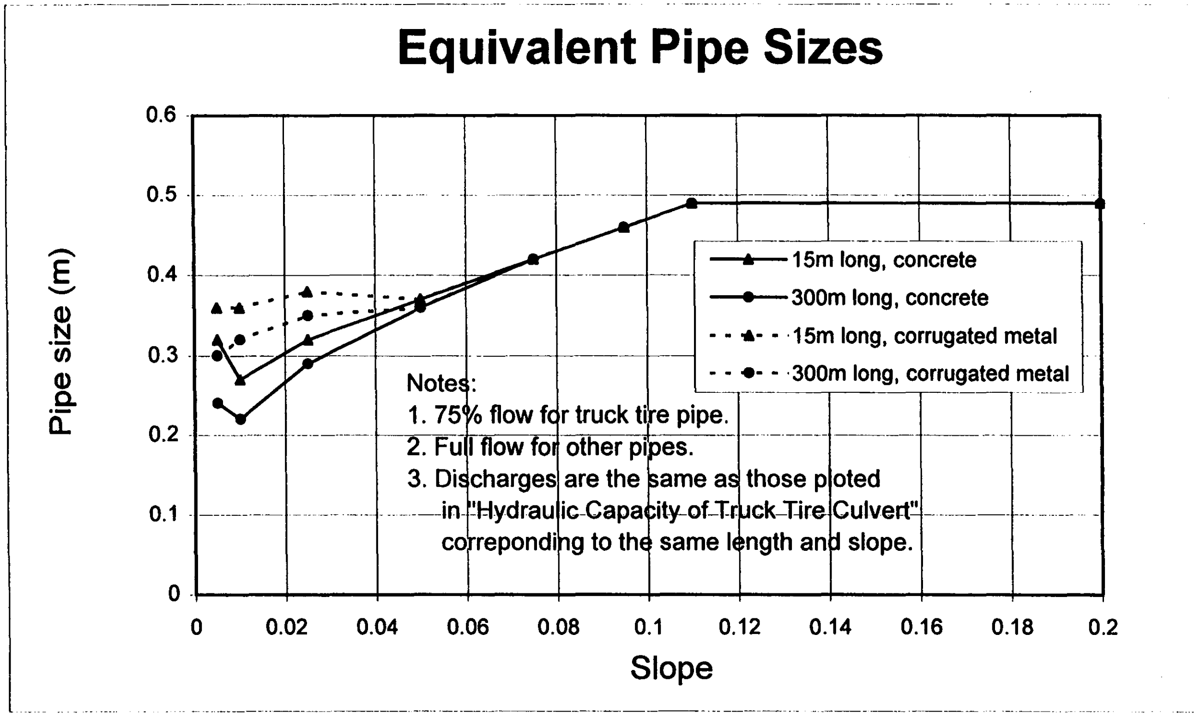


Figure 3.3 Comparison of the hydraulics of convential pipes with the hydraulics of a truck tire culvert

4. Parallel Plate Tests

4.1 Background

The American Society of Testing and Materials (ASTM) parallel plate test (D2412) is used to determine the external load-deflection characteristics and the stiffness of plastic pipe. As described in ASTM D2412, the parallel plate test consists of placing a short section of pipe between two rigid parallel platens and compressing it at a controlled rate. Load versus pipe outside diameter change data are obtained, and pipe stiffness values are calculated for specific deflections. The results from this test are used for design.

Because the load-deformation characteristics of scrap whole truck tires have not been measured previously, parallel plate tests were used to quantify the load-deformation response and observe the failure modes of the scrap truck tires under compression load. Tests were carried out on a total of 37 tires; three were bald tires (tires without treads). The tests did not exactly follow the provisions of ASTM D2412 due to the nature of this pipe material. In particular, the pipe section tested should have a length along the axis of the pipe at least equal to the inside diameter of the pipe. The width of a truck tire, as noted in section 2, is much smaller than the inside diameter and, unlike conventional pipe, the inside diameter for conducting water is significantly smaller than the outside diameter due to the tire sidewall. Moreover, as a truck tire culvert comprises sections of three truck tires banded together and placed side by side in a trench, it would be logical to test a three truck tire banded section (hereafter referred to simply as "section") in the parallel plate test. The length of this section, however, is about 0.79 m, which is slightly less than the outside diameter (1.02 m) of the truck tires. Hereafter, the length along the axis of the tire or tire section is referred to as "width".

Because single tires are easier to test in compression than tire sections, it is useful to compare the response of tire sections to single tires, with the results normalized to the unit load bearing width of the tested specimen. The total width of tire tread in contact with the platens was used as the load bearing width. Note, however, that for a tire section comprising three tires the gross width of the section is about 0.79 m while the total tread width in contact with the platens would be about 0.63 m (three tires with an average tread width of 0.21 m per tire).

4.2 Test apparatus and methods

Single tires were tested using the Satec compression test machine (ISU Civil Engineering Structures Laboratory) while a specially designed loading system was used to test tire sections. A schematic of this loading frame is shown in Fig. 4.1.

The outside and the inside diameters of the tires were measured. Following measurement of the initial tire dimensions, the single tire or tire section was placed in the testing apparatus and the platen was brought into contact with the top of the tire(s). The test was carried out by compressing the tire(s) at a rate of 0.038 m/min to a maximum deflection of 0.254 m. Readings of platen deflection (change in tire outside diameter), change in inside diameter, and applied load were taken every 0.025 m.

The pipe, or in this case tire stiffness (TS) is defined the same as the pipe stiffness in ASTM D2412 and may be calculated as:

$TS=F/\Delta Y$ (kN/m^2), where;

F = load/width (kN/m)

ΔY is the deflection of the tire (m)

4.3 Test Results

4.3.1 Single Tires

Parallel plate tests were conducted on 37 single truck tires. Fig. 4.2 shows the results of these tests. Outside diameter change is plotted against the corresponding load per unit load bearing width (load/width) for each of the tires. Note that both the relationship between load/width for each of the tests and the average load/width for all of the tests and the corresponding outside diameter change are close to linear. A linear regression fit of the average load/width for all of the tests versus the corresponding outside diameter change gives a correlation coefficient very close to one. These tests also showed that the load response of the truck tires depends on: condition and thickness of the tire tread, tire wear and damage, including the presence of holes in the sidewall, and truck tire diameter. Smaller diameter tires with deeper treads generally are stiffer. Tires without treads (bald tires), excessively worn tires and tires with damaged sidewalls were observed to have the lowest load bearing capacity and should not be used for a truck tire culvert.

4.3.2 Tire Sections

Parallel plate tests were carried out on 9 tire sections. As shown in Fig. 4.3, the relationship between outside diameter change and load/width is nearly linear for these tests. Two curves have been fit to the data. The dashed curve is the average of the load/width test results at each outside diameter change while the solid line represents a linear fit to the data. Note that the linear regression equation for the average tire section data is very close to the linear regression equation for the average single tire test data shown on Fig 4.2. This indicates that the load response per unit load bearing width of a tire section may be adequately represented by parallel plate tests on single tires. The lower slope (i.e. stiffer response) of the dashed line from zero to 0.025-m outside diameter change is most likely due to a reinforcing effect from the steel banding holding the three tires together. Except for test series 8 and 9, which indicate significantly stiffer behavior than the other tire sections, the test results fall within a fairly narrow range.

In Figs. 4.4 to 4.12, the response of a tire section is compared with the responses of the individual truck tires comprising the section. The graphs show the load-deformation response of the tires in terms of change of OD (outside diameter) and ID (inside diameter) versus load in kN per meter load bearing width of the individual tire or tire section. The load-deformation curves for the tire sections are essentially an average response of the three individual tires making up the section. These tests reinforce the hypothesis noted above that the load-deformation response of a tire section is adequately defined by testing single tires. In addition, the change in the inside, water-conducting diameter of the truck tires is only about 15 % of the change in outside diameter.

Collapse or buckling of the tires was observed to occur at outside diameter changes greater than about 0.13 m. An example of this phenomenon is the response of tire 19 in Fig. 4.5, in which the diameter change continues to increase beyond a value of 0.2 m but with a decrease in load/width.

Tire Stiffness (TS) values, defined in the equation above, were calculated using the load/width versus outside diameter change results of the tests on single tires and are shown in Figs 4.13 to 4.21. Fig. 4.13, for example, shows the variation of tire stiffness with deflection for the same tires of Fig. 4.4. "Deflection" is the tire outside diameter (OD) change divided by the initial tire OD and expressed as a percentage. Because of the sidewalls, tires have a different inside configuration than conventional pipe and the analysis, therefore, is based on outside diameter. The response of these three tires is typical of the other single tires tested. Fig 4.13 shows that tire stiffness values decrease initially to 7.5% deflection and are almost constant for deflections from 7.5%

to 20%. Beyond 20% deflection the tire stiffness values tend to increase. Tire stiffness values, however, decrease markedly with tire buckling. Note, for example, that the tire stiffness values for tire 19 (see Fig. 4.14) decrease significantly with deflections greater than about 15%.

When compared with HDPE pipe (see Table 4.1), truck tires are generally less stiff than HDPE pipe at deflections less than 10%. At higher deflections, however, the stiffness of truck tires becomes equal to or even greater than the stiffness of HDPE pipe.

Fig. 4.21 shows the tire stiffness versus deflection values for the tires without treads (the same three tires of Fig.4.12). These tire stiffness values tend toward the lower bound of tire stiffness values and also show a trend of decreasing tire stiffness with increased deflection.

For all of the single tires tested, tire stiffness values averaged over deflections from 5 to 20% ranged from 62 to 186 kN/m^2. The overall average value, which was used in the CANDE analyses for development of the design guidelines, is 110 kN/m^2.

4.3.3 Repetitive Tests on Single Tires

The effect of repetitive loading on truck tire load response was assessed by carrying out six consecutive parallel plate tests on the same three single tires. Each loading cycle comprised compressing the tire to the maximum outside diameter change of 0.254 m at the standard rate noted above, releasing the load and allowing the tire to rebound back to its original shape. The time between the consecutive tests varied from 1 hour to 20 days. The results of these tests are shown in Figs 4.22 to 4.24.

The results indicate that the load bearing capability of the truck tires (in terms of load/width) for a given diameter change does not decrease by more than about 5 to 10% over the six consecutive tests. The most significant decrease in load/width occurs after the first test, with smaller decreases thereafter. In addition, the time between the consecutive tests did not appear to affect the responses. In practical terms, this indicates that repetitive loading, such as from traffic, should not cause excessive deformation of truck tire culverts.

Parallel plate tests were also conducted on 9 single tires that were used in the buried conduit tests (discussed in section 5 of this report). The results of these tests are shown in Fig. 4.25. Note that a linear regression fit of the average load/width for all of the tests versus the corresponding outside diameter change gives a correlation coefficient very close to one and the coefficients of the linear equation are very similar to those for the parallel plate tests on single tires shown in Fig. 4.2. These results indicate that the average load response of the tires was not significantly affected by the loading from the buried conduit tests and support the results of the repetitive parallel plate tests described above.

4.3.4 Creep Tests on Single Tires

Creep tests were conducted on three single tires to give a preliminary assessment of the amount and rate of continuing deformation under a constant applied load. The applied load of 3 kN was selected to be in the midrange of loads and resulting outside diameter changes observed in the parallel plate tests on single tires. To carry out the tests, the single tire was placed in the Satec compression test machine, the target load was achieved by loading at a rate consistent with the parallel plate test and the compression of the tire was measured with the target load held constant.

The results of the tests are shown in Figs 4.26 to 4.28. These relatively short duration tests (up to a maximum time of two hours) indicate that at least 90% of the total tire compression takes place in the first 5 to 10 minutes. It may be noted, however, that the compression continues to increase, albeit at a relatively low rate, within the entire period of the tests. While there is continuing compression with time, it should not significantly impact the long term performance of the truck tire culvert system. Recall that the change in the inside, water conducting diameter of the truck tire is only about 15% of the change in outside diameter and the truck tires will have lateral structural support from the compacted backfill soil in the field; the tires in the creep tests were not supported laterally. It is recommended, however, that since rubber is a material that is highly prone to long term creep, further tests of a longer duration should be carried out to confirm potential long term impacts to truck tire culvert performance.

Table 4.1. Comparison of the stiffness (in kN/m^2) of scrap truck tires and HDPE pipes.

	Diameter (m)	Manufacturer	Deflection			
			5%	10%	20%	30%
HDPE Pipes[1]	0.91	A	253	185	133	80
	0.91	C	169	125	95	65
Tires	1.02	-	110	110	110	110

(1) F. W. Klaiber, R. A. Lohnes, T. J. Wipf, and B. M. Phares, Investigation of High Density Polyethylene Pipe for Highway Application, ISU-ERI-Ames 96407, Engineering Research Institute, Iowa State University, Jan. 1996.

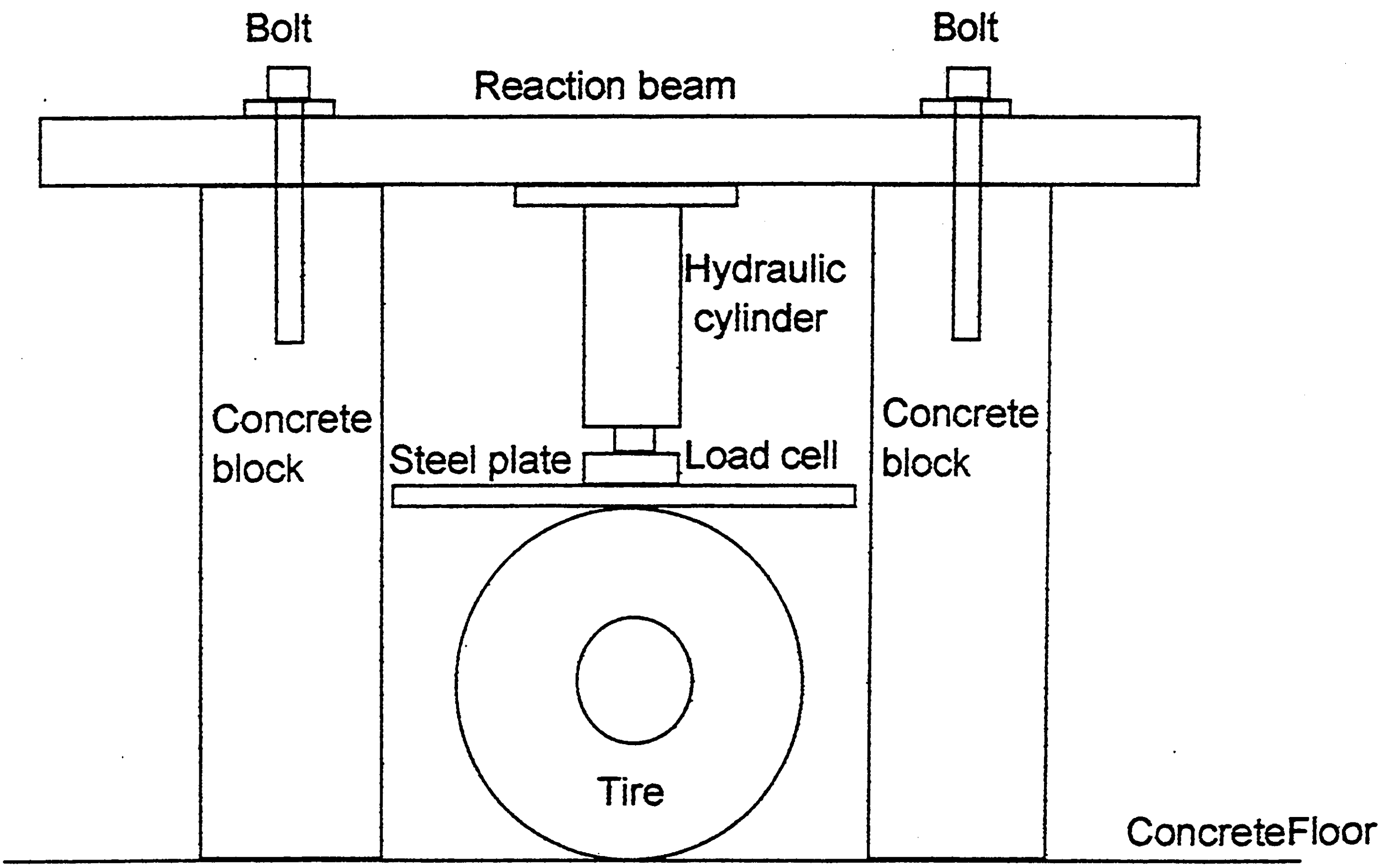


Figure 4.1. Parallel plate test loading frame for testing truck tire culvert sections.

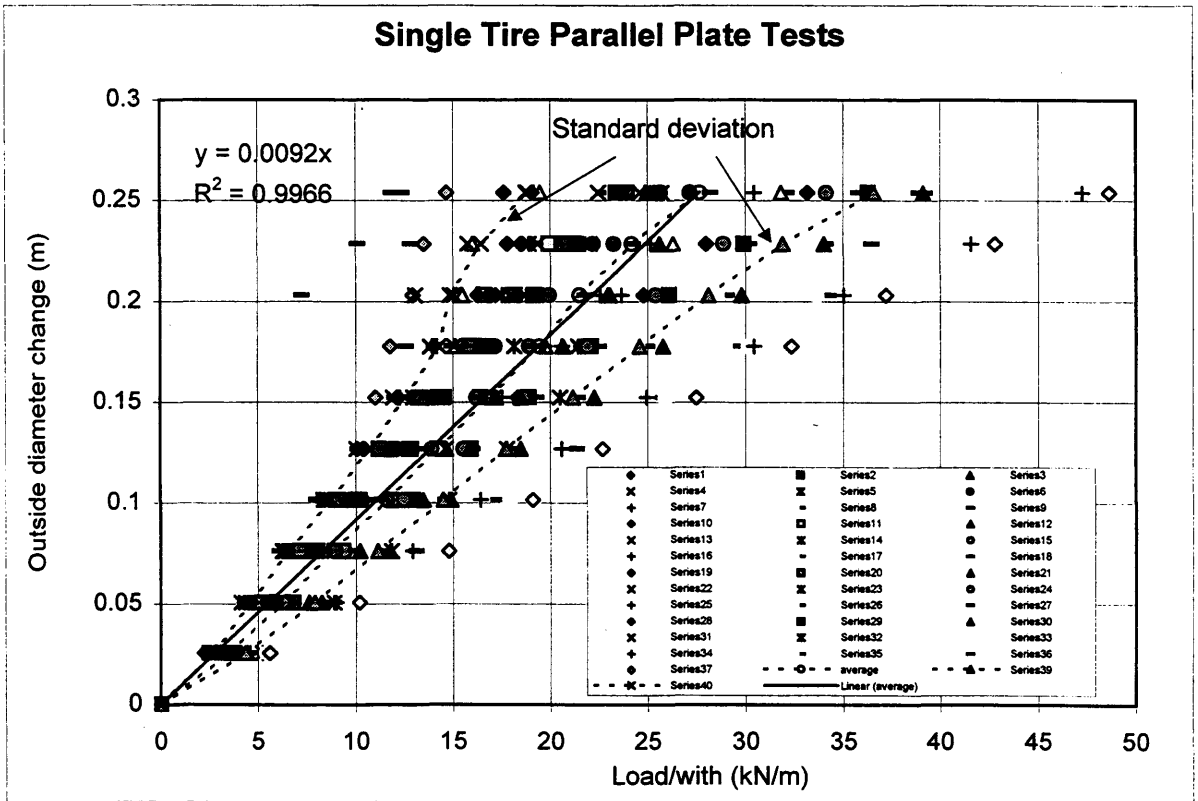


Figure 4.2. Parallel plate tests for single tires.

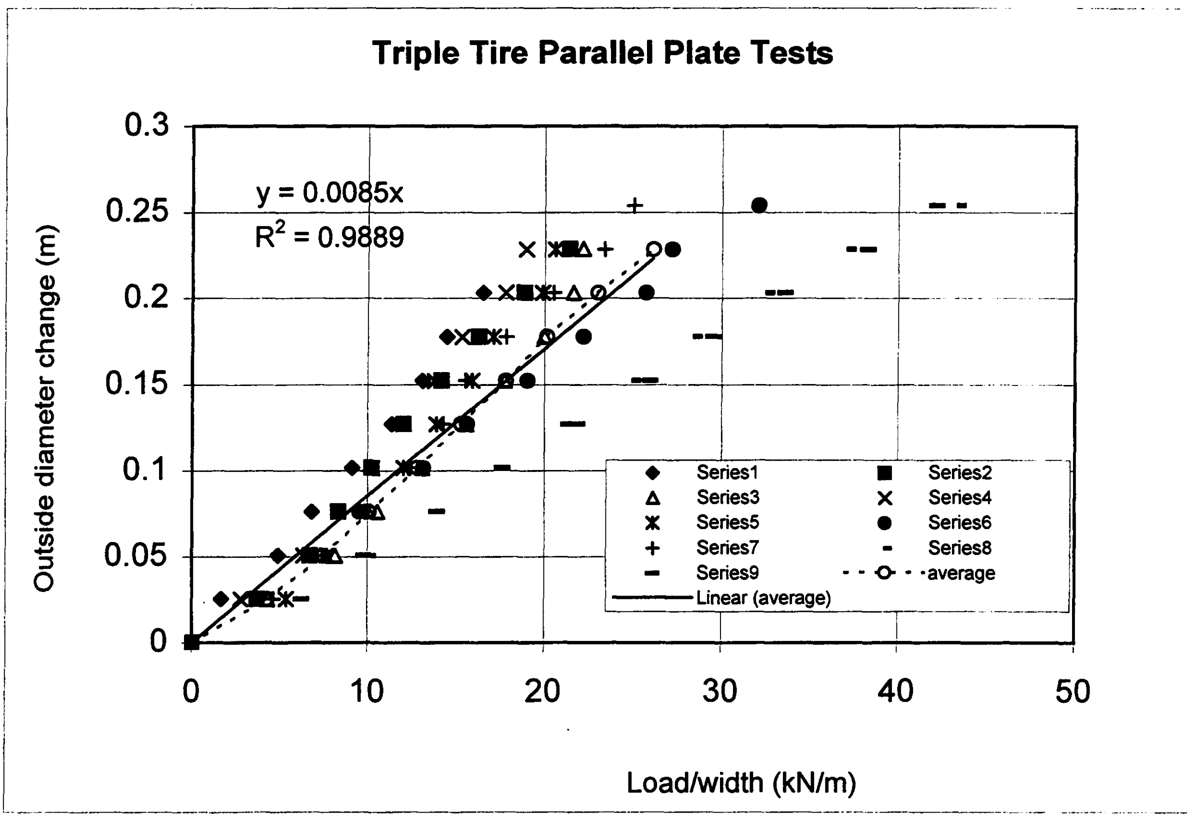


Figure 4.3. Parallel plate tests tire sections.

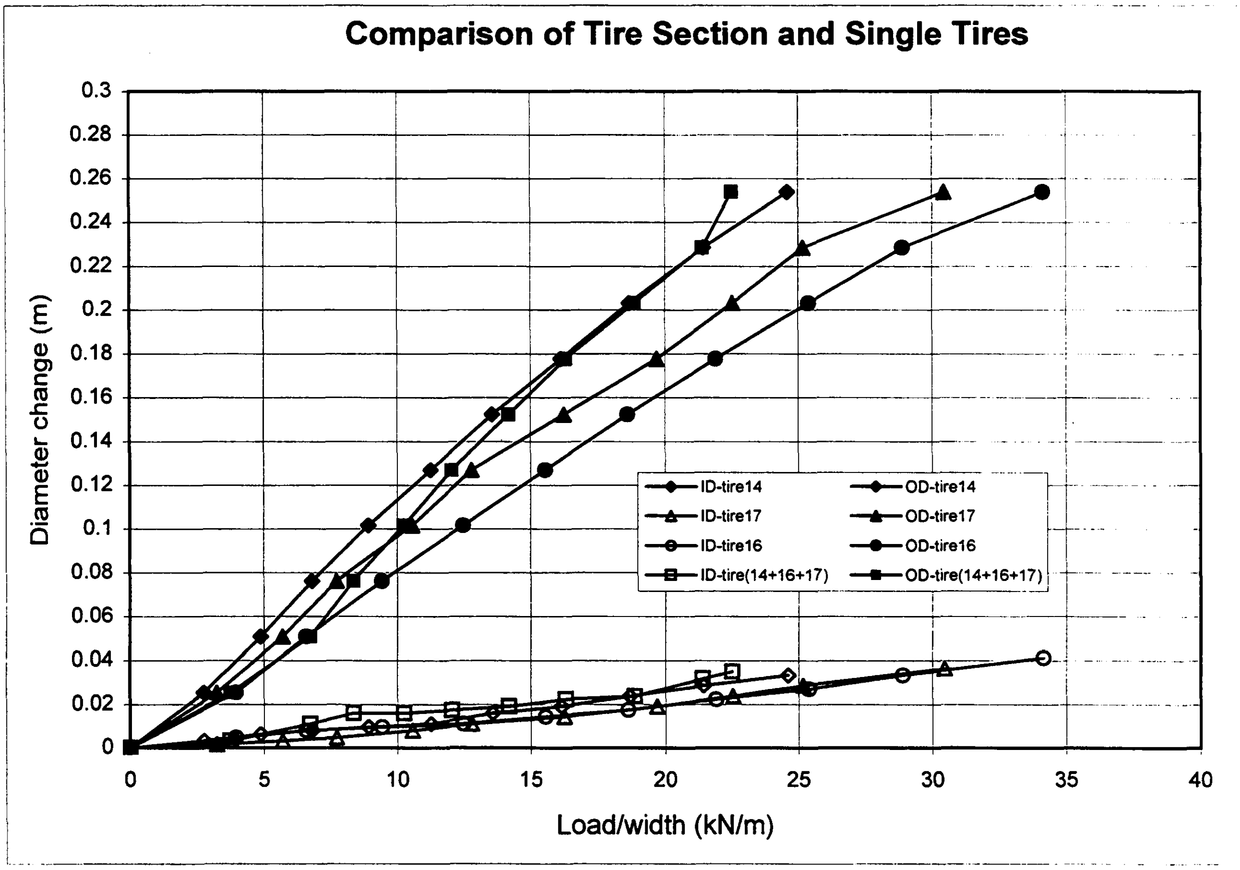


Figure 4.4. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 14, 16 and 17).

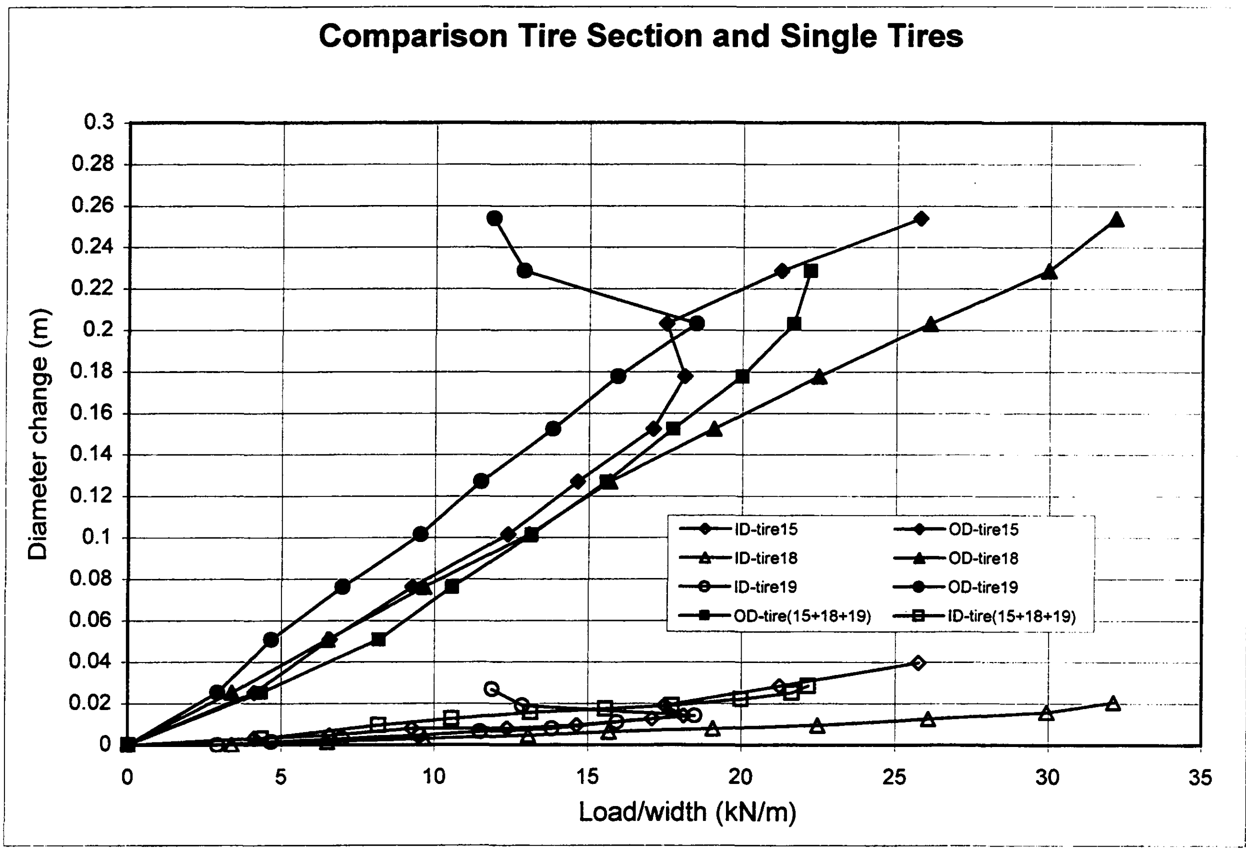


Figure 4.5. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 15, 18 and 19).

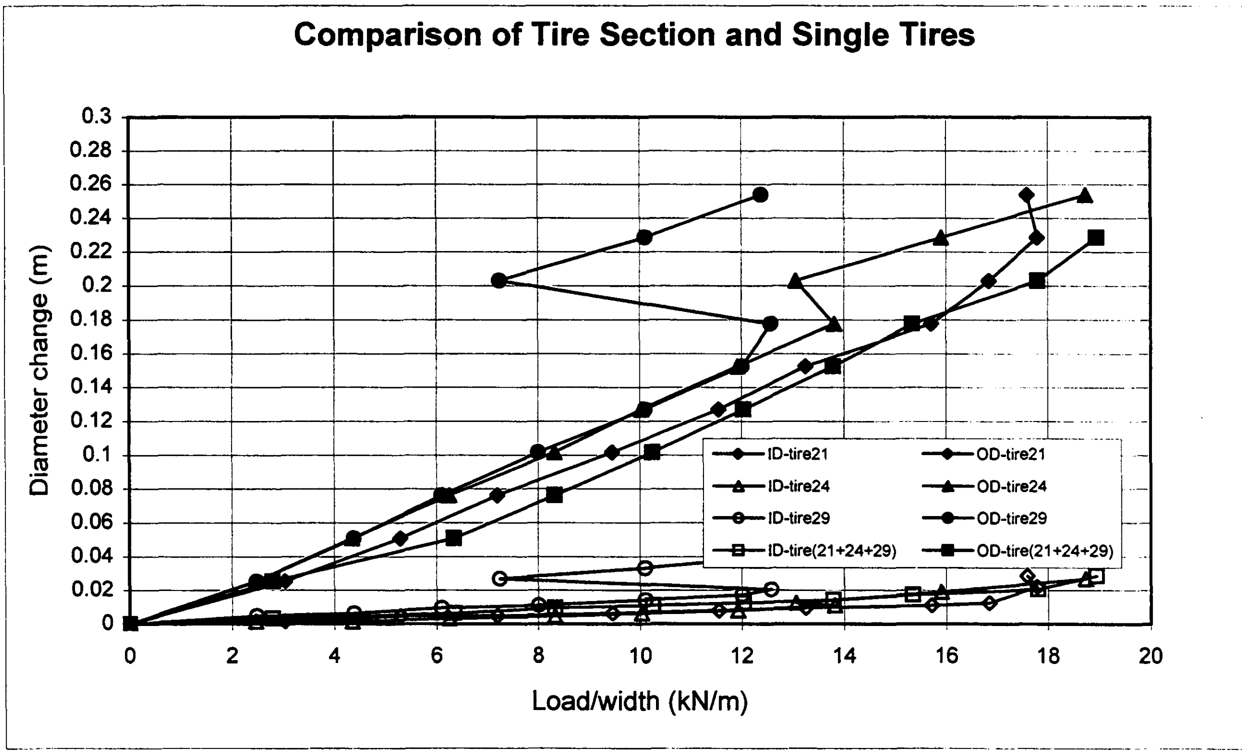


Figure 4.6. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 21, 24 and 29).

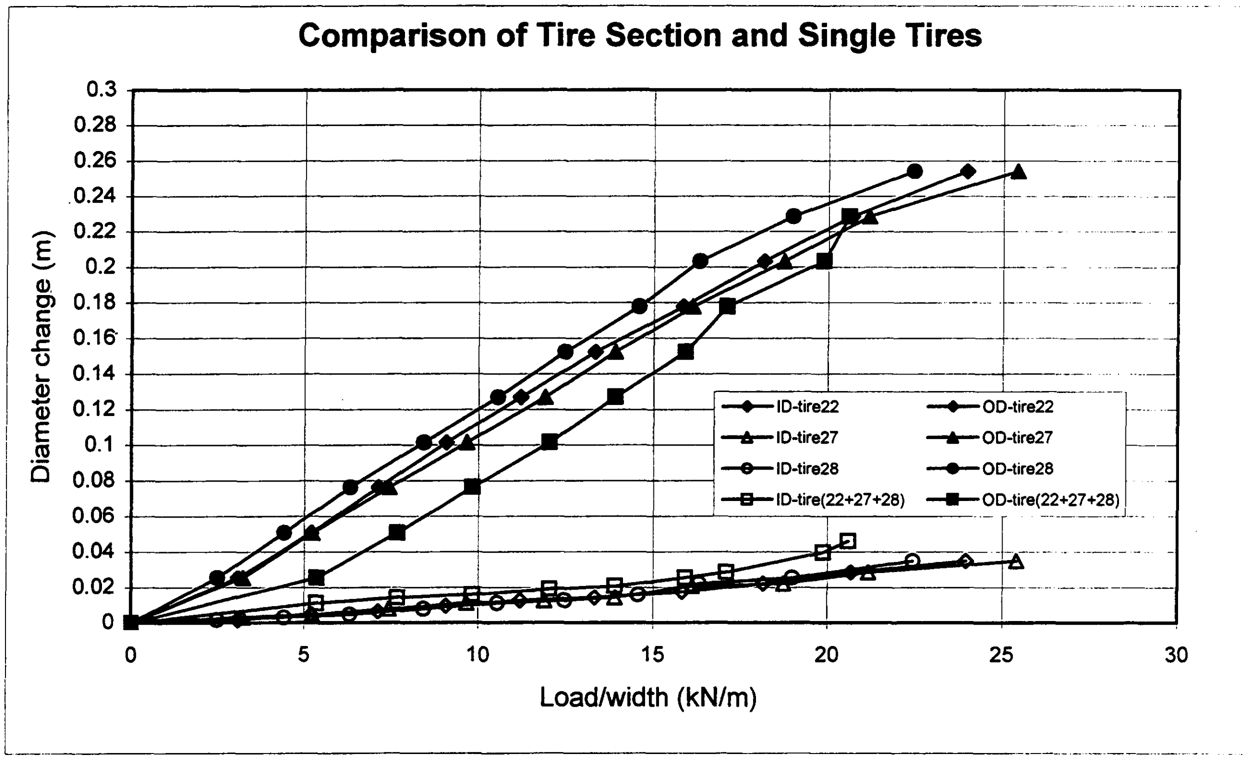


Figure 4.7. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 22, 27 and 28).

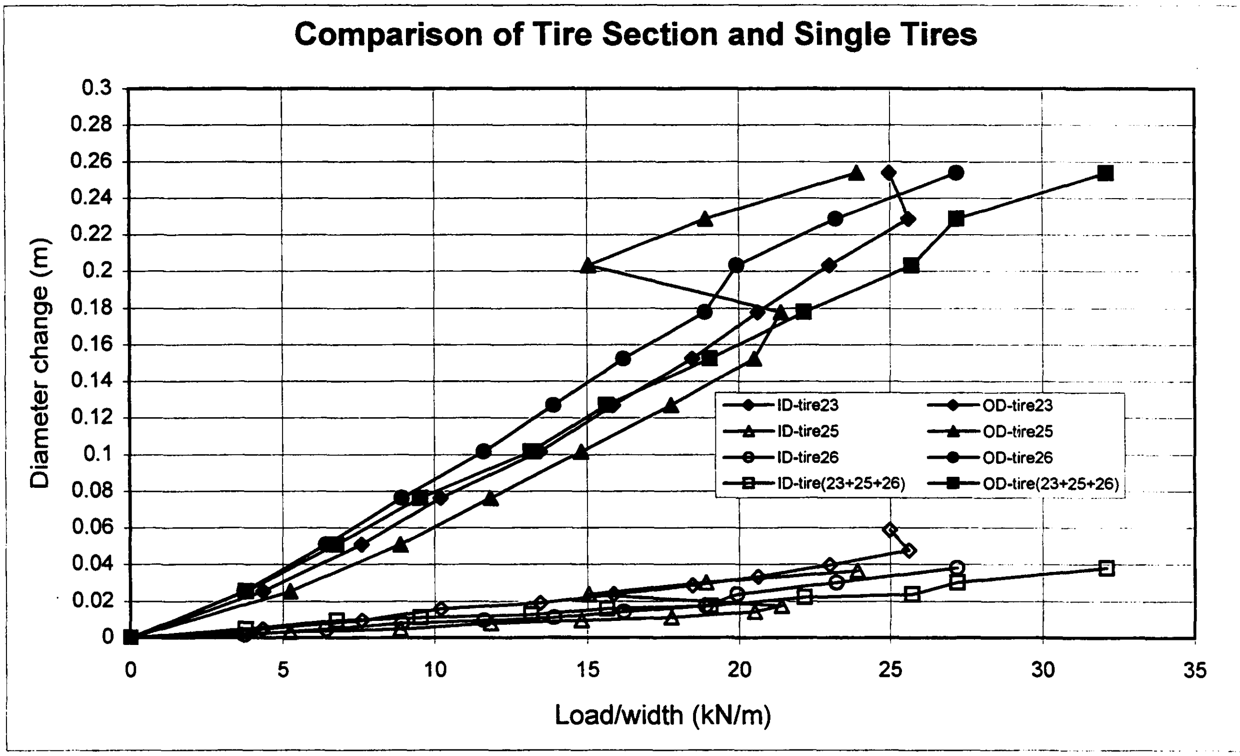


Figure 4.8. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 23, 25 and 26).

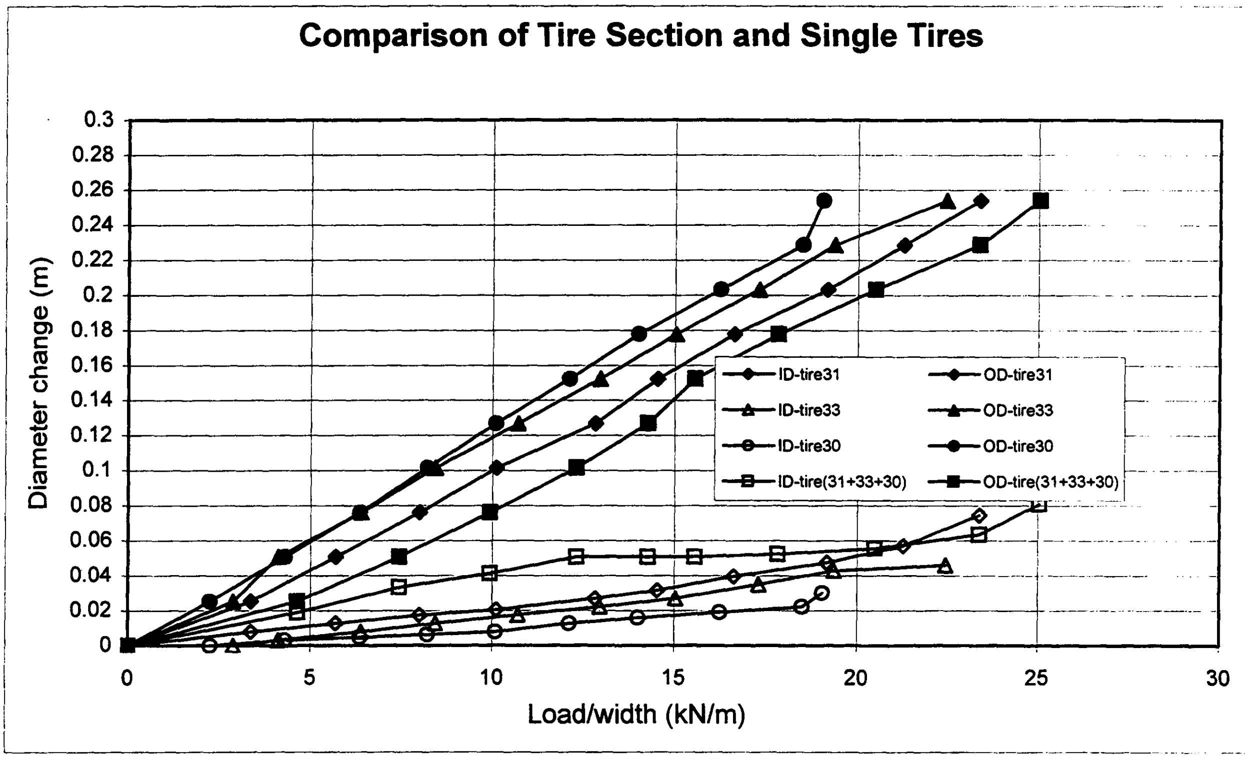


Figure 4.9. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 31, 33 and 30).

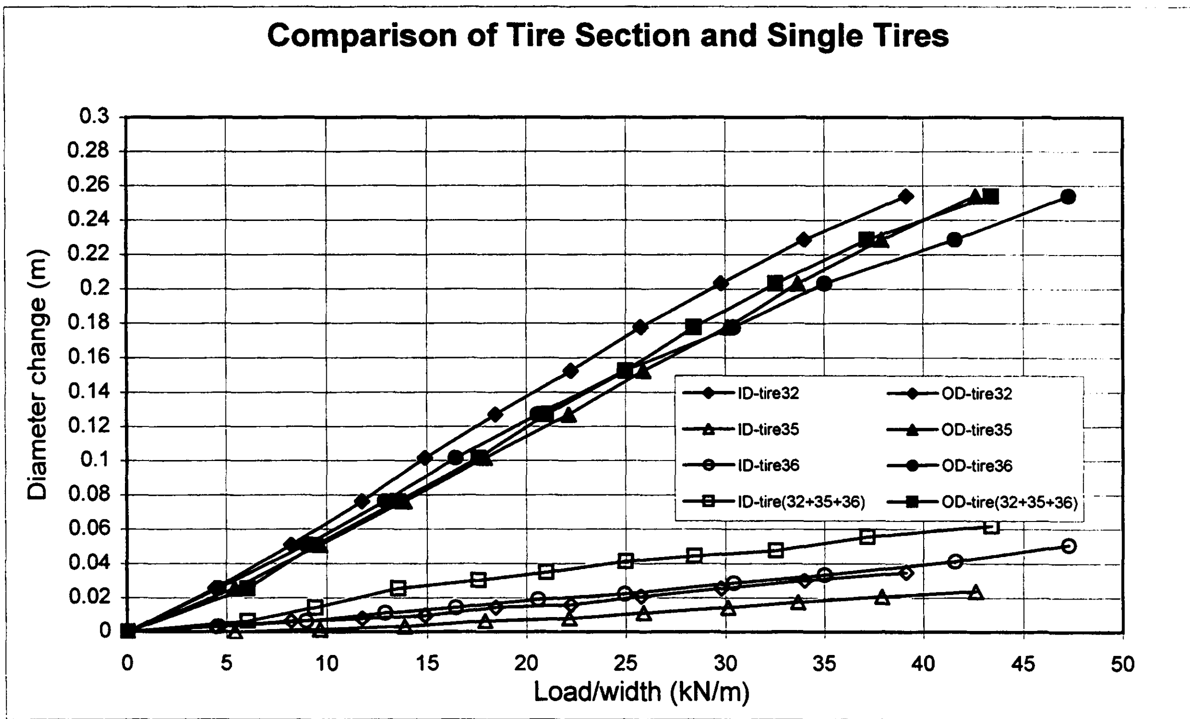


Figure 4.10. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 32, 35 and 36).

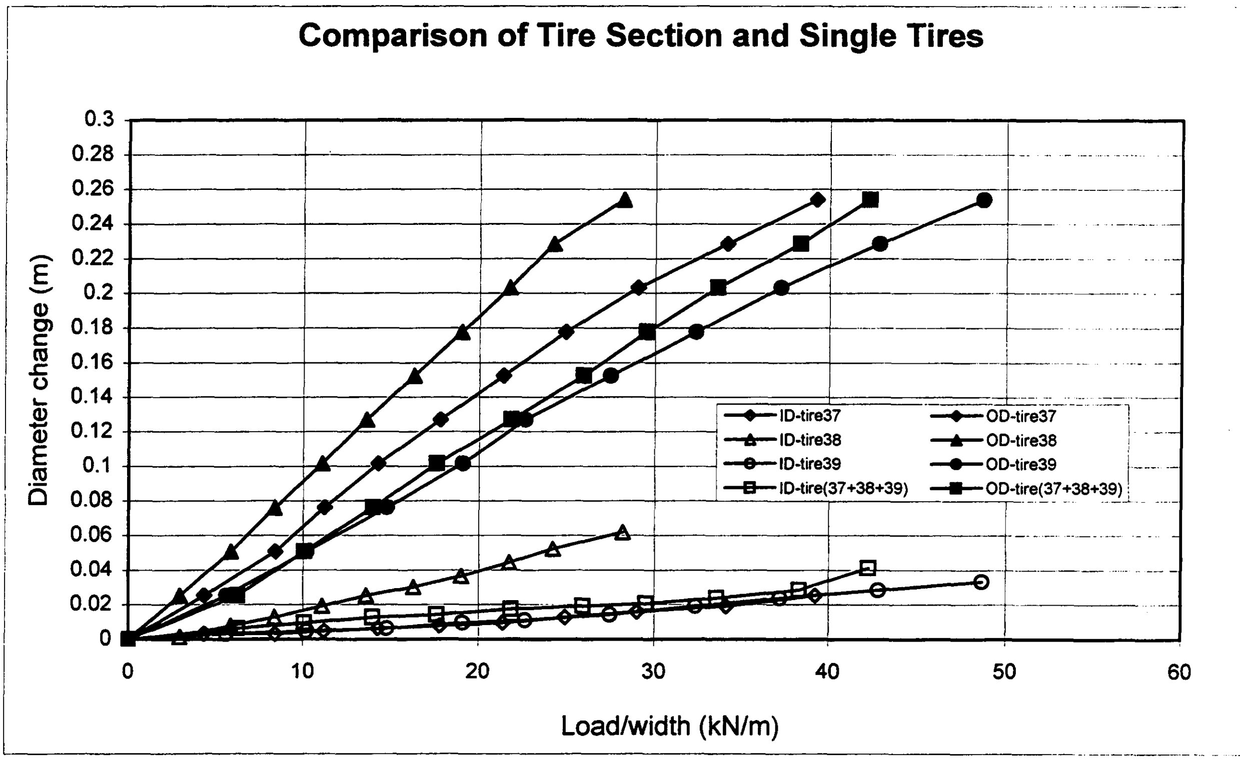


Figure 4.11. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 37, 38 and 39).

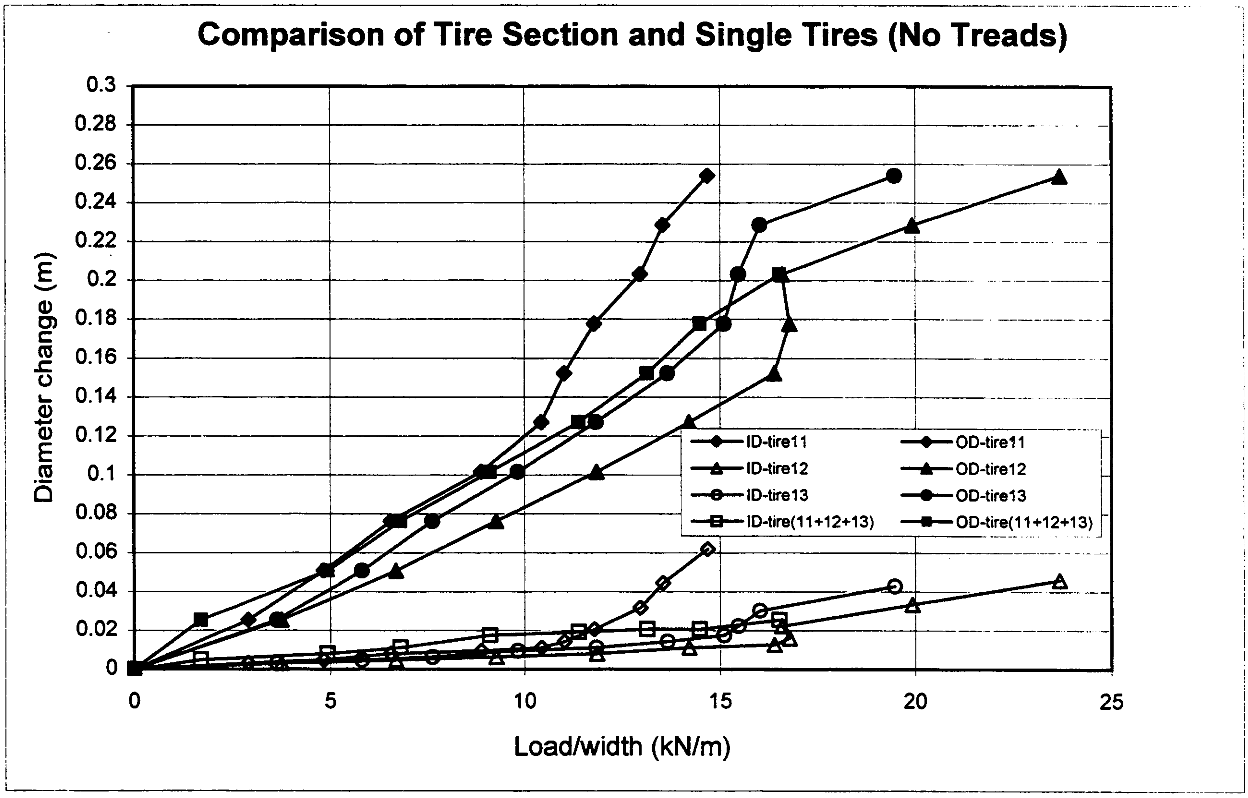


Figure 4.12. Parallel plate test on a tire section versus parallel plate tests on the individual tires comprising the tire section (Tires 11, 12 and 13).

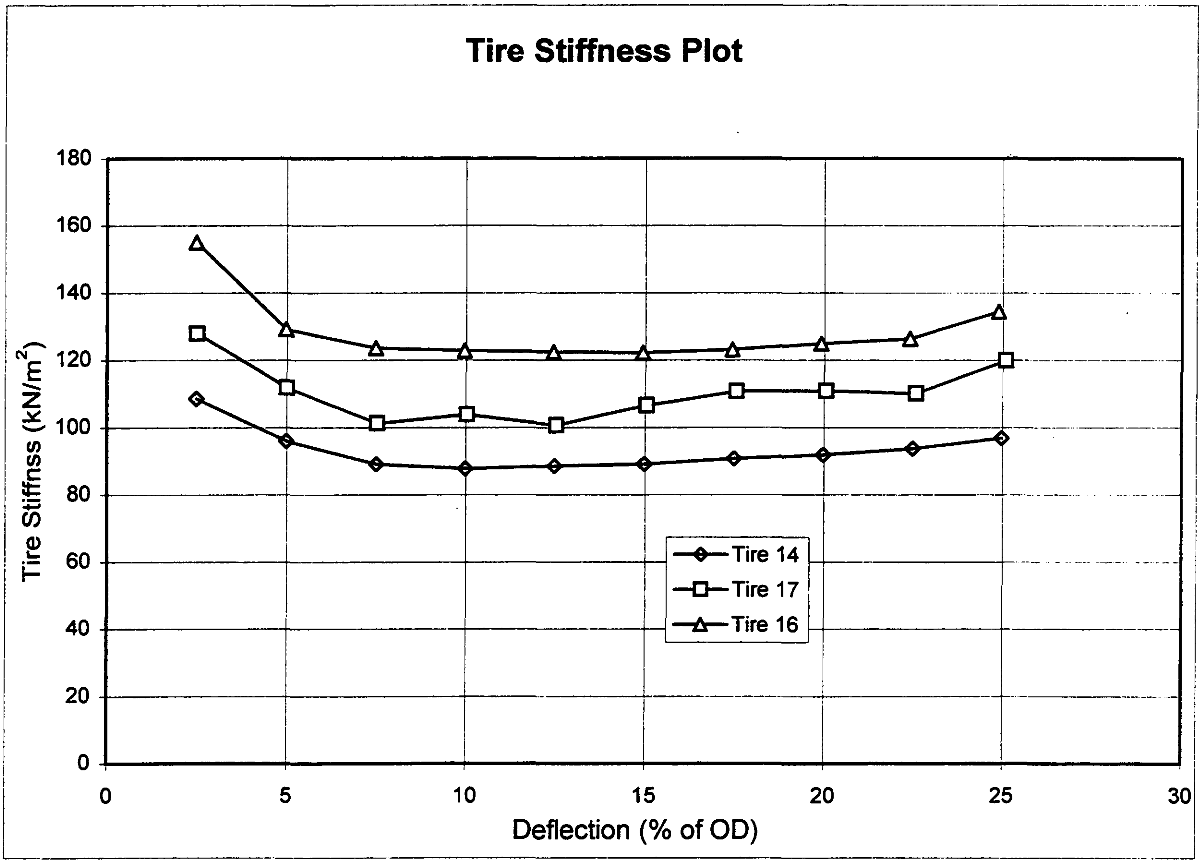


Figure 4.13. Tire stiffness versus deflection for Tires 14, 16 and 17.

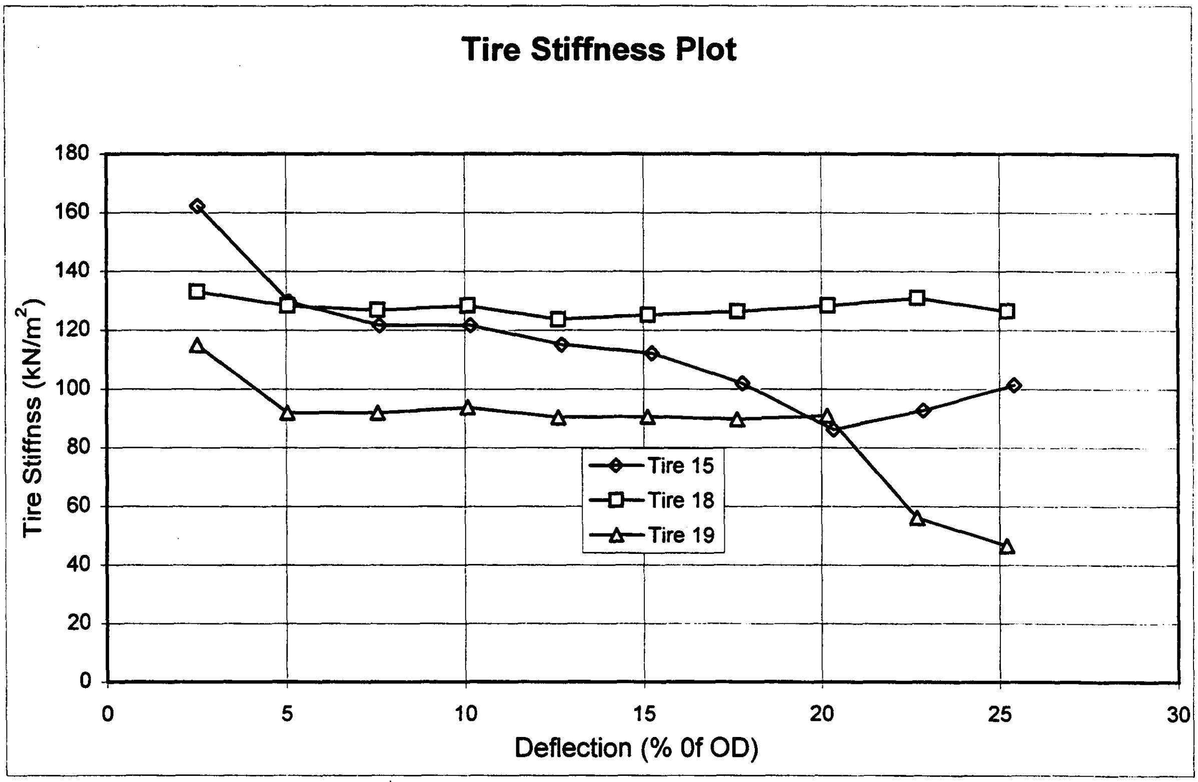


Figure 4.14. Tire stiffness versus deflection for Tires 15, 18 and 19.

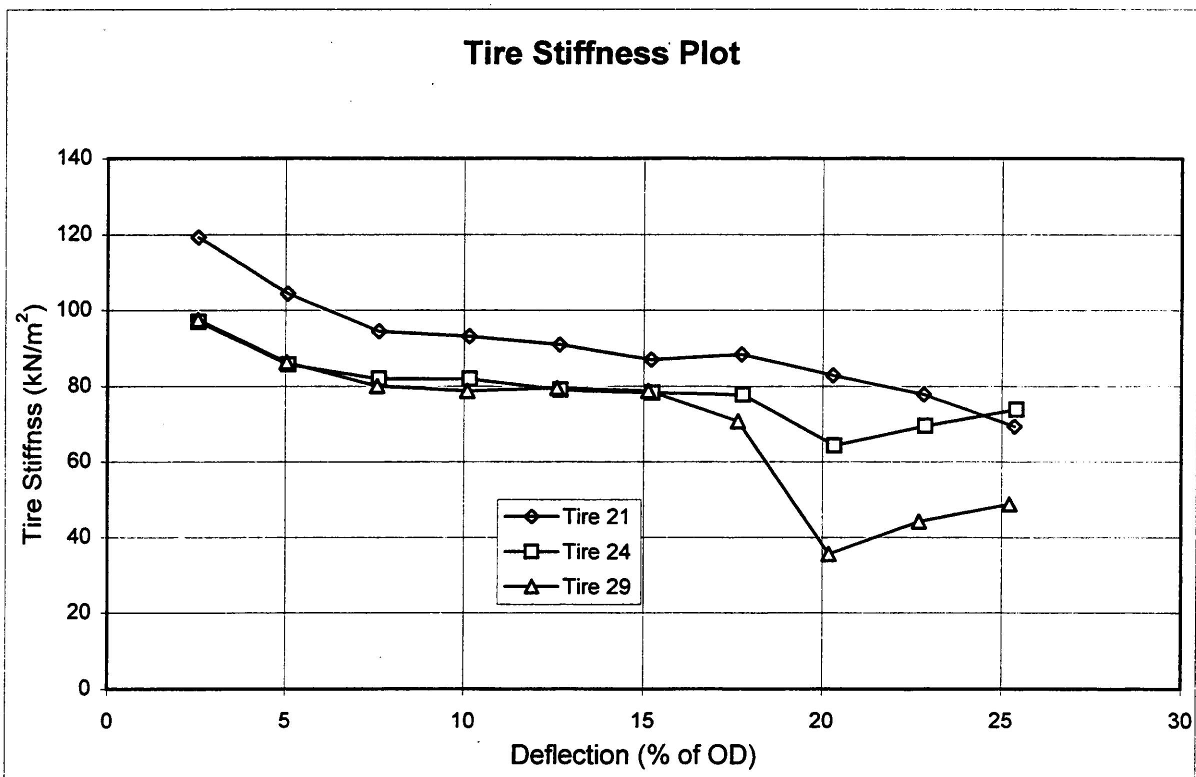


Figure 4.15. Tire stiffness versus deflection for Tires 21, 24 and 29.

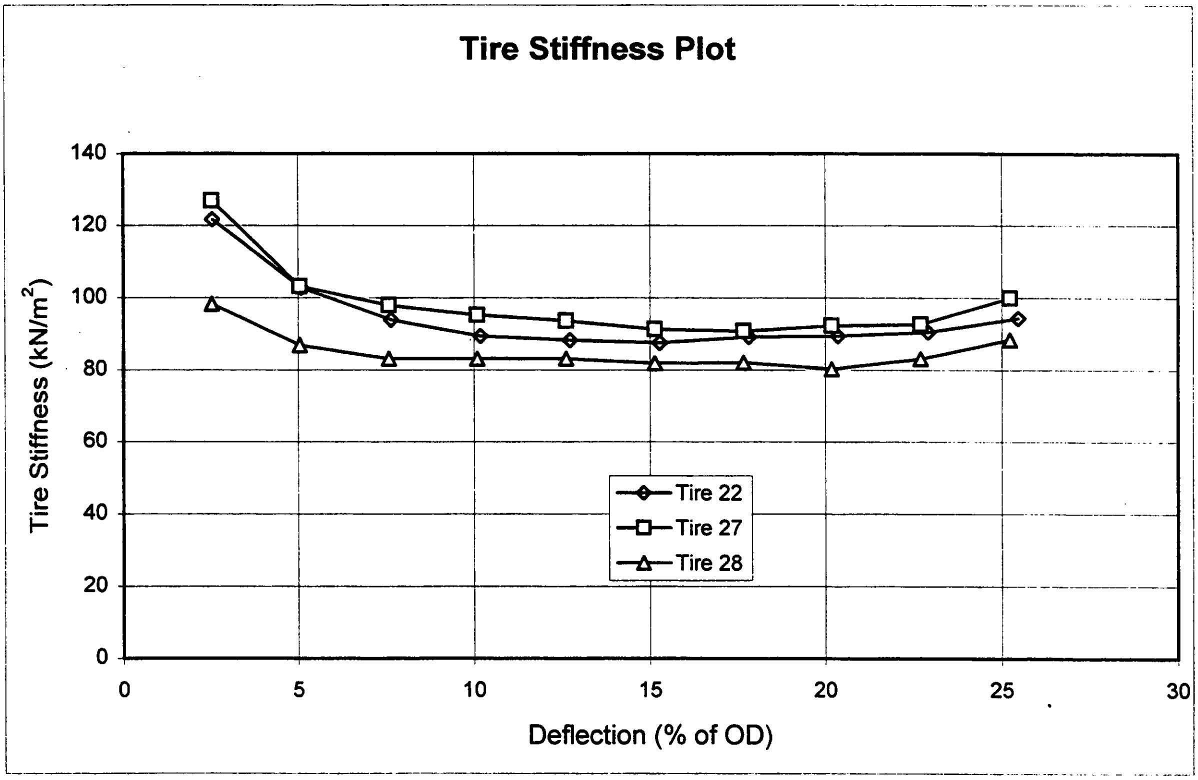


Figure 4.16. Tire stiffness versus deflection for Tires 22, 27 and 28.

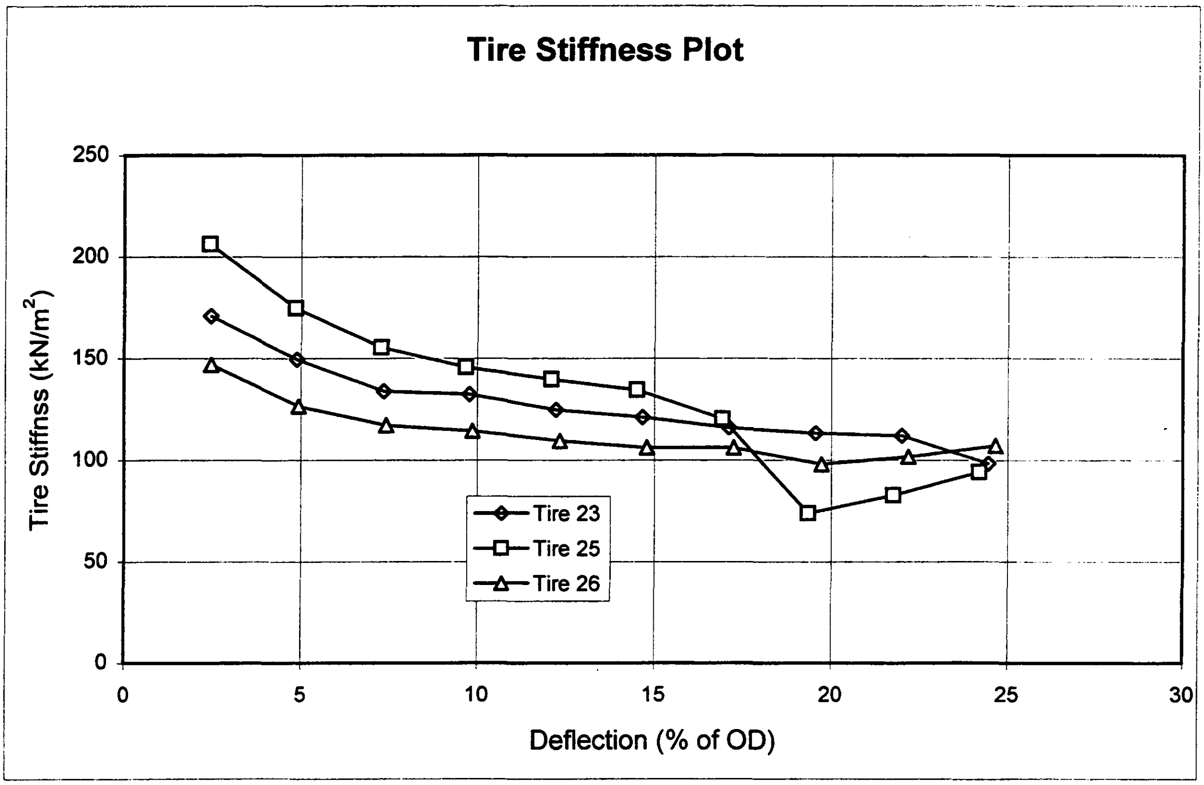


Figure 4.17. Tire stiffness versus deflection for Tires 23, 25 and 26.

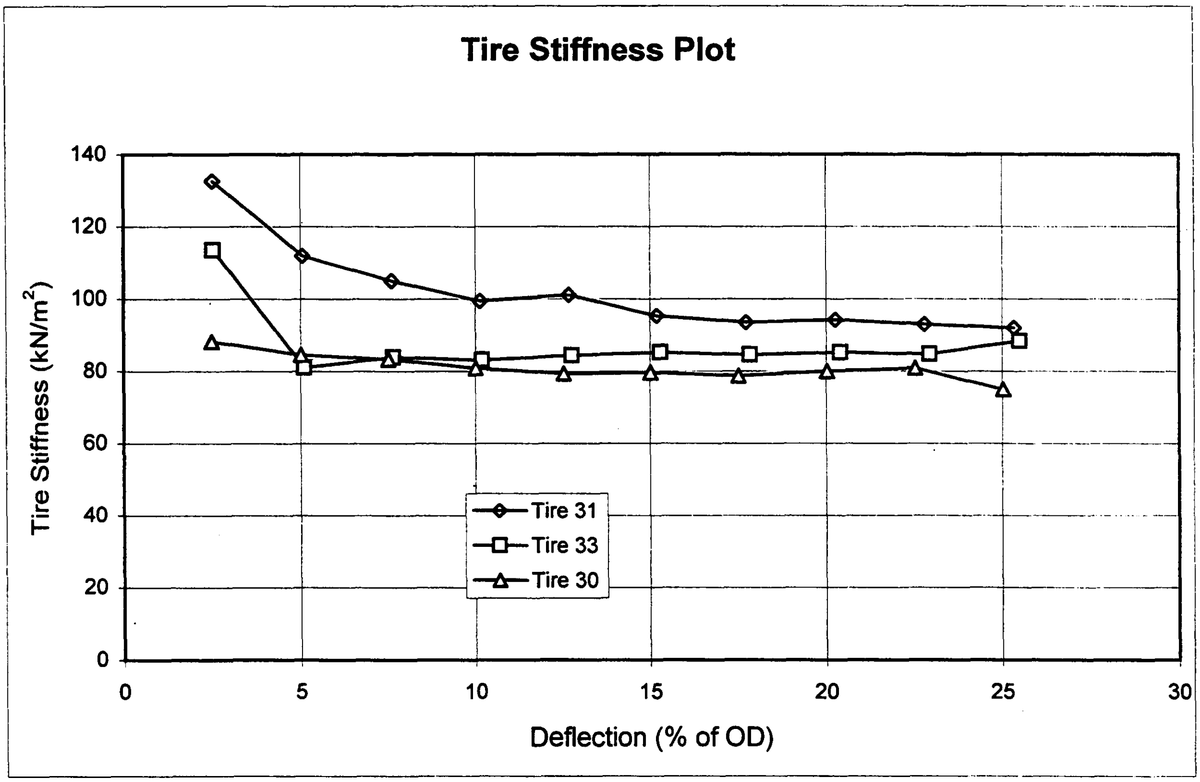


Figure 4.18. Tire stiffness versus deflection for Tires 31, 33 and 30.

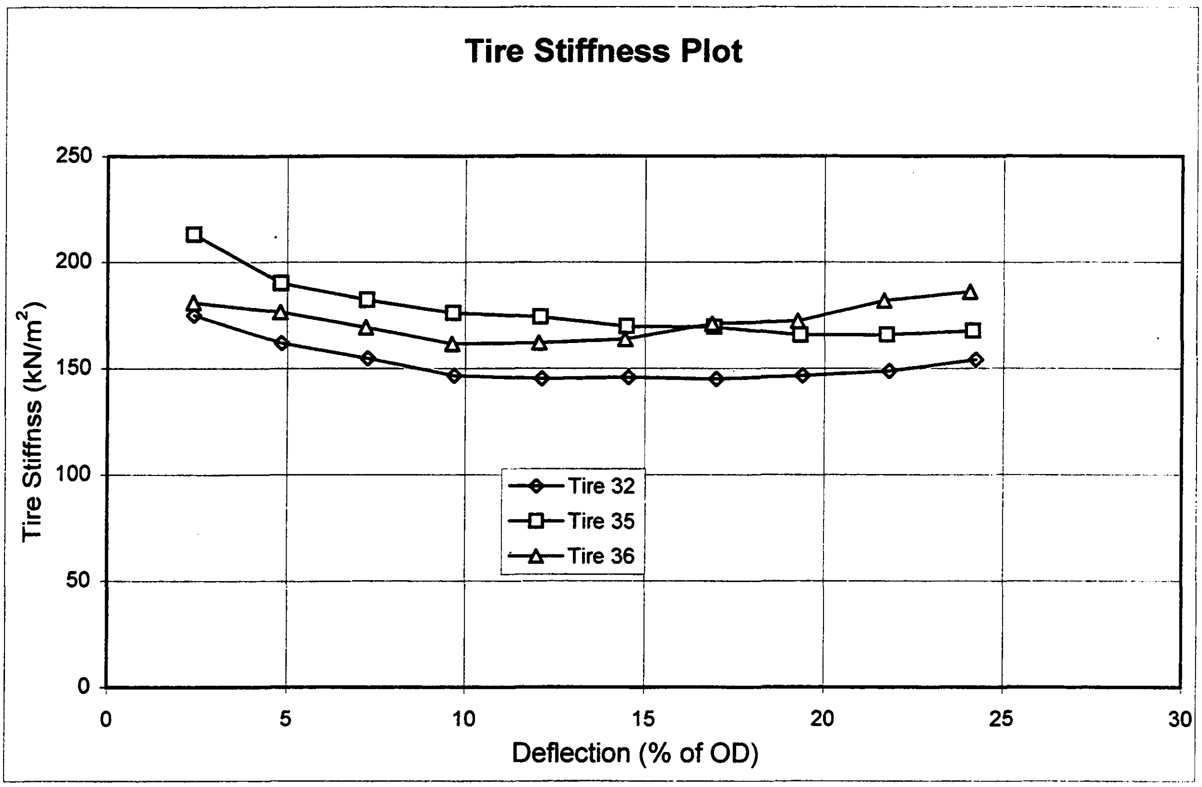


Figure 4.19. Tire stiffness versus deflection for Tires 32, 35 and 36.

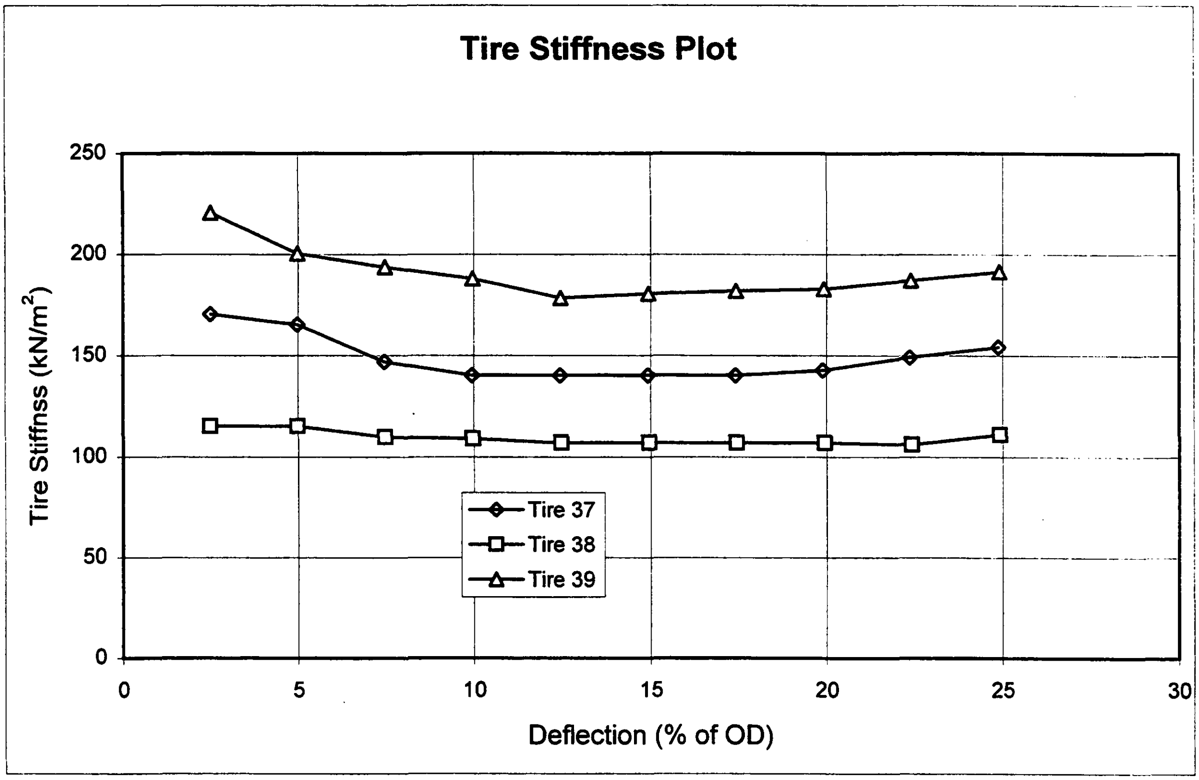


Figure 4.20. Tire stiffness versus deflection for Tires 37, 38 and 39.

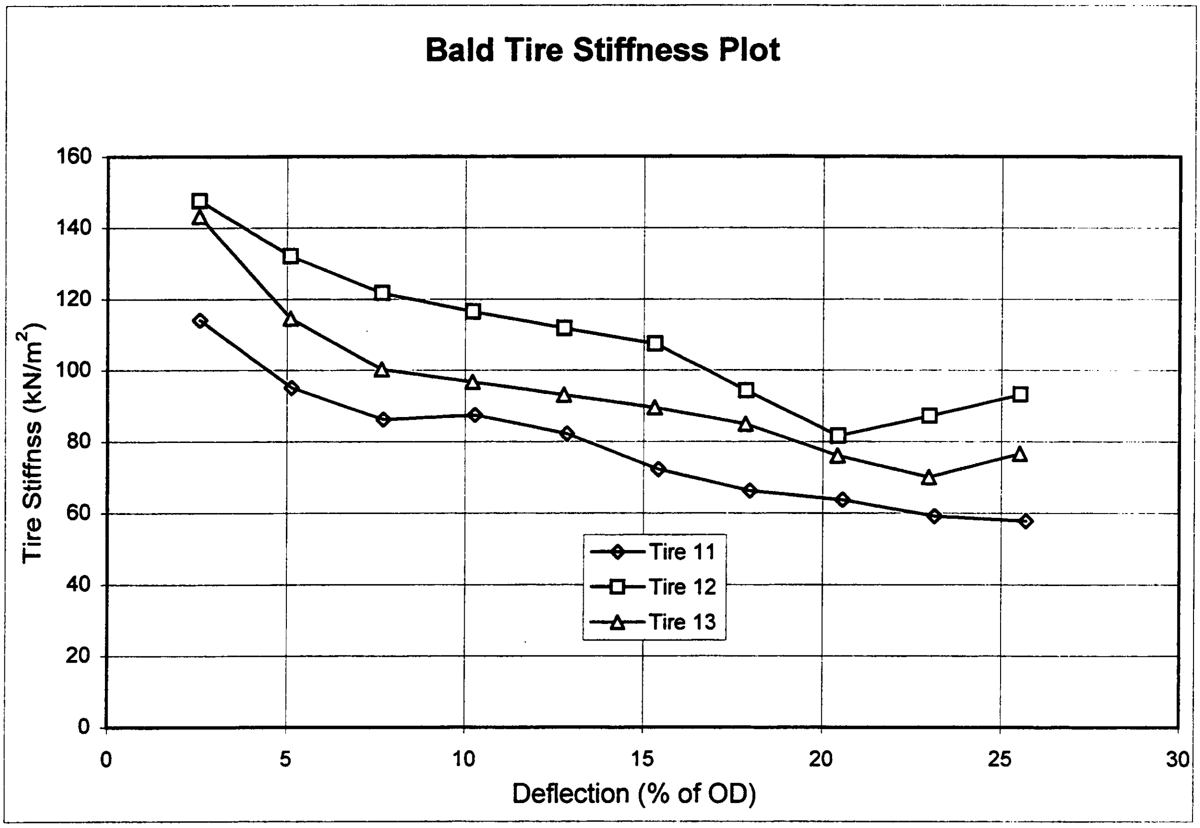


Figure 4.21. Tire stiffness versus deflection for Tires 11, 12 and 13.

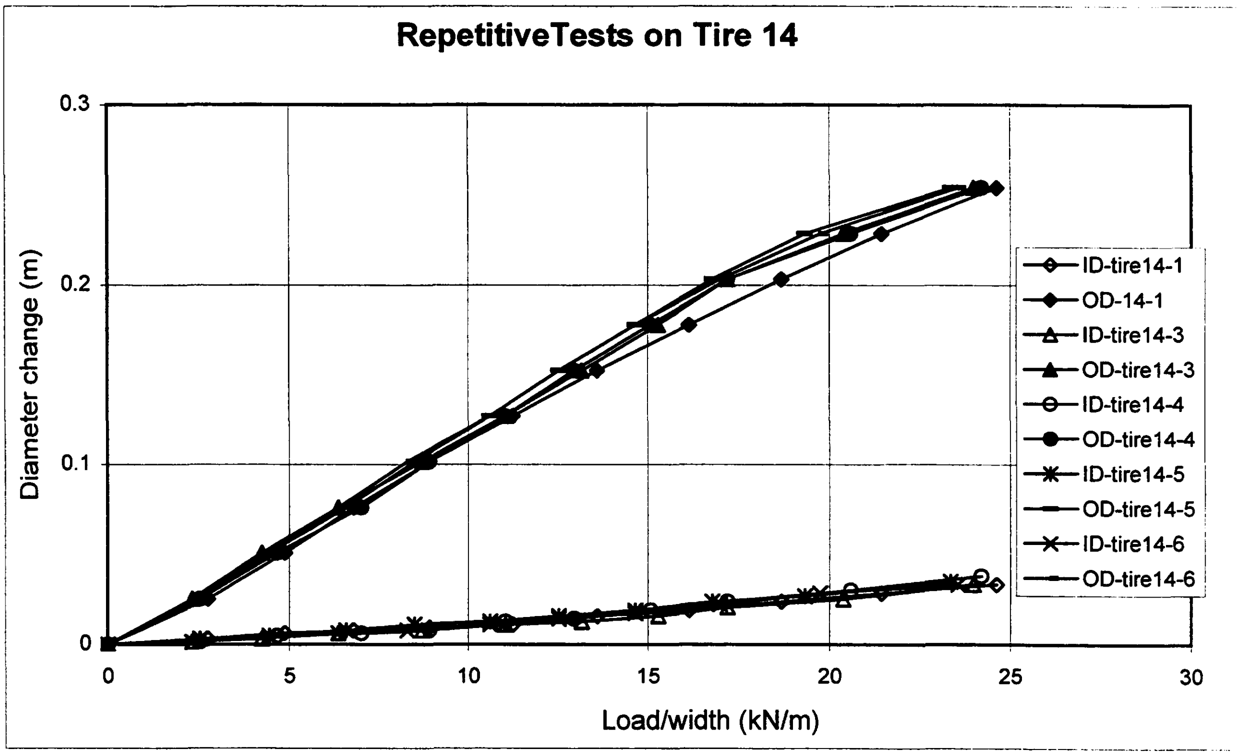


Figure 4.22. Repetitive parallel plate tests for Tire 14.

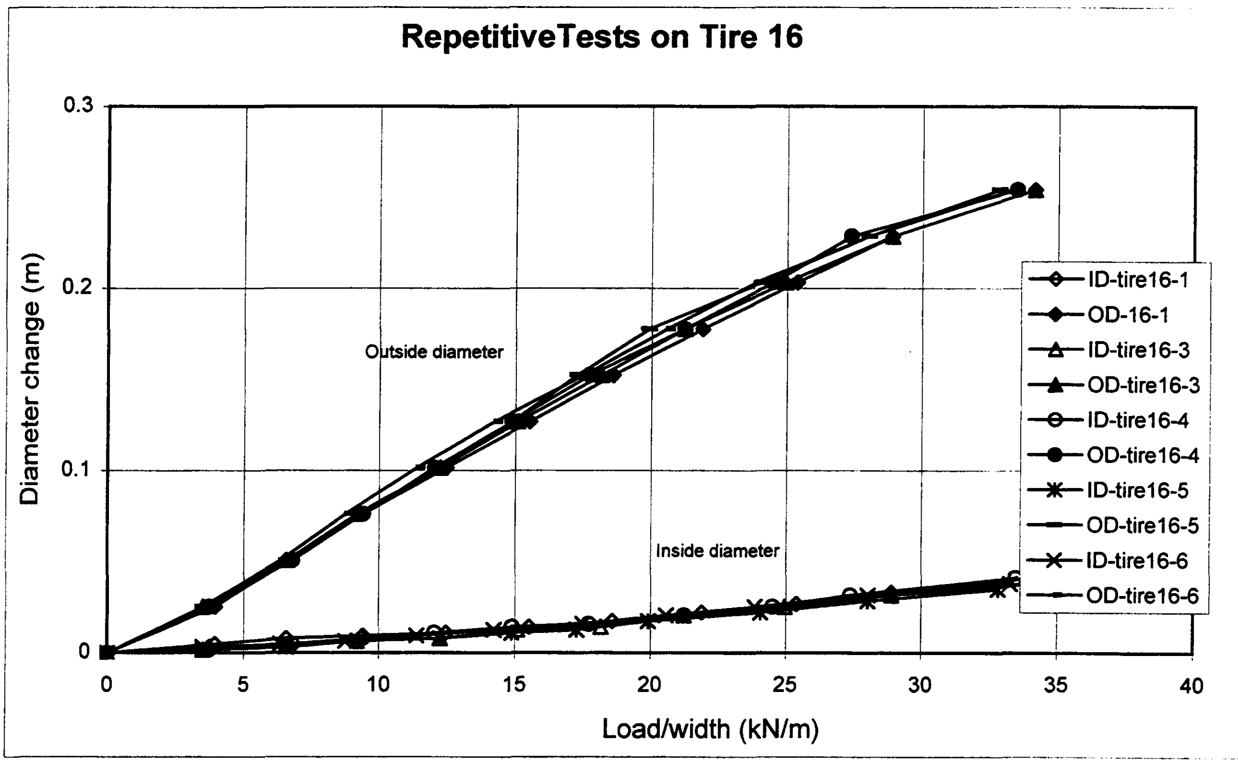


Figure 4.23. Repetitive parallel plate tests for Tire 16.

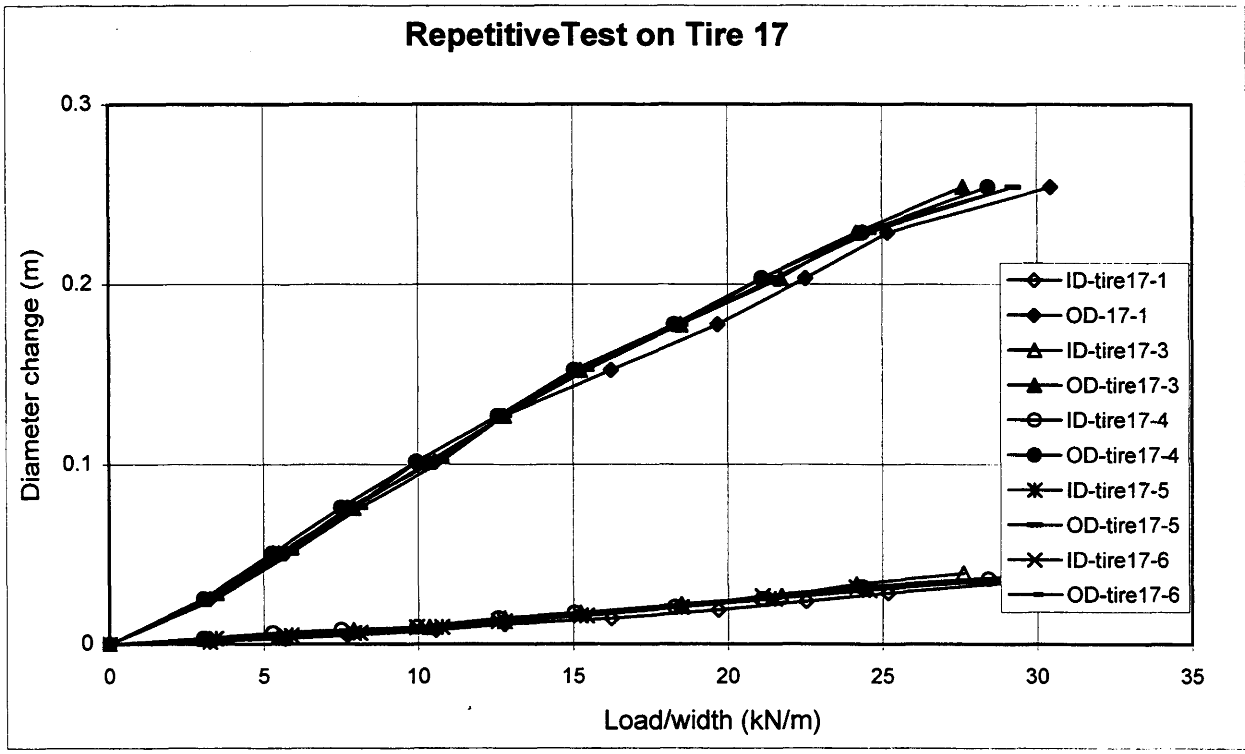


Figure 4.24. Repetitive parallel plate tests for Tire 17.

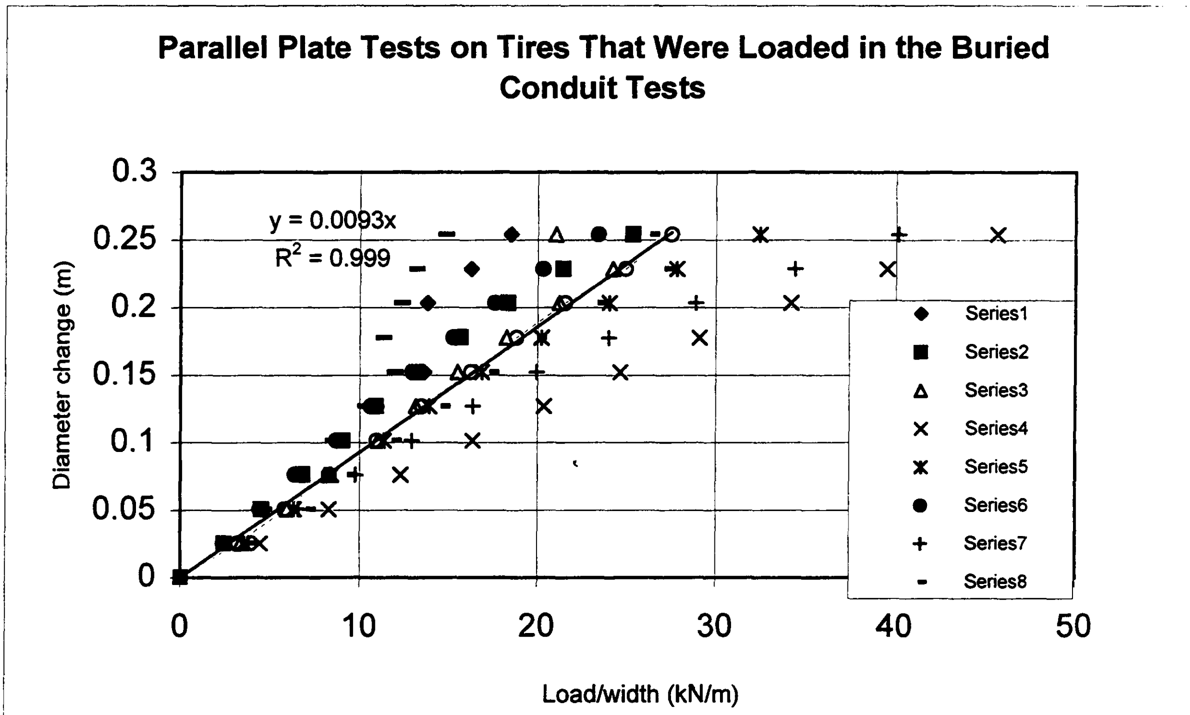


Figure 4.25. Parallel plate tests on single tires that were loaded in the buried conduit tests.

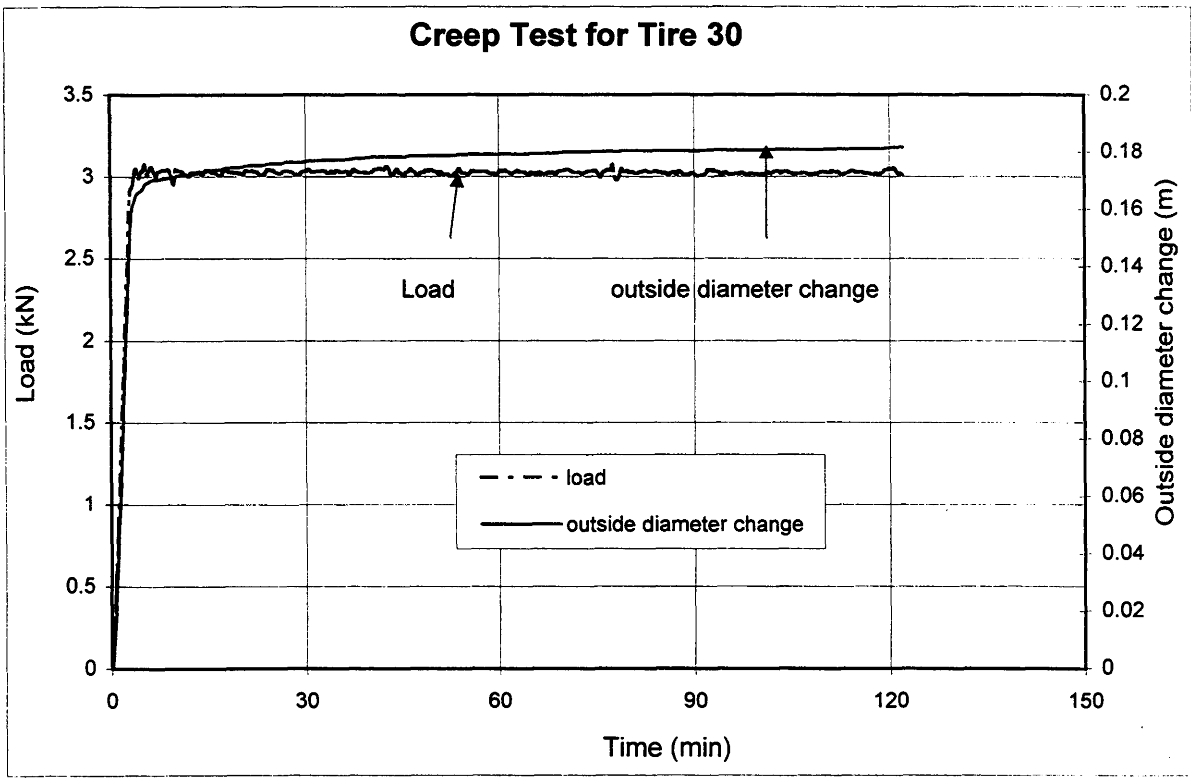


Figure 4.26. Creep parallel plate test for Tire 30.

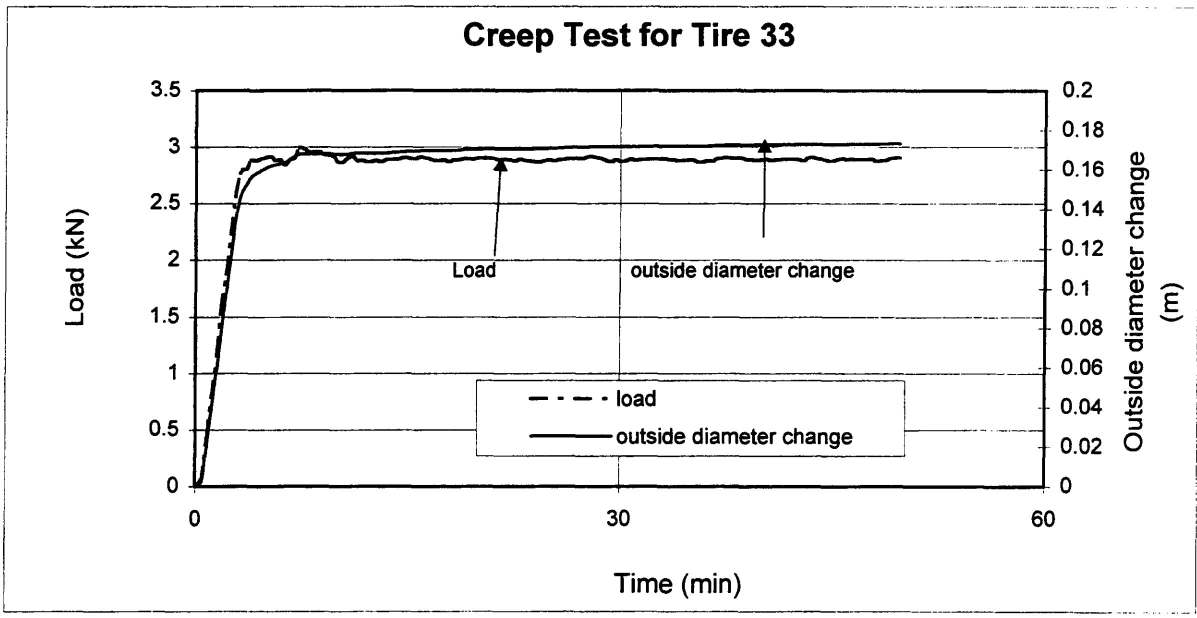


Figure 4.27. Creep parallel plate test for Tire 33.

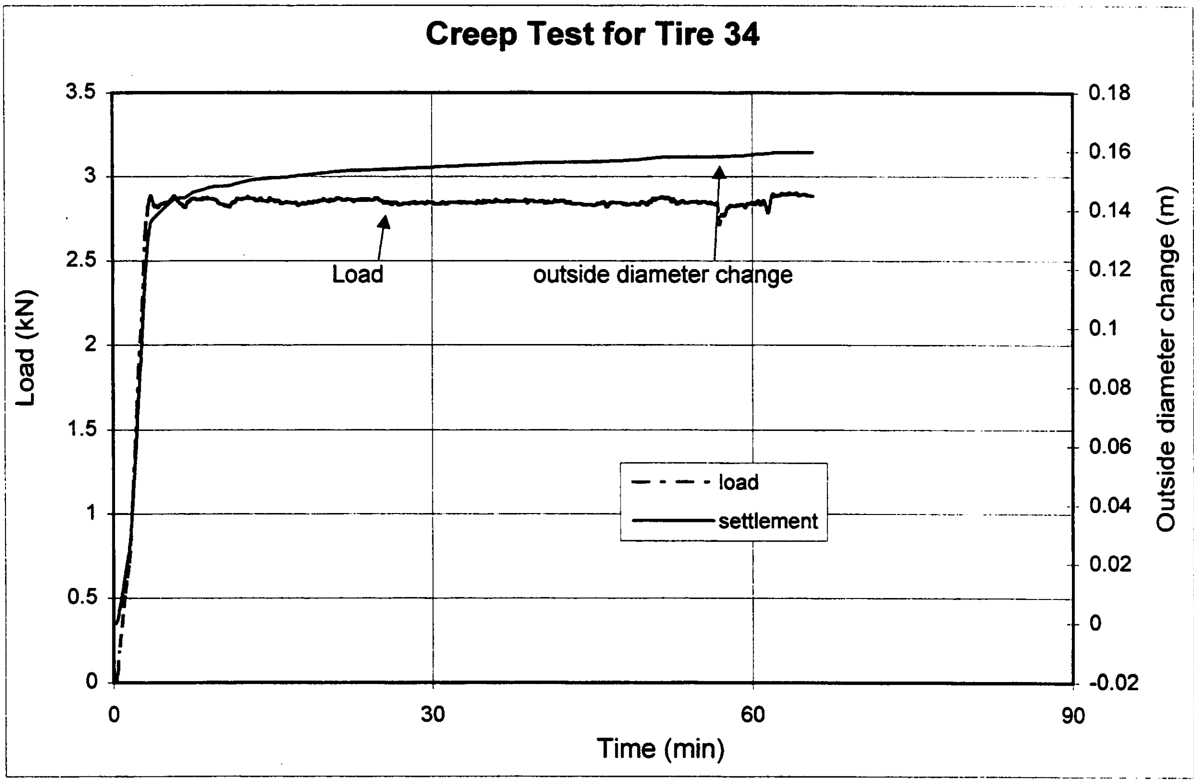


Figure 4.28. Creep parallel plate test for Tire 34.

5. Buried Conduit Tests

5.1 Background

The strength and stiffness characteristics of truck tires were investigated using the parallel plate test, as described in the previous section. In a typical field situation, the truck tire culvert would be buried in a trench and the culvert behavior would depend not only on its own strength and stiffness but also on its interaction with the surrounding backfill soil. Buried conduit testing was carried out to assess the truck tire culvert structural performance and interaction with surrounding backfill soil in a controlled, yet realistic, setting.

The buried conduit tests were performed in a specially constructed facility on the west side of the Town Engineering Building on the ISU campus. The effects of soil backfill compaction, trench configuration, loading magnitude, and load location on truck tire culvert performance were examined in three specially designed tests. The results of these tests were used to calibrate the analytical model that was in turn used to develop the structural performance aspects of the truck tire culvert design guidelines.

5.2 Backfill Characterization

The moisture-density (compaction), the stress-strain, and the shear strength characteristics of the backfill soil were required to analyze and interpret the response and performance of the truck tire culvert structure in the buried conduit facility tests. The backfill soil used for these tests was a native glacial till soil. Index tests, including particle size distribution and Atterberg limits, and standard Proctor compaction tests had been carried out on representative glacial till samples by previous researchers. A particle size distribution curve is shown in Fig. 5.1. The soil, classifying as a sandy-silty-clay (CL-ML) by the Unified Soil Classification System, has a standard Proctor maximum dry unit weight of 18.6 kN/m^3 and an optimum moisture content of 12%.

As the required stress-strain and shear strength properties of the glacial till soil were not available, a series of consolidated-drained triaxial tests were conducted on representative, compacted glacial till samples. The results from these tests were interpreted in terms of the Duncan-Chang constitutive model (Duncan and Chang, 1970) for stress-strain response and in terms of the Mohr-Coulomb failure criterion for shear strength.

5.2.1 Triaxial test soil sample preparation and testing

To simulate field conditions, the compacted soil samples for the triaxial tests were prepared using a range of moisture contents and were tested at different confining pressures. It was found, however, that soil samples with moisture contents higher than 13% were difficult to handle and could not be tested in the triaxial test machine. Consolidated-drained triaxial tests were conducted, therefore, on soil samples at moisture contents of 10% and 5%.

The glacial till soil was prepared for compaction according to ASTM D-698 (82). The samples were formed using a compaction mold with a diameter of 0.071 m, a height of 0.194 m and a corresponding volume of $7.695X10^{-4}$ m^3. These sized samples can be directly placed into the triaxial test apparatus. The samples were compacted in three equal layers using a hammer with a mass of 6.85 kg and drop distance of 0.457 m ; four blows were applied to each layer. This gives a compaction energy per unit volume of:

$$E = \frac{3layers \times 4blows \times 6.85kg \times 9.81m/s^2 \times 0.457m}{0.0007695m^3} = 478.9kJ/m^3$$

This energy per unit volume corresponds to 81% of standard Proctor compactive effort. Relevant information for the compacted soil samples is listed in Table 5.1. The average dry unit weight for the 10 soil samples with 10% moisture content is 17.8 kN/m^3, which corresponds to a standard-Proctor-based relative compaction of 96%. The average dry unit weight for the six soil samples with 5% moisture content is 16.7 kN/m^3, which corresponds to a standard-Proctor-based relative compaction of 90%.

A schematic of the triaxial test apparatus is shown in Fig 5.2. For a consolidated-drained (CD) test, following installation of the cylindrical soil sample in the apparatus and placement of the triaxial cell in a compression test machine, a pressure is applied within the sealed chamber (called confining pressure) and the drains leading to the top and bottom of the sample are kept open, allowing the sample to consolidate. After consolidation of the sample is complete, the sample is strained axially by applying a constant rate of deformation to the loading ram by activating the compression test machine. The drains at the top and bottom of the sample are kept open during this second stage of the test. The all around confining pressure is σ_3 and the applied axial stress is (σ_1 - σ_3), where σ_1 is the major principal stress and σ_3 is the minor principal stress. The applied axial stress at failure is determined for each test and the results of several tests at different confining pressures are typically plotted and interpreted in terms of "p" and "q" at failure, where:

$$p = \frac{\sigma_1 + \sigma_3}{2} \quad and \quad q = \frac{\sigma_1 - \sigma_3}{2}$$

5.2.2 Triaxial test results

Fig. 5.3 shows a p-q plot for the 10 CD tests conducted on samples with a moisture content of 10%. The confining pressures for these tests ranged from 16 kPa to 279 kPa. From a linear regression analysis of these 10 points on the p-q graph, the friction angle ϕ was calculated to be 29° and the cohesion intercept to be 28 kPa. Note that the p-q results for the 10 tests fall very close to a straight line.

A plot of initial tangent modulus versus confining pressure, with both parameters normalized to atmospheric pressure (P_{at}), for the CD tests on samples with a moisture content of 10% is shown on Fig 5.4. This plot is used for determination of parameters for the Duncan-Chang stress-strain model (For more information on the Duncan-Chang model and interpretation of the parameters the reader is referred to Duncan and Chang, 1970). Because the test carried out at a confining pressure of 16 kPa gave an unreasonably high initial tangent modulus, this point was not included on the plot. Through regression analysis of the remaining nine tests, the modulus number K and the modulus exponent n were determined to be 160 and 0.22, respectively. Note the relatively large scatter and low correlation coefficient for this plot.

Fig. 5.5 shows a p-q plot for the six CD tests conducted on samples with a moisture content of 5%. The confining pressures for these tests ranged from 39 kPa to 280 kPa. From a linear regression analysis of these six points on the p-q graph, the friction angle ϕ was calculated to be 38° and the cohesion intercept to be 13 kPa. Note that the p-q results for the six tests fall very close to a straight line, as was the case for tests shown in Fig 5.3.

A plot of initial tangent modulus versus confining pressure, with both parameters normalized to atmospheric pressure (P_{at}), for the CD tests on samples with a moisture content of 5% is shown on Fig 5.6. Through regression analysis of these six tests, the modulus number K and the modulus exponent n were found to be 403 and 0.18, respectively. As with Fig 5.4, there is also relatively large scatter in these data, with a low correlation coefficient.

As described in section 6 of this report, the CUlvert ANalaysis and DEsign (CANDE) program is a finite element computer program for culvert design and analysis. The Duncan-Chang stress strain model was used in the CANDE program to model the response of the backfill soil and its interaction with the buried conduit under applied loading conditions. The shear strength and Duncan-Chang soil parameters from the CANDE data library (for a CL silty clay soil) and from our CD tests on the 10% moisture content samples are compared in Table 5.2. The application of these parameters for the CANDE modeling of the buried conduit tests will be discussed in section 6.

5.3 Buried Conduit Test Equipment, Procedures and Results

Buried conduit facility testing was carried out to evaluate the effects of soil backfill placement and degree of compaction, trench configuration, loading magnitude and load location on truck tire culvert performance. To conduct a test, six instrumented tire sections (a total of 18 tires) were placed side-by-side in a trench and backfilled according to the specific test requirements. Live loads were applied to the surface of the backfill with a hydraulic ram using an overhead frame for reaction (see Fig. 5.7). Up to 1388 kN of force could be generated with this system. A steel plate of 0.093-m^2 (i.e. one square foot) area was attached to the hydraulic ram to represent a truck tire. For all loading tests, the hydraulic ram was extended for a total of 0.34 m of displacement. The loading tests were typically completed in about 20 to 30 minutes. Tire response was measured during both the backfilling and live loading stages.

5.3.1 Buried conduit test 1

Test 1 was carried out to evaluate truck tire culvert performance under the condition of backfill placed loosely with no compactive effort. The backfill was expected to provide little lateral support to the tires and represents a lower bound, potential worst case backfill scenario.

Fig 5.8 shows a transverse cross section through the buried culvert while Fig 5.10 shows a longitudinal profile along the truck tire culvert length. Prior to placing the tire sections into the trench, electronic potentiometer gages (Celesco transducers) were installed on selected tires to measure the change of inside or outside diameter. The locations of these gages and the diameter being measured on a specific tire are shown on Fig. 5.9. A computer controlled Data Acquisition System in the ISU Structures laboratory was used to record the electronic potentiometer gage data.

For this test, the instrumented tire sections were placed into a trench about 1.8 m wide at the bottom by 6.7 m long by 1.8 m deep with sides sloping at about 1:1. Next, glacial till backfill was placed beside and on top of the truck tire culvert using a skid loader to give the final configuration as shown in Fig 5.8. The backfill was not compacted. Note that about 0.6 m of backfill was placed over the crown of the truck tire culvert. Fig 5.8 also gives in situ moisture contents and dry unit weights for the backfill as determined with two nuclear densometer tests performed at the surface of the fill. These tests give an in situ dry unit weight that is about 80% of the standard Proctor maximum for this backfill soil. Klaiber et al., 1996, carried out a test in the same facility using 0.9 m diameter plastic pipe backfilled with dumped, uncompacted glacial till. Their 30 in situ density measurements showed a variation in relative compaction from about 32% to 61% of the standard Proctor maximum; the average was about 50%. It is highly likely that a significant portion of the backfill in Test 1 has a relative compaction closer to 50% than to the 80% shown by our in situ tests. The higher value was likely due to compaction of the surface of the fill by installation activities.

Fig 5.10 indicates the change in the inside or outside diameter of the instrumented tires induced by placing backfill beside the tires and above the crown of the tires. Negative values indicate a decrease in the diameter. Diameter changes due to backfilling were minimal, ranging from about 0.0005 m to 0.005 m.

Three load tests were carried out at the locations shown on Fig 5.9. The results for the test at the north end of the culvert are shown on Fig 5.11, for the test in the central region of culvert on Fig 5.12 and at the south end of the culvert on Fig 5.13. These figures illustrate the applied loading (stress in kN/m^2) versus inside or outside diameter change response for the tires beneath the loaded plate at the three locations. (Due to a data recording malfunction, some of the data beyond the point at which the maximum stress was mobilized in the northern and central tests were lost.) The curves for the northern test and tire 15 of the southern test indicate relatively small diameter changes for both the inside and outside tire diameters; a maximum diameter change of 0.006 m is noted in the outside diameter of tire 4 in the northern test. Tire 18 of the southern test underwent a final inside diameter change of about 0.014 m. As Fig 5.9 indicates, this tire is at the end of the culvert. It is believed that the tire tilted and buckled at the end of the load test, resulting in the higher permanent diameter change after the hydraulic ram was unloaded. The maximum stresses mobilized in these tests ranged from about 60 to 70 kN/m^2.

The curves for the central test (Fig 5.12) indicate relatively small diameter changes until a maximum stress is reached, at which point the stresses decrease and diameter changes increase markedly. The maximum stress reached in this test was about 130 kN/m^2. {As a point of reference, a tire inflation pressure of 690 kN/m^2 (i.e. 100 pounds per square inch) produces a stress of 690 kN/m^2 over a loaded area of 0.093-m^2 (i.e. one square foot)}. It may also be noted from Fig 5.12 that while maximum outside diameter deflections for tire 10 are on the order of 0.105 m, the maximum inside diameter changes for the neighboring tire 9 are about 0.03 m. After the test was completed, tire 9 was noted to have buckled.

5.3.2 Buried conduit test 2

Test 2 was carried out to evaluate truck tire culvert performance under the condition of the backfill soil placed to a dry unit weight exceeding a relative compaction of 95% of the standard Proctor maximum for this glacial till soil. This condition was expected to give significant lateral support to the truck tire culvert and represents a potential best case scenario for lateral backfill support.

Fig 5.14 shows a transverse cross section through the backfilled culvert while Fig 5.15 shows a longitudinal profile along the truck tire culvert length. The locations of the potentiometer displacement gages and the diameter being measured on a specific tire are shown on Fig. 5.15. Note that the same tires from Test 1 were used, but their positions are different.

For this test, the instrumented tire sections were first placed into a trench about 1.8 m wide at the bottom by 6.7 m long by 1.8 m deep with sides sloping at about 1:1. Next, glacial till backfill was placed and compacted in three lifts using a tracked-excavator-mounted vibratory plate; the final test configuration is shown in Fig 5.14. Note that about 0.6 m of backfill was compacted over the crown of the truck tire culvert. The results of six nuclear densometer density tests (see Fig 5.14) indicate that the target relative compaction specification (i.e. >95%) was met for all backfill lifts.

Fig 5.16 indicates the change in the inside or outside diameter of the instrumented tires induced by placing backfill lifts beside the tires and above the crown of the tires. Compaction of the backfill lifts produced net upward deflections (increasing diameter changes) ranging from about 0.01 to 0.03 m in most of the tires. The upward deflections occur because of lateral compression of the tires from the compaction of the soil beside the tires. The upward deflections are decreased or reversed to downward deflections in most cases with the application of lift 3 above the crown of the tires.

Three load tests were carried out at the locations shown on Fig 5.15. The results for the test at the northern end of the culvert are shown on Fig 5.17, for the central 1 test on Fig 5.18 and for the central 2 test on Fig 5.19. The curves indicate that very little diameter change occurs until a maximum stress is reached, at which point the stress rapidly decreases and diameter change increases markedly. The central 1 and central 2 load tests produced maximum stresses of about 575 kN/m^2 and 540 kN/m^2, respectively, while the maximum stress for the test on the northern end was about 325 kN/m^2. While the stresses mobilized for this test are significantly higher than those mobilized in Test 1, the two tires under the central 1 loading location (tires 7 and 10) underwent maximum diameter changes from about 0.10 to 0.15 m (see Fig 5.18) and severely buckled at the top. Moreover, tire 4 under the central 2 location underwent a maximum diameter change of about 0.18 m. Diameter changes for the two tires under the northern loading location were significantly less.

As with Test 1, the maximum stresses mobilized in the central region of the culvert for Test 2 are higher than on the end. In addition, it is interesting to note that for the northern test and the central 2 test, the maximum inside diameter changes are about 10 to 15% of the maximum outside diameter changes recorded for the neighboring tire. This ratio of inside to outside diameter change is similar to that observed in the parallel plate tests.

5.3.3 Buried conduit test 3

Test 3 was carried out to evaluate truck tire culvert performance when installed in a relatively narrow trench with vertical walls. This test involved first compacting 1.2 m of glacial till soil to 95% of standard Proctor maximum dry unit weight within the original large trench with sloping walls. As with buried conduit test 2, a tracked-excavator-mounted vibratory plate was used to compact the soil. Next, a 1.2-m wide trench with vertical walls was excavated to a depth of 1.2 m. Following this, the instrumented tire sections were placed into the trench. Soil backfill was hand tamped between the tires and the trench walls and then soil was machine compacted to 0.3 m above the top of the trench.

Fig. 5.20 shows a transverse cross section through the backfilled culvert. Backfill lifts and corresponding moisture contents and unit weights are shown on this figure. The results of nine nuclear densometer density tests indicate that a relative compaction of >95% was essentially met for all backfill lifts except lift 6 in which 93% was achieved. A profile along the truck tire culvert length is shown in Fig. 5.21.

Fig 5.22 indicates the change in the inside or outside diameter of the instrumented tires induced by placing backfill lifts beside and above crown of the tires. Diameter changes after backfill lift 7 was applied ranged from about 0.013 m to 0.048 m. Although the maximum of 0.048 m is significant, it is below the acceptable deflection, which is defined as 5% of the outside diameter of the tires, or 0.05 m. Fig. 5.22 also shows the tire diameter changes for the application of backfill lifts 4 through 7. Slight upward deflection from the application of lift 4 beside the tires occurs because of lateral compression of the tires from the compaction of the soil between the tires and the trench walls. This deflection is immediately reversed with the application of lift 5 above the tires with continued vertical compression of the tires with lifts 6 and 7.

Three load tests were carried out at the locations shown on Fig 5.21. The results for the test at the northern end of the culvert are shown on Fig 5.23, for the central part of the culvert on Fig 5.24 and for the southern end of the culvert on Fig 5.25. The curves indicate very small diameter changes until a maximum stress is reached, at which point the stress rapidly decreases and diameter change increases markedly. Maximum stresses at the three locations ranged from about 285 to 410 kN/m^2, which are somewhat less than the highest maximum stresses mobilized in buried conduit test

2. Tires under the central and southern loading locations (tires 7a and 13) underwent maximum outside diameter changes from about 0.10 to 0.115 m (see Figs 5.24 and 5.25). Diameter changes for the two tires under the northern loading location were significantly less. In addition, for the northern test and the southern test, the maximum inside diameter changes are about 15 to 20% of the maximum outside diameter changes recorded for the neighboring tire. This ratio of inside to outside diameter change is again, as with buried conduit test 2, similar to what was observed in the parallel plate tests.

5.4 Summary

For these buried conduit facility tests, the backfill cover over the top of the truck tire culvert was only about 0.6 m thick, so that arching (load transfer from the backfill to the walls of the trench) was not mobilized. In addition, the loading test was displacement rather than stress controlled. In other words, the ram was hydraulically pushed into the soil backfill for a total of 0.34 m and the corresponding mobilized load was recorded as opposed to simply increasing the load on the plate without forcing it into the soil backfill. This latter condition would correspond more to reality while the methodology used in these tests could be considered as an extremely severe loading condition.

The results of these three tests with different backfill conditions have shown that the load carrying capacity of the truck tire culvert system is very dependent on the strength and stiffness of the backfill (i.e. moisture content and degree of compaction). In addition, the load carrying capacity depends on the location of the loading along the length of the culvert for shallow trench configurations (i.e. about 0.6 m of fill above the top of the tires). Lower maximum mobilized stresses generally occur at the ends of the culvert relative to the center. Moreover, backfill with a higher strength and stiffness yielded higher maximum mobilized stresses. In addition, the results indicate that maximum diameter changes recorded for the inside diameter are typically much smaller than for the outside diameter of the neighboring tire for tests near the midlength of the culvert. These results imply that while the outside diameter may be undergoing relatively large deflections, the inside, water conducting diameter may not be significantly affected.

Table 5.1 Triaxial test soil sample data and results

Sample #	Moisture content (%)	Height (m)	Degree of saturation (%)	Void ratio	Porosity	γt (kN/m3)	γd (kN/m3)	σ_3 (kPa)	$(\sigma_1-\sigma_3)_f$ (kPa)
10	10	0.1460	60	0.45	0.31	19.95	18.13	15.9	110
22	10	0.1492	54	0.49	0.33	19.36	17.60	36.5	140
11	10	0.1460	60	0.45	0.31	19.95	18.13	53.8	206
9	10	0.1460	60	0.45	0.31	19.95	18.13	65.5	252
12	10	0.1492	56	0.48	0.32	19.52	17.75	88.2	246
8	10	0.1460	60	0.45	0.31	19.95	18.13	108	260
13	10	0.1499	55	0.49	0.33	19.44	17.67	123	360
7	10	0.1473	58	0.46	0.32	19.77	17.98	141	380
24	10	0.1473	55	0.49	0.33	19.44	17.67	210	486
25	10	0.1460	56	0.47	0.32	19.61	17.83	279	596
72	5	0.1460	23	0.57	0.36	17.56	16.73	38.6	145
71	5	0.1460	23	0.57	0.36	17.56	16.73	72.4	282
74	5	0.1448	24	0.56	0.36	17.71	16.87	106	408
73	5	0.1460	23	0.57	0.36	17.56	16.73	139	530
75	5	0.1460	23	0.57	0.36	17.56	16.73	208	730
76	5	0.1460	23	0.57	0.36	17.56	16.73	280	916

Note: 1) γt = total unit weight
2) γd = dry unit weigh
3) G = 2.68 was used for the weight and volume calculations

Table 5.2. Duncan-Chang soil parameters from CANDE manual and consolidated-drained triaxial tests results

Unified classification	Degree of compaction (standard AASHTO)	Total unit weight γ_m (kN/m^3)	Friction angle Φ_o (degree)	Cohesion intercept C (kN/m^2)	Modulus number K	Modulus exponent n	Failure ratio R_f	Bulk modulus number K_b	Bulk modulus exponent m
CANDE: Silty clay (CL)	95	20.4	30	14	120	0.45	0.7	110	0.2
CD TESTS: Sandy-silty-clay (CL-ML)	97	19.7	29	28	160	0.22	0.92	55	0.22

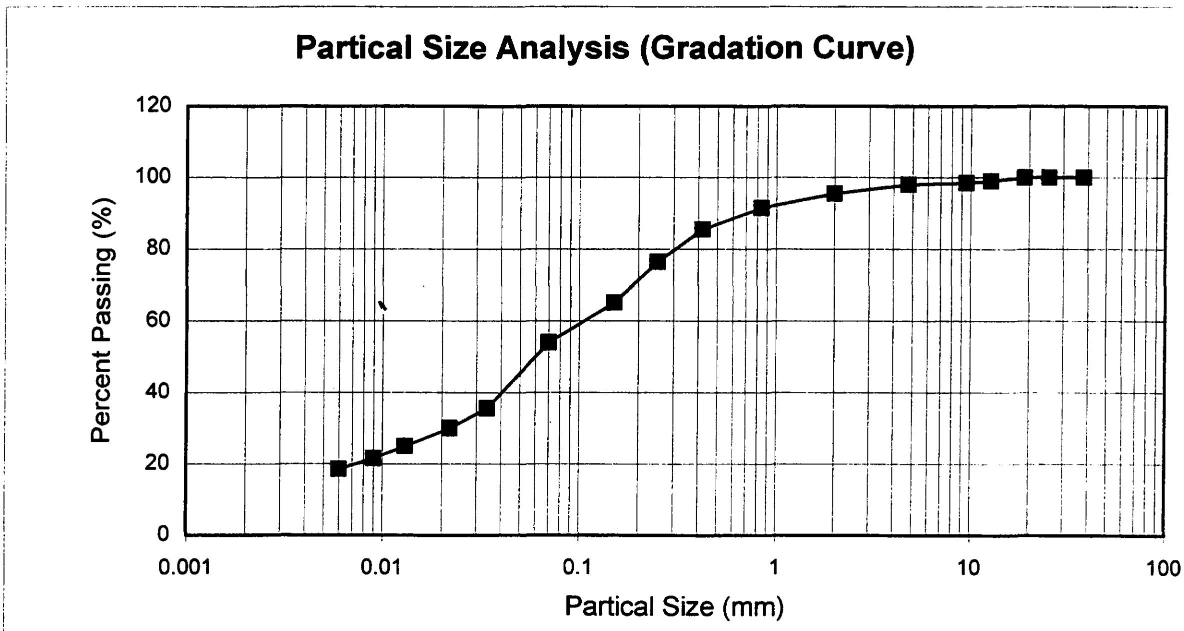


Figure 5.1. Particle size distribution curve for glacial till backfill soil (from Ng, 1997).

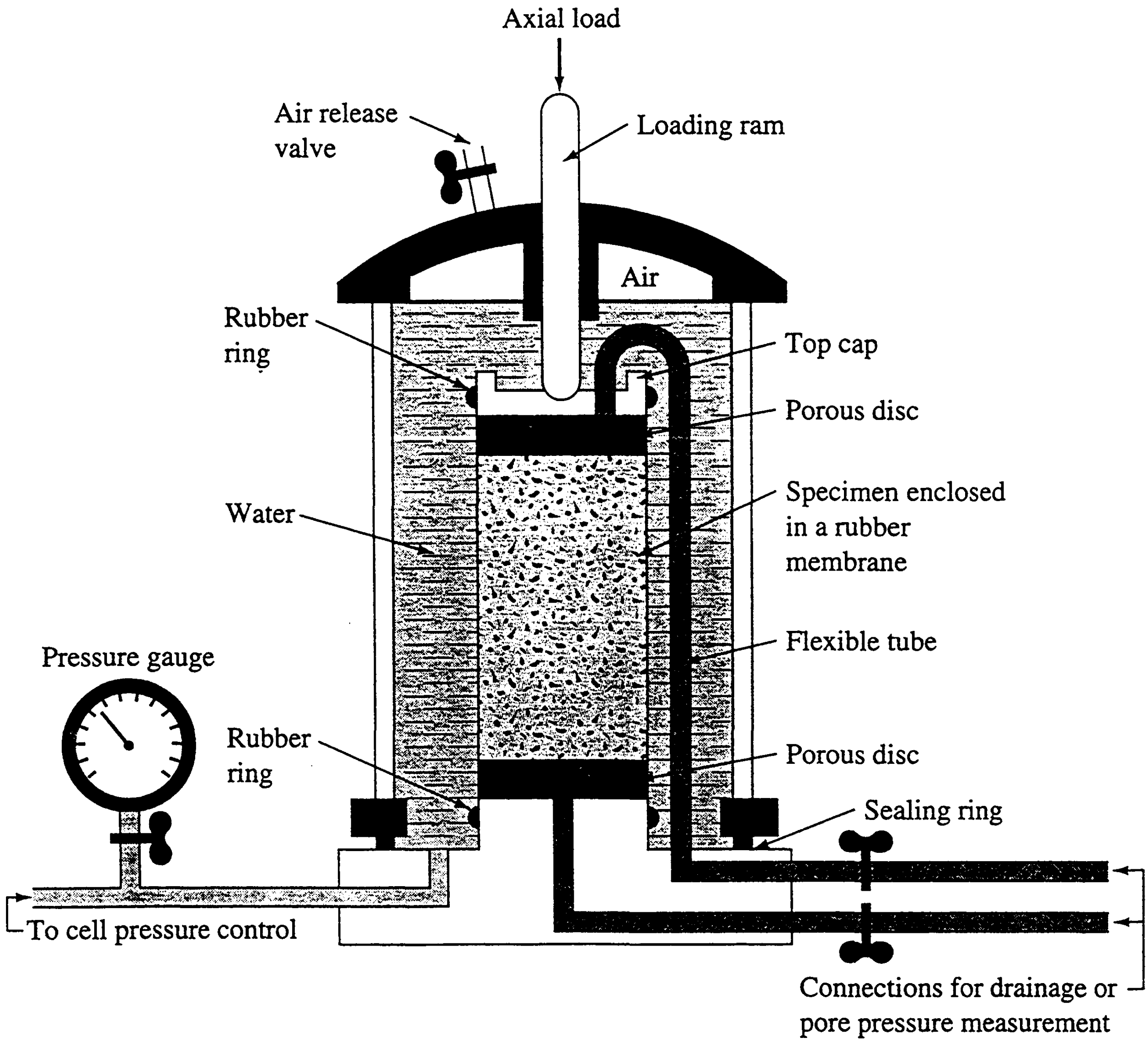


Figure 5.2. Triaxial test apparatus (from Das, 1998).

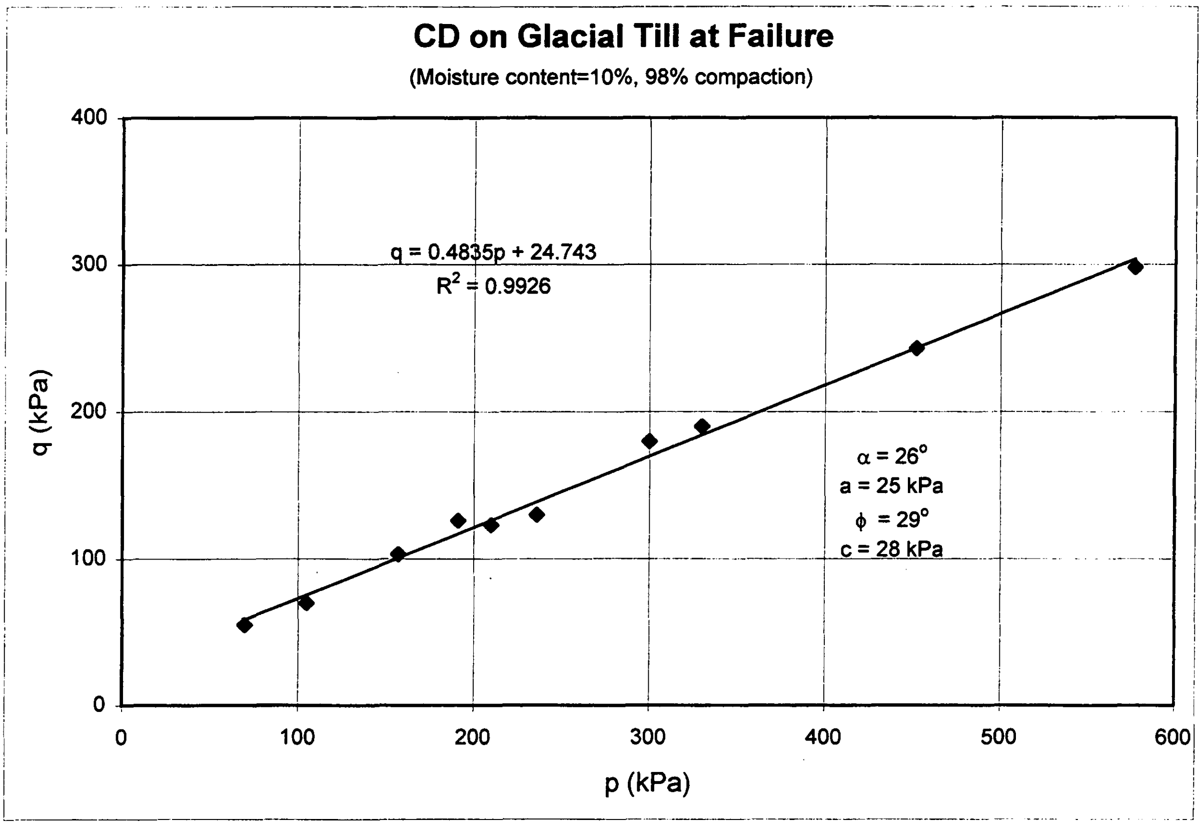


Figure 5.3. p-q plot for consolidated drained triaxial tests on glacial till at 10% moisture content.

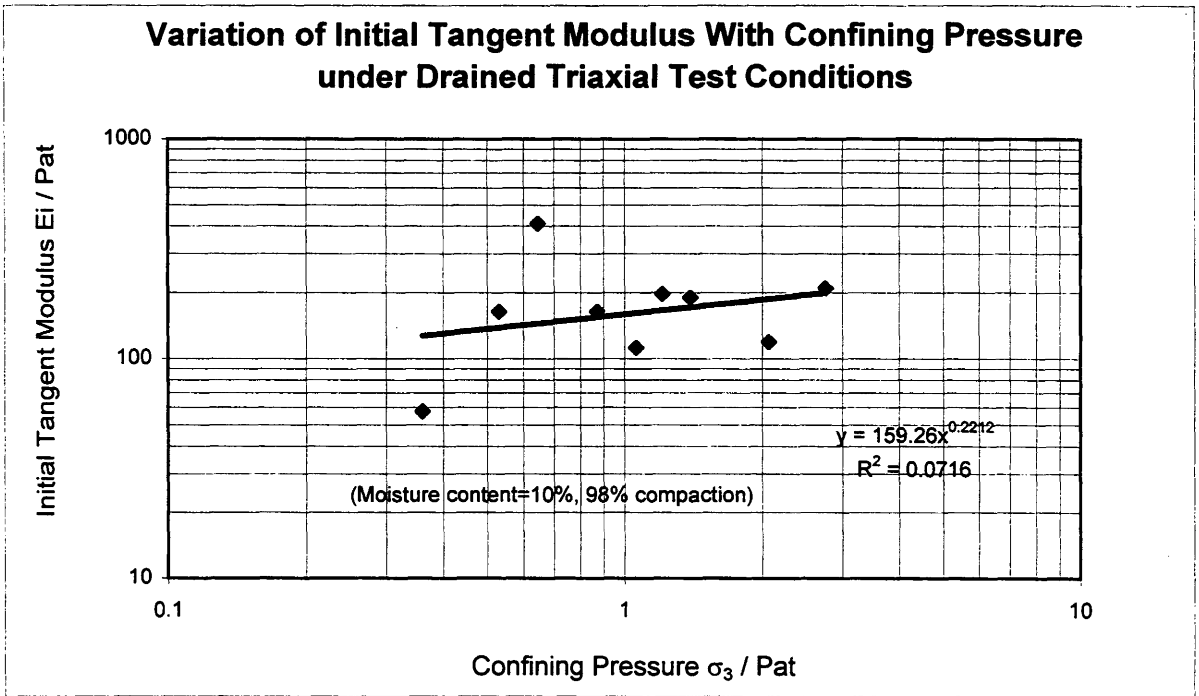


Figure 5.4. Initial tangent modulus versus confining pressure for consolidated drained triaxial tests on glacial till at 10% moisture content.

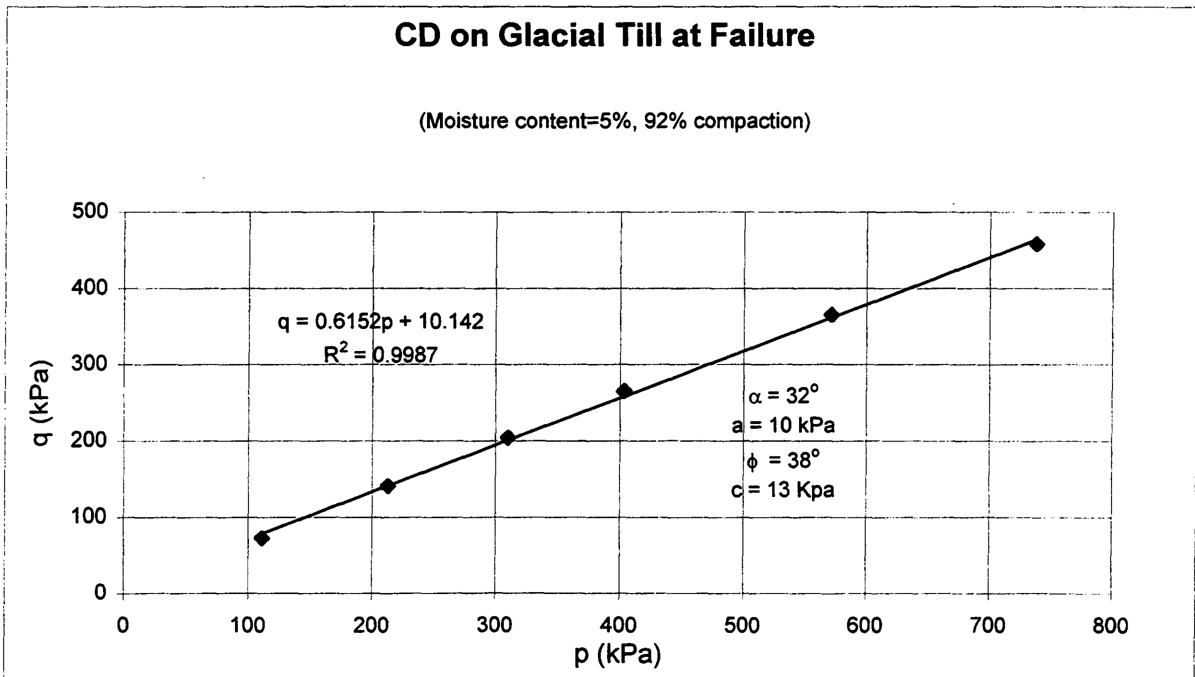


Figure 5.5. p-q plot for consolidated drained triaxial tests on glacial till at 5% moisture content.

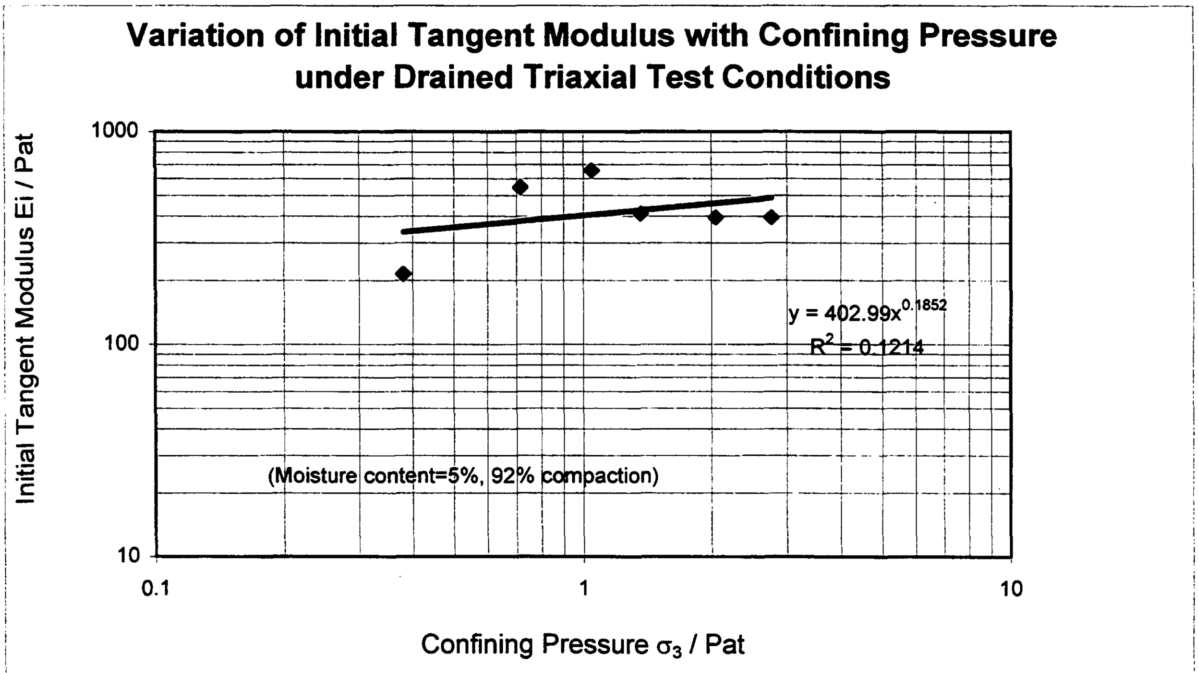
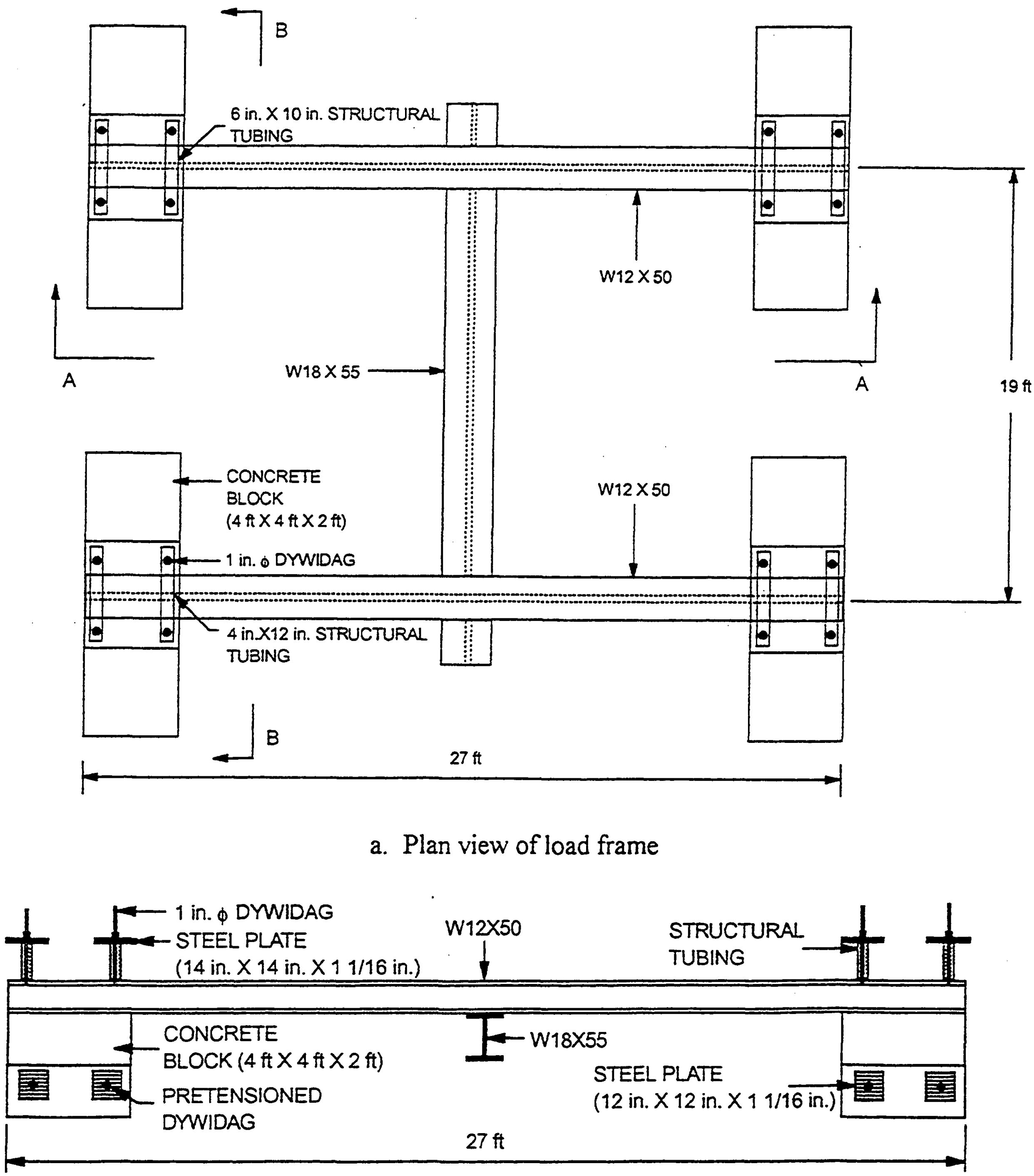


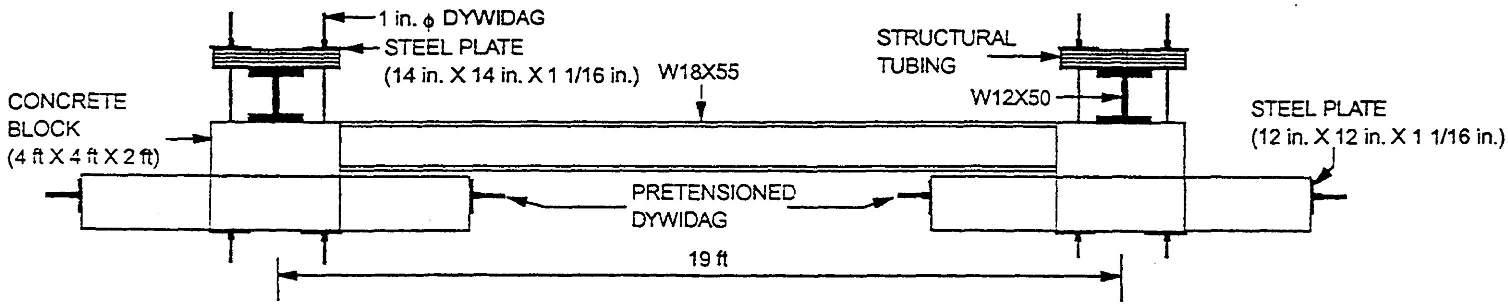
Figure 5.6. Initial tangent modulus versus confining pressure for consolidated drained triaxial tests on glacial till at 5% moisture content.



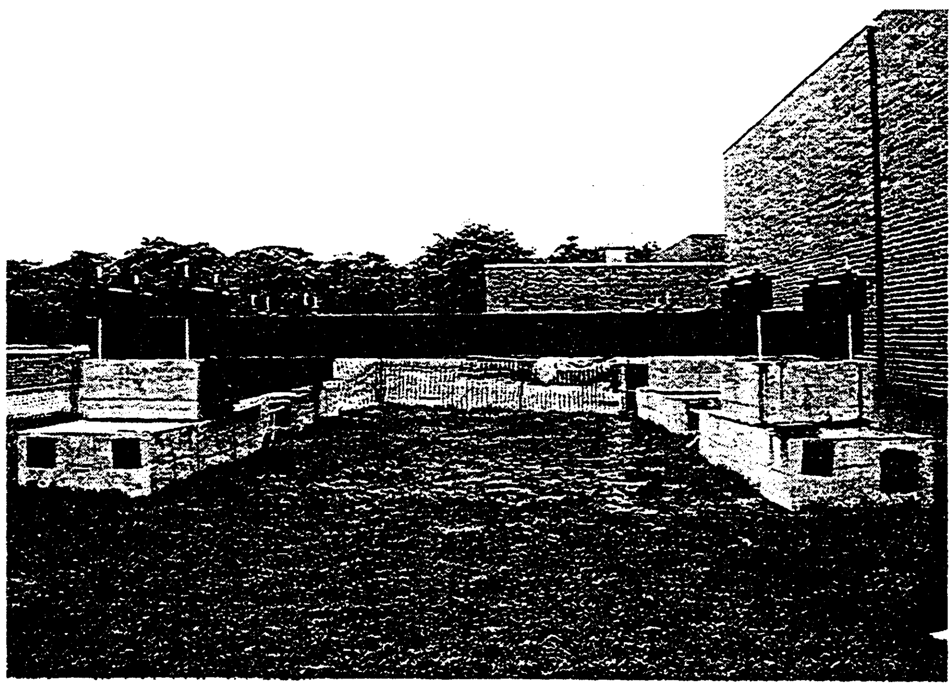
a. Plan view of load frame

b. Section A-A

Figure 5.7. Buried conduit test facility load test frame (from Klaiber et al., 1996).

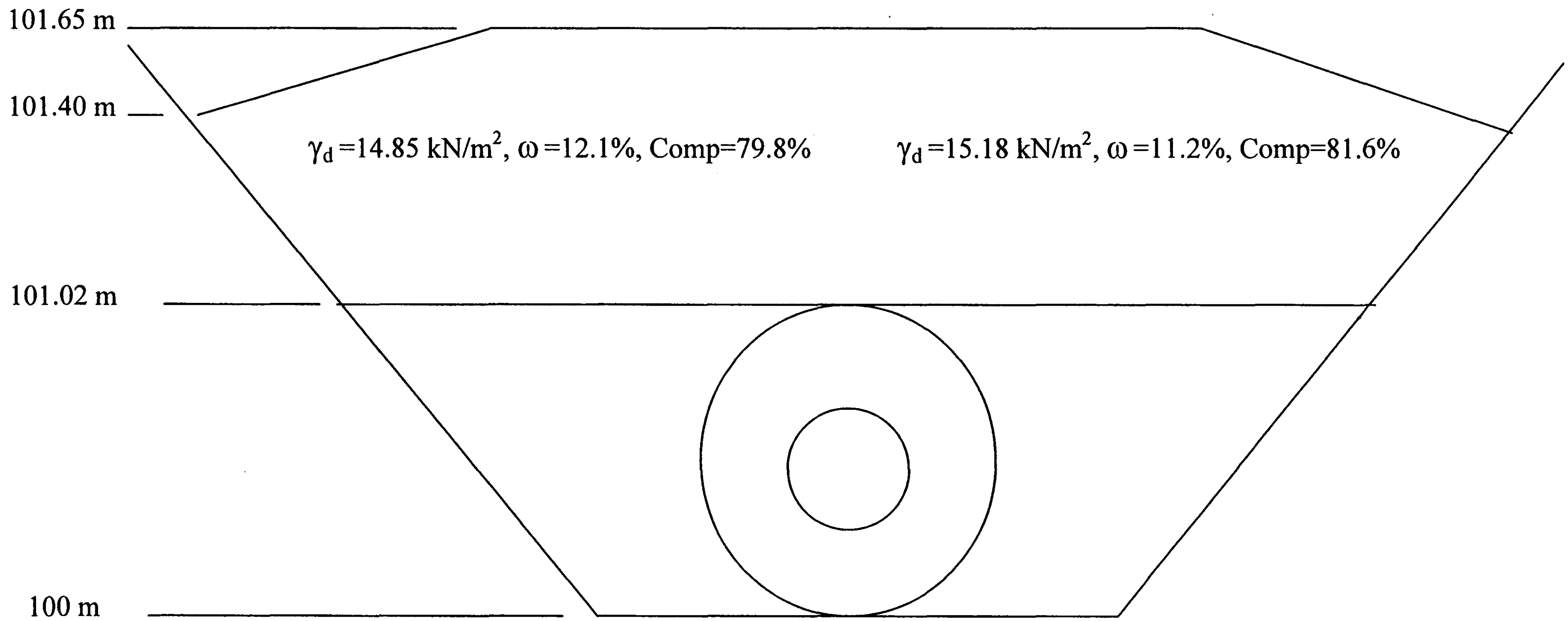


c. Section B-B



d. Photograph of in situ test frame

Figure 5.7. Buried conduit test facility load test frame (cont'd).



Note: not to scale

Figure 5.8. Buried conduit test I cross section

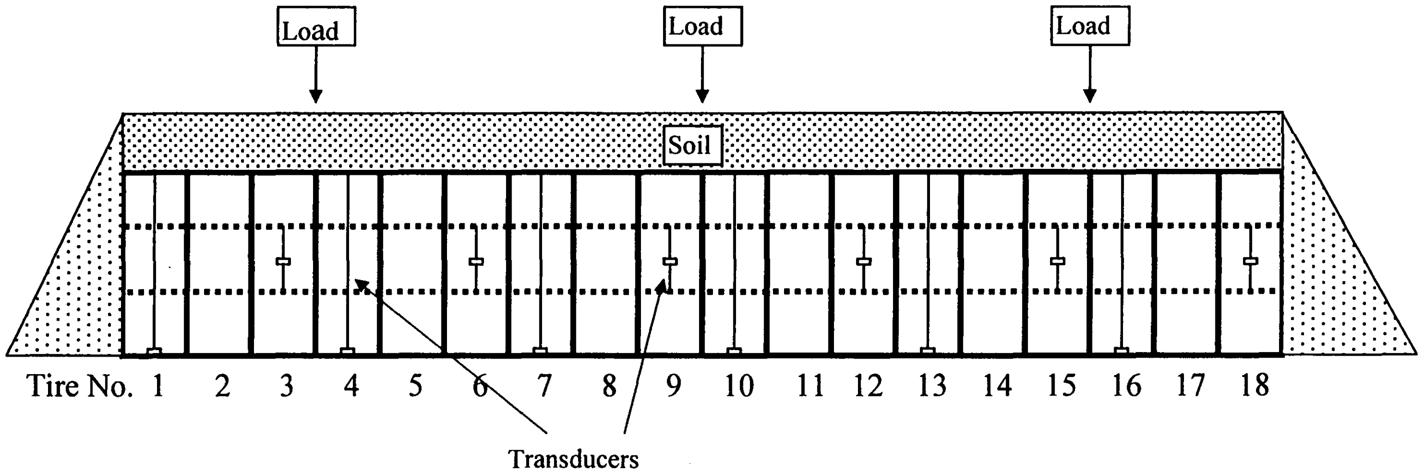


Figure 5.9. Tire and transducer arrangement and loading positions for buried conduit test I

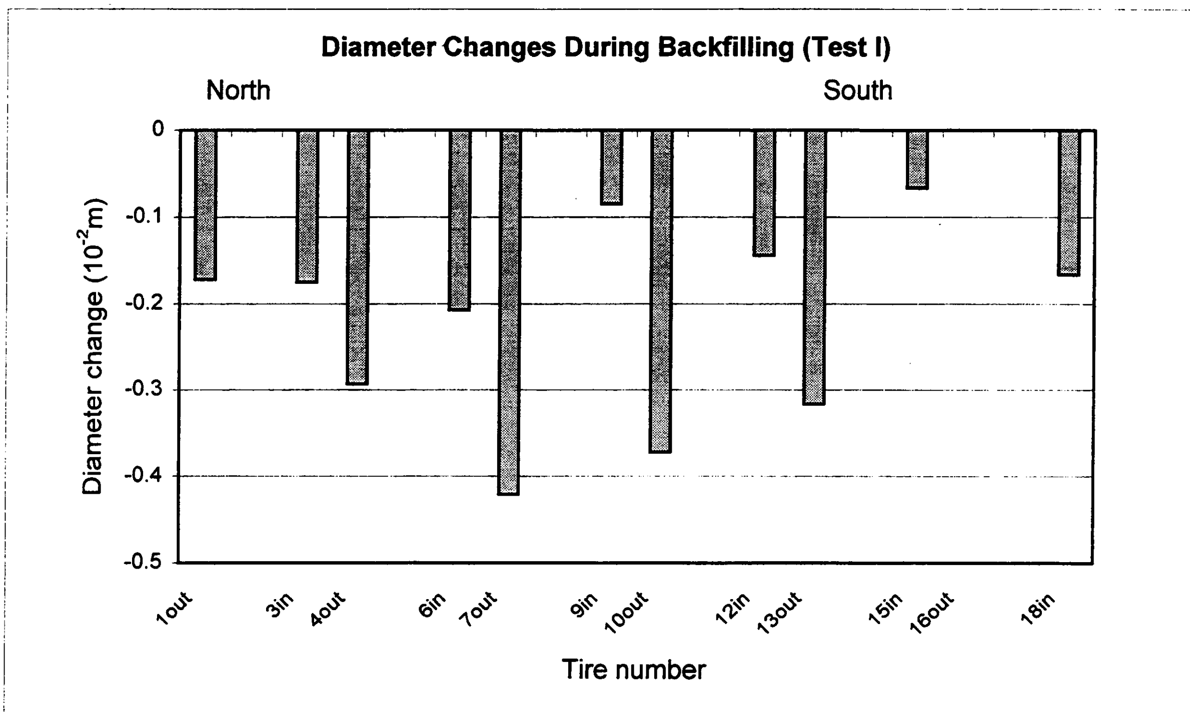


Figure 5.10. Tire diameter changes during backfilling of buried conduit test 1.

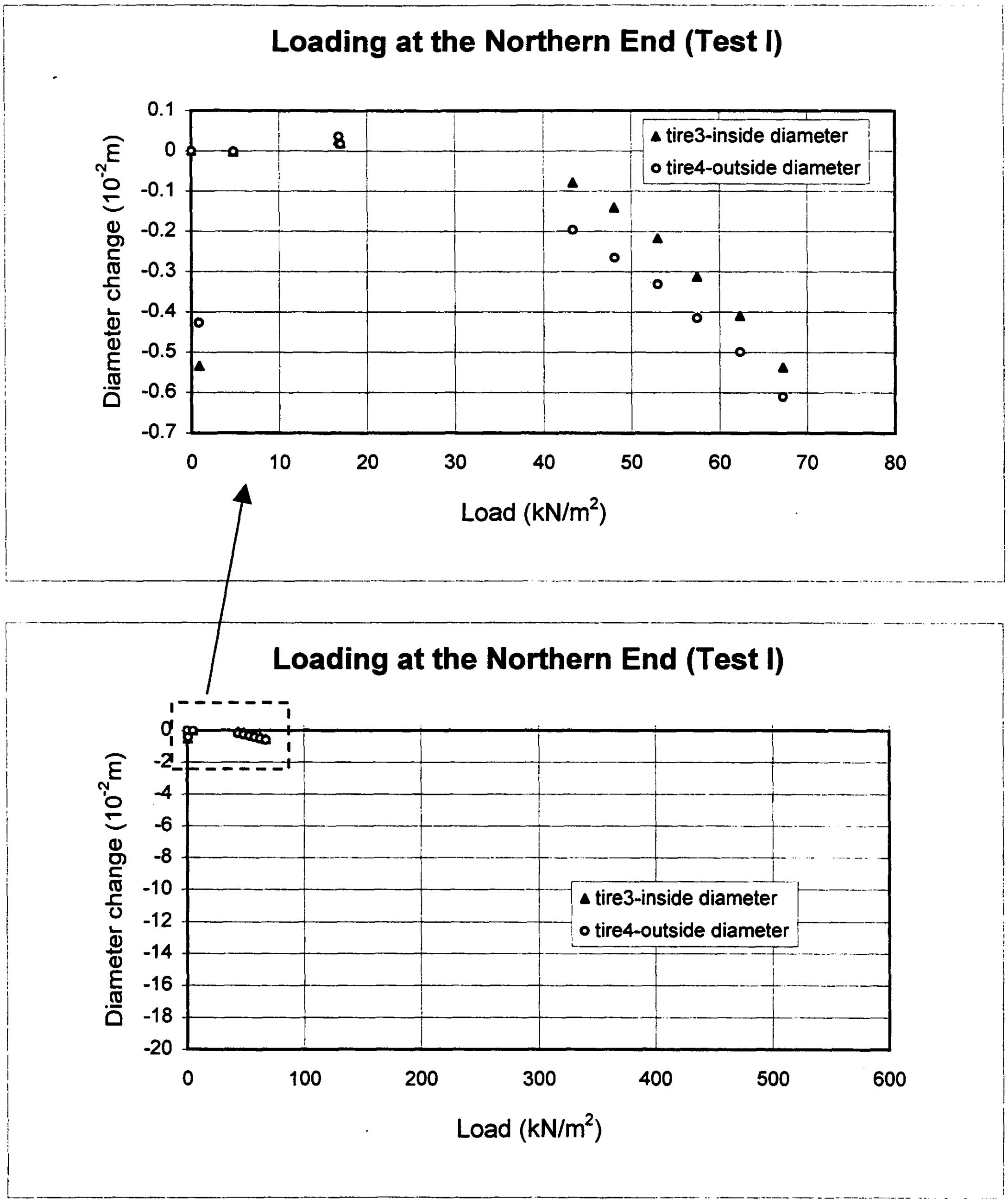


Figure 5.11. Diameter changes of tire 3 and tire 4 during the loading test at the northern end of the culvert for buried conduit test 1.

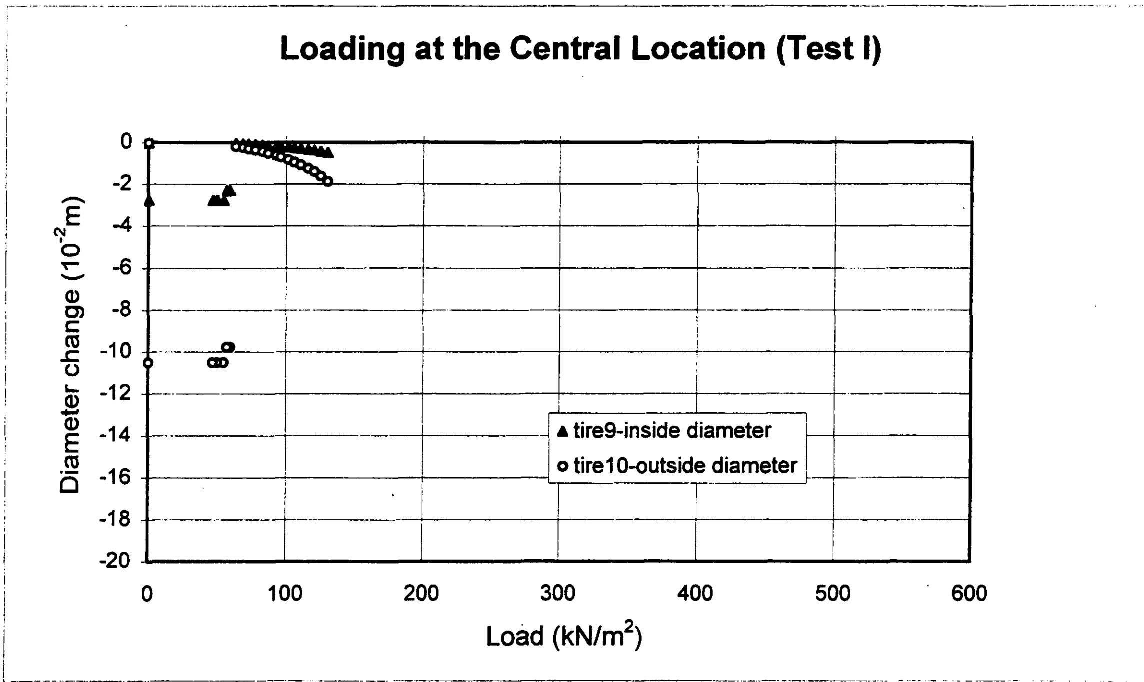


Figure 5.12. Diameter changes of tire 9 and tire 10 during the loading test at the central region of the culvert for buried conduit test 1.

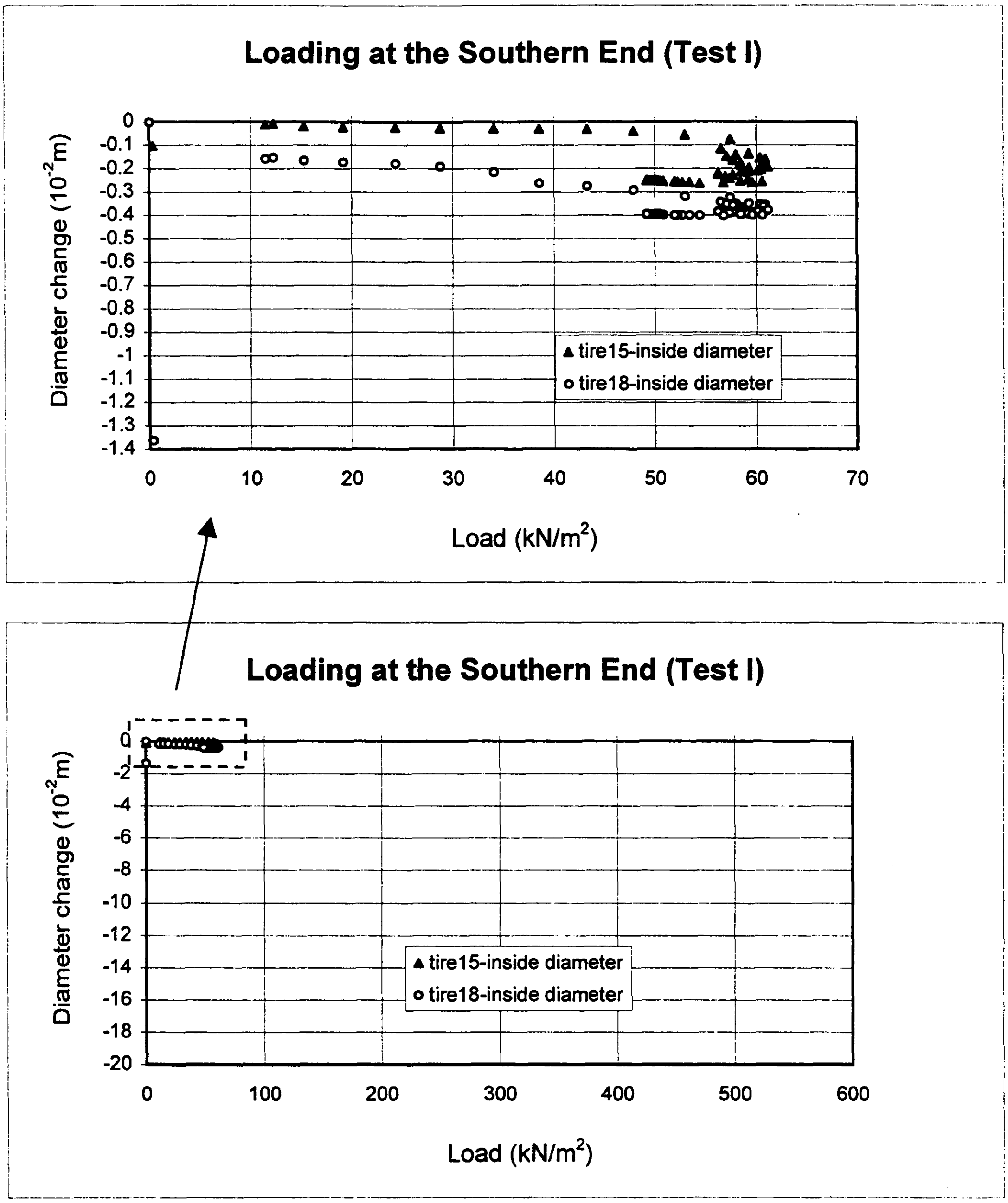


Figure 5.13. Diameter changes of tire 15 and tire 18 during the loading test at the southern end of the culvert for buried conduit test 1.

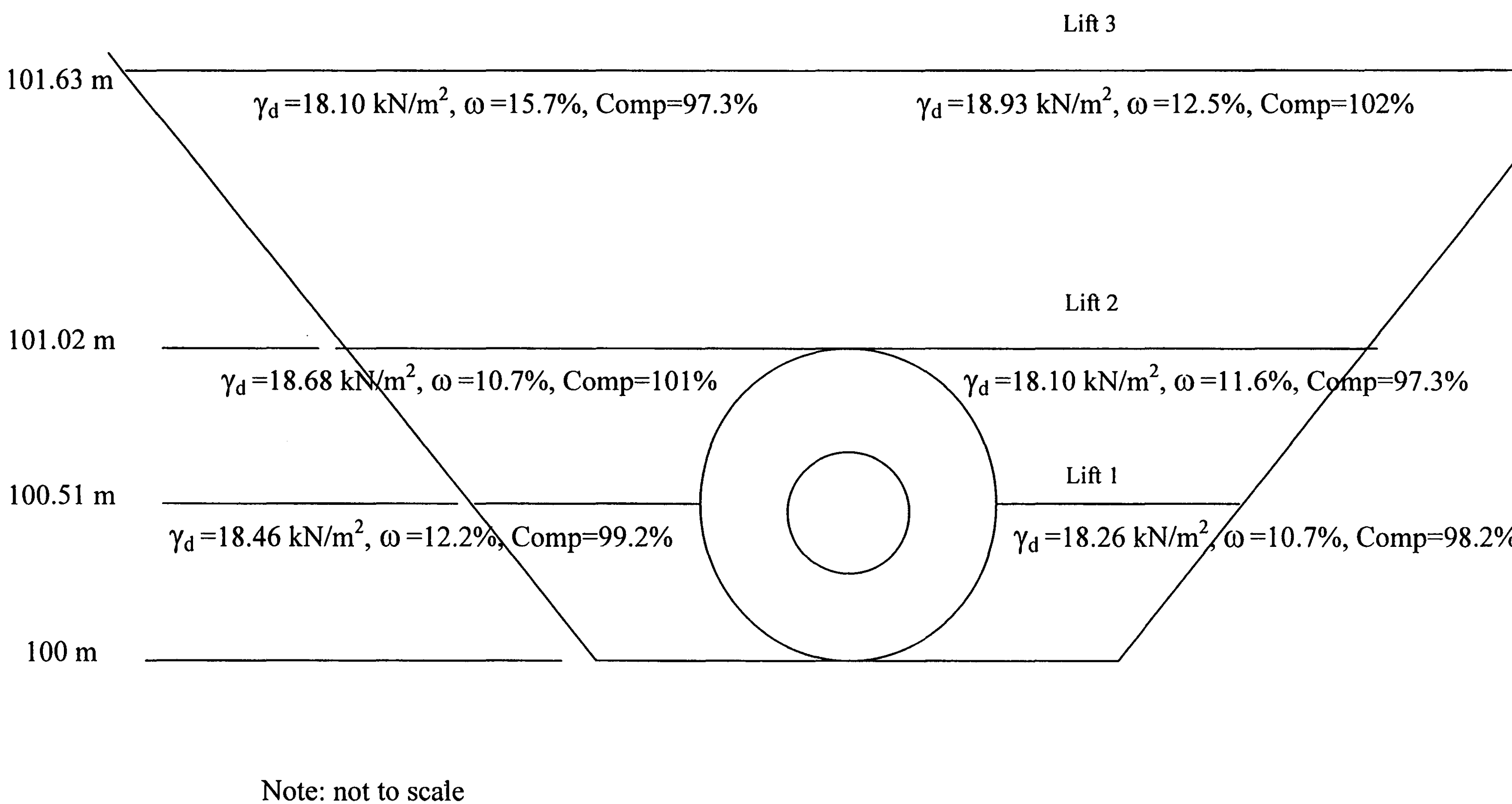


Figure 5.14. Buried conduit test II cross section

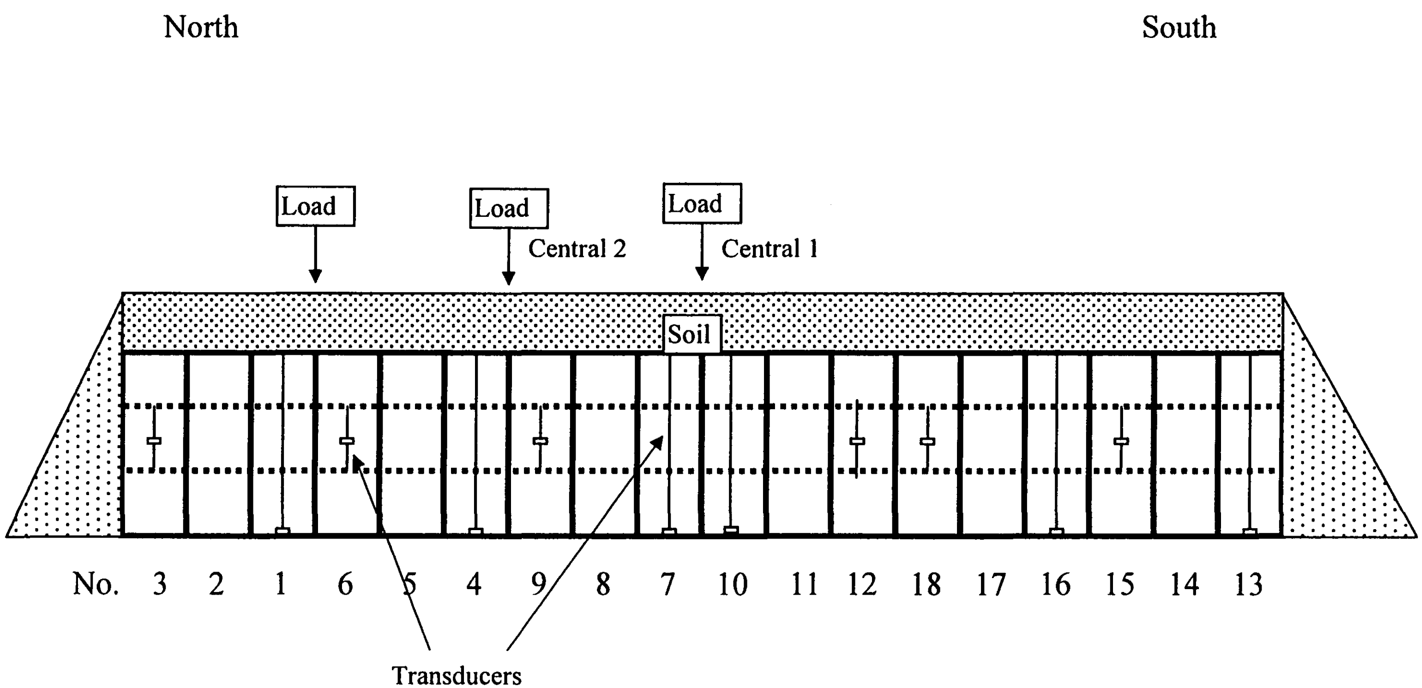


Figure 5.15. Tire and transducer arrangement and loading positions for buried conduit test II

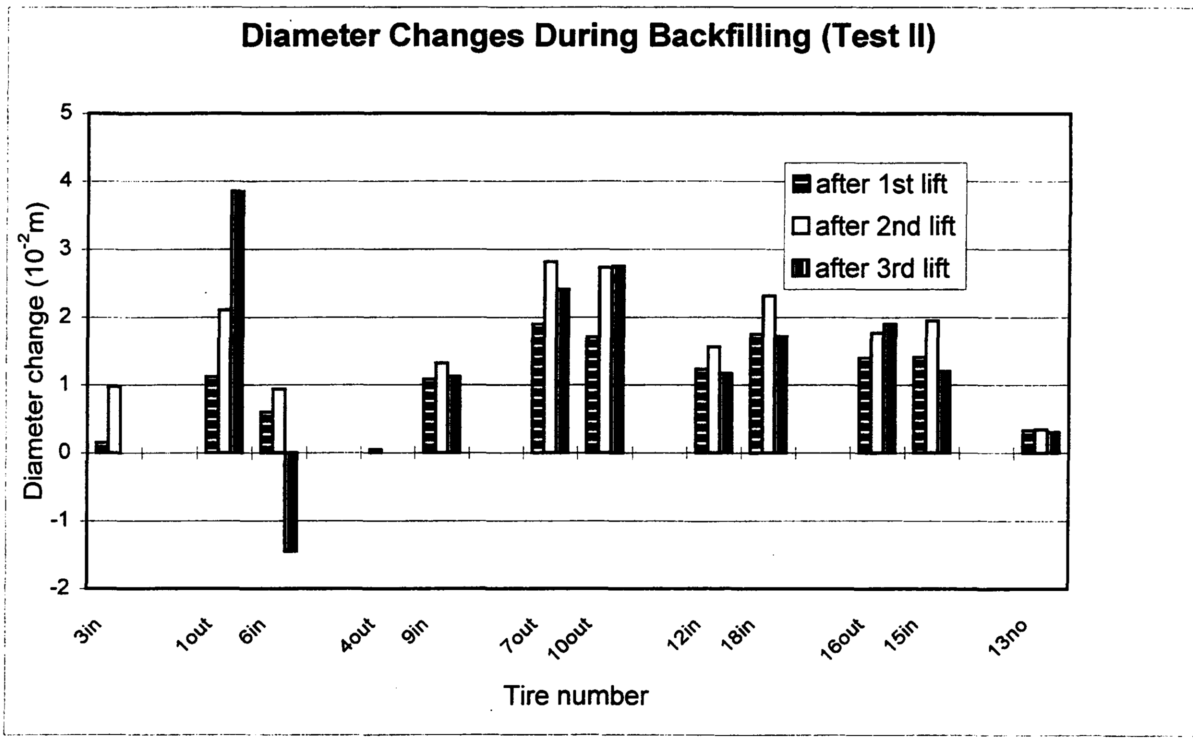


Figure 5.16. Tire diameter changes during backfilling of buried conduit test 2.

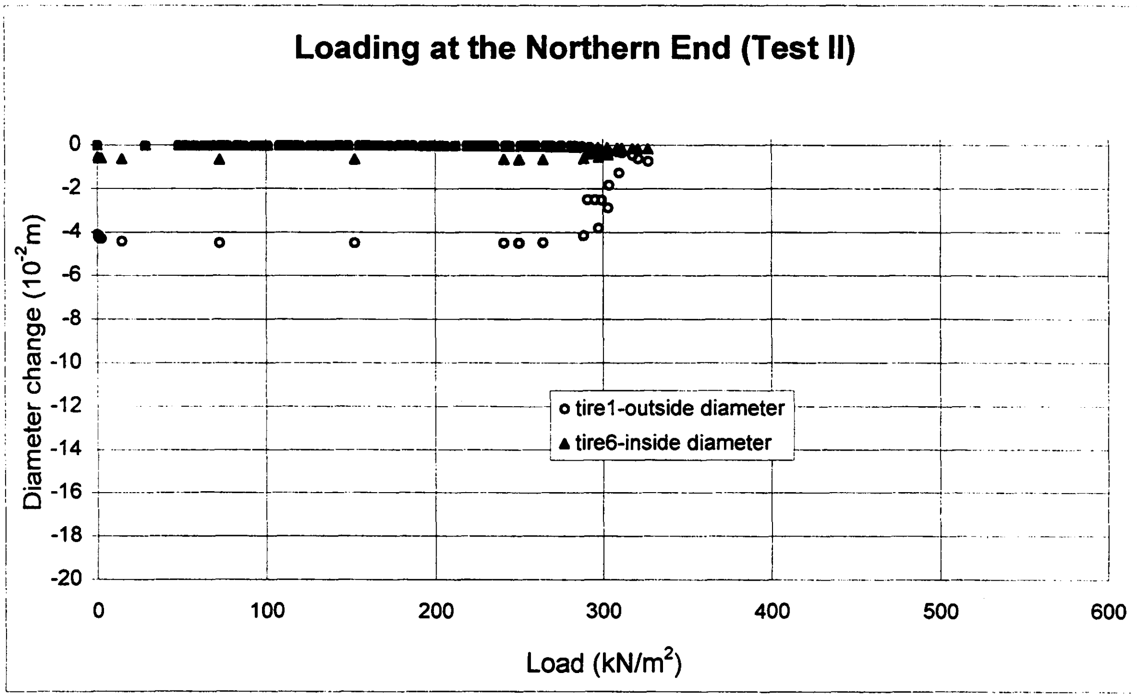


Figure 5.17. Diameter changes of tire 1 and tire 6 during the loading test at the northern end of the culvert for buried conduit test 2.

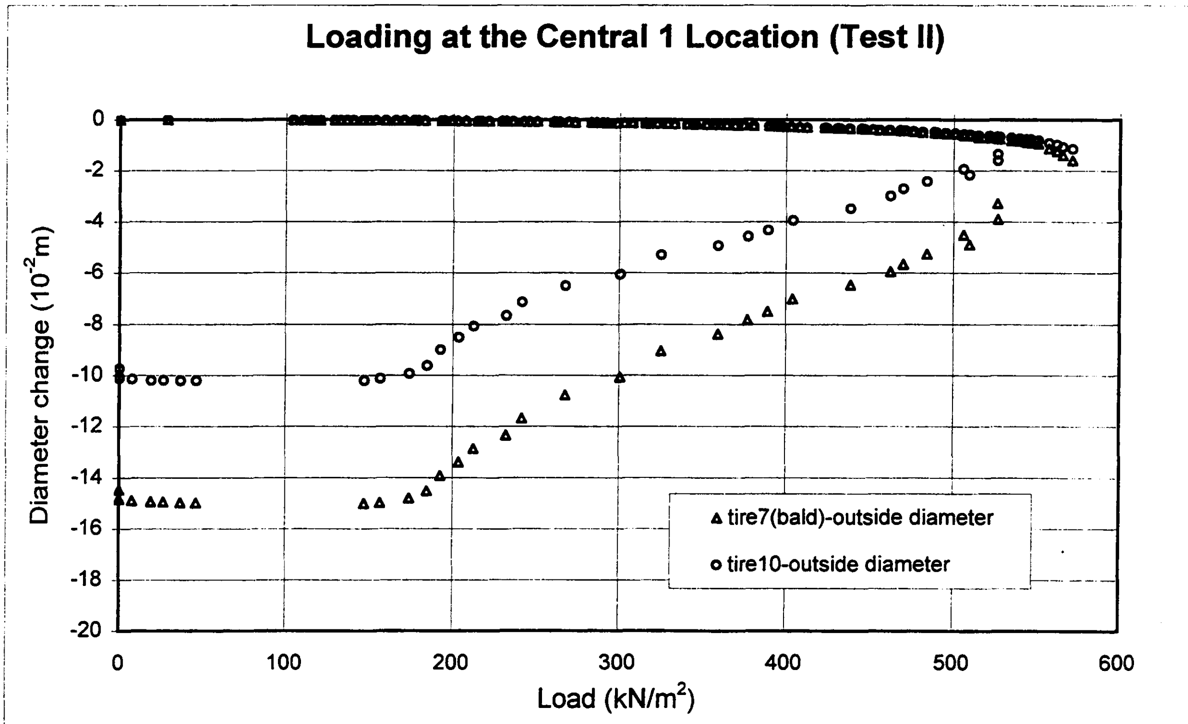


Figure 5.18. Diameter changes of tire 7 and tire 10 during the loading test at the central 1 location of the culvert for buried conduit test 2.

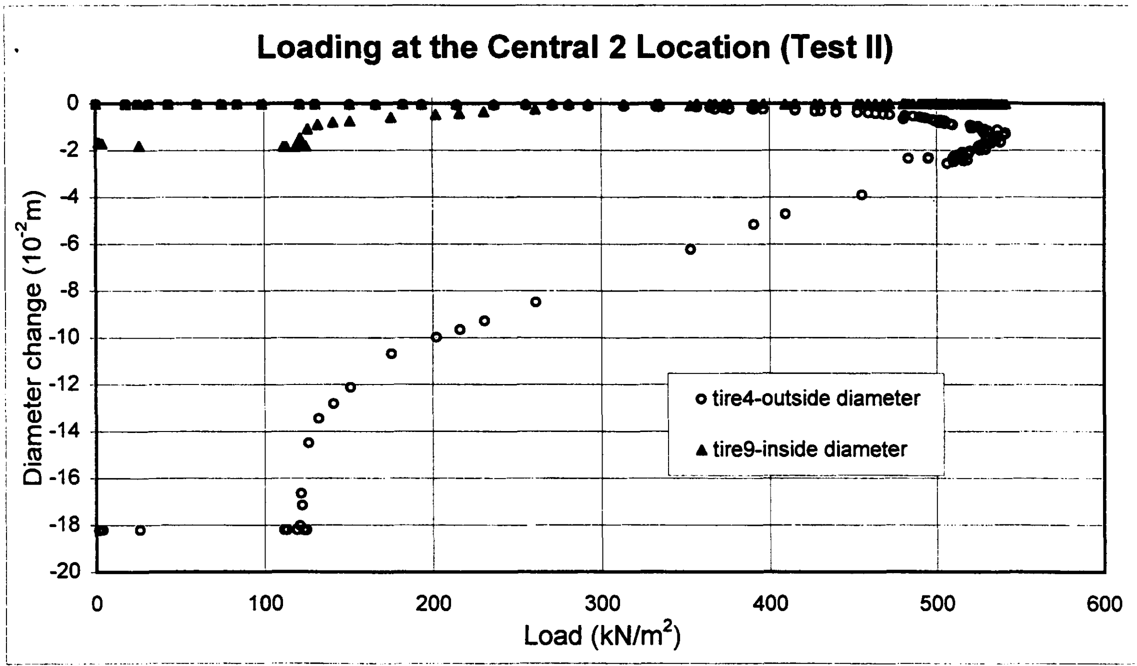
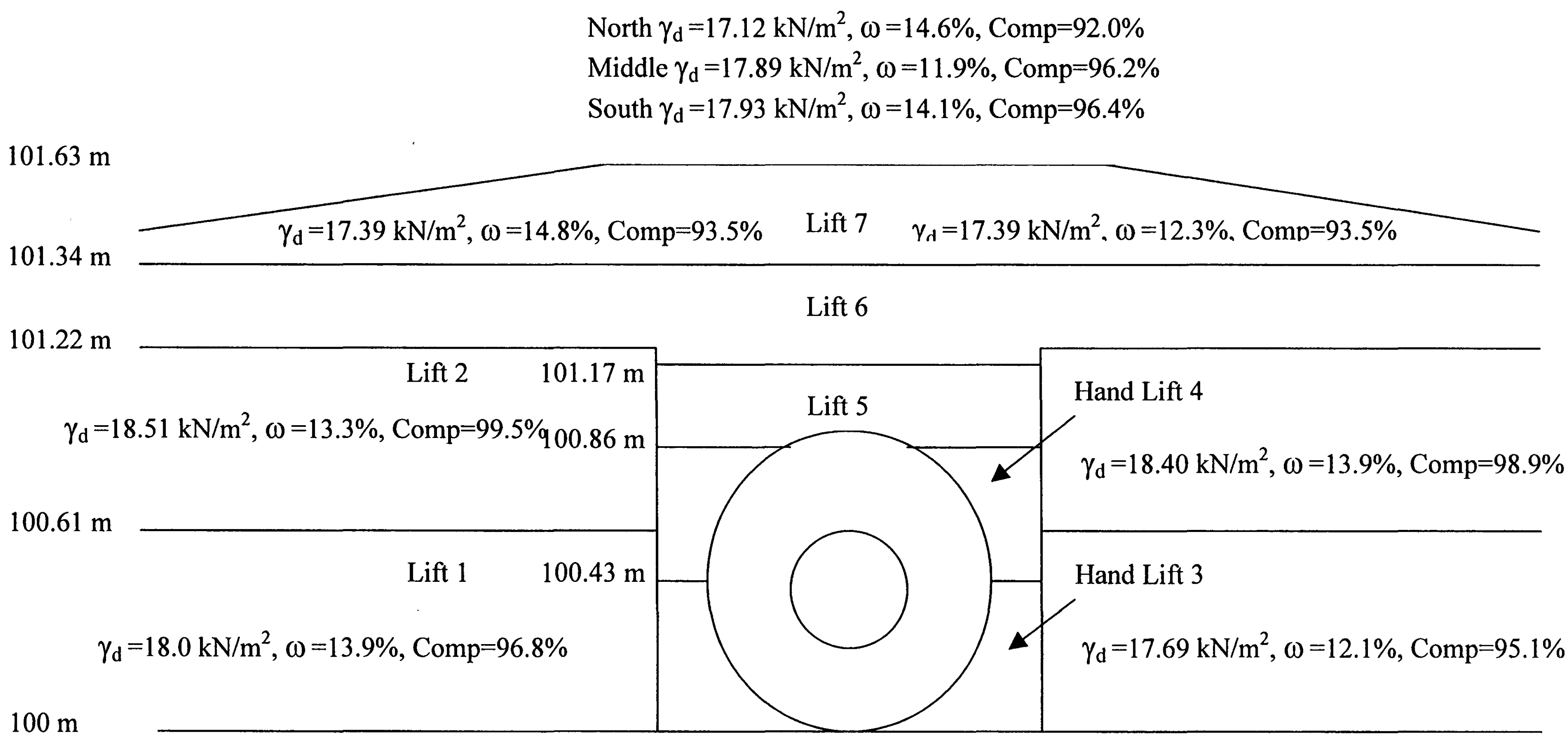


Figure 5.19. Diameter changes of tire 4 and tire 9 during the loading test at the central 2 location of the culvert for buried conduit test 2.



Note: not to scale

Figure 5.20. Buried conduit test III cross section

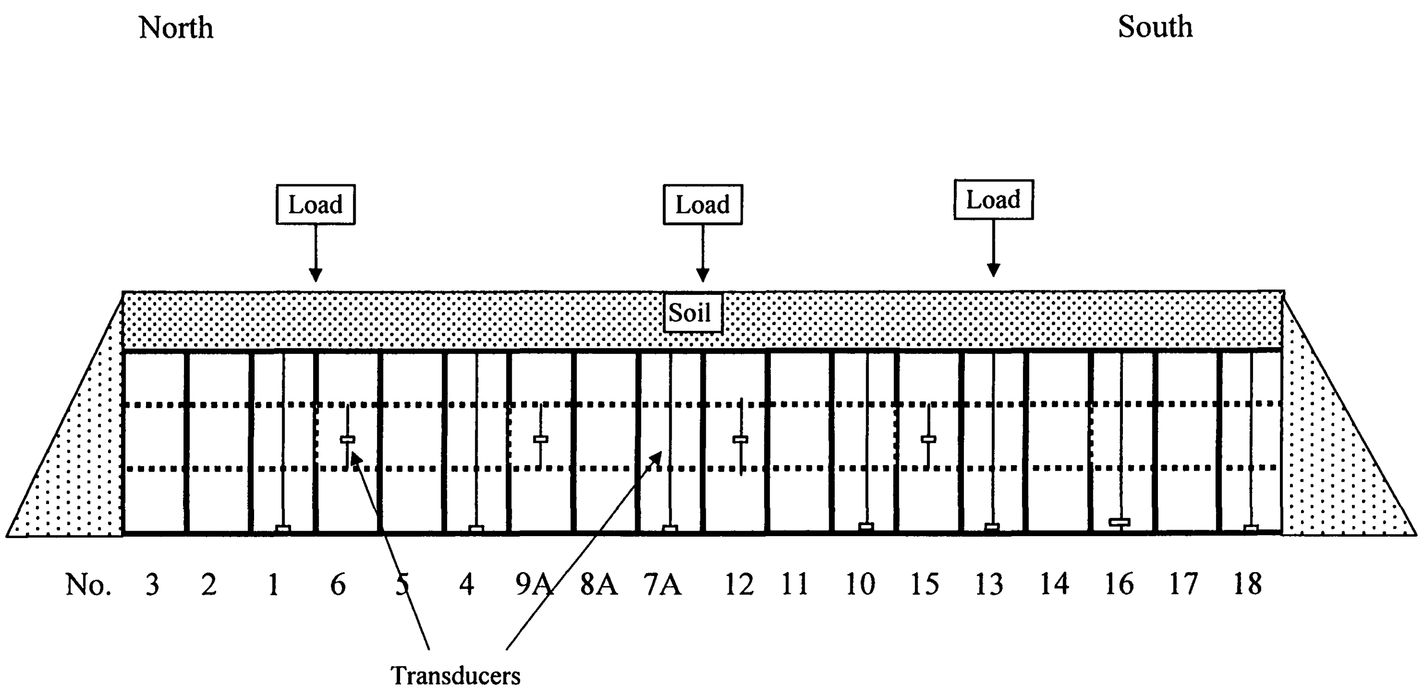


Figure 5.21. Tire and transducer arrangement and loading positions for buried conduit test III

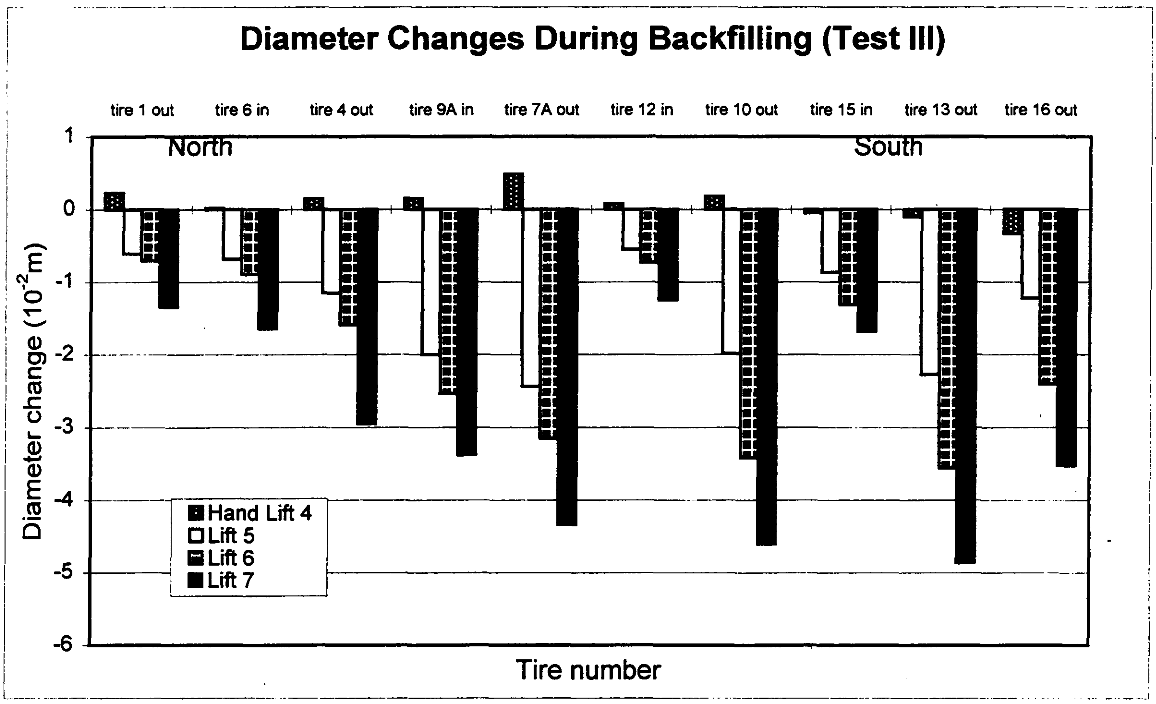


Figure 5.22. Tire diameter changes during backfilling of buried conduit test 3.

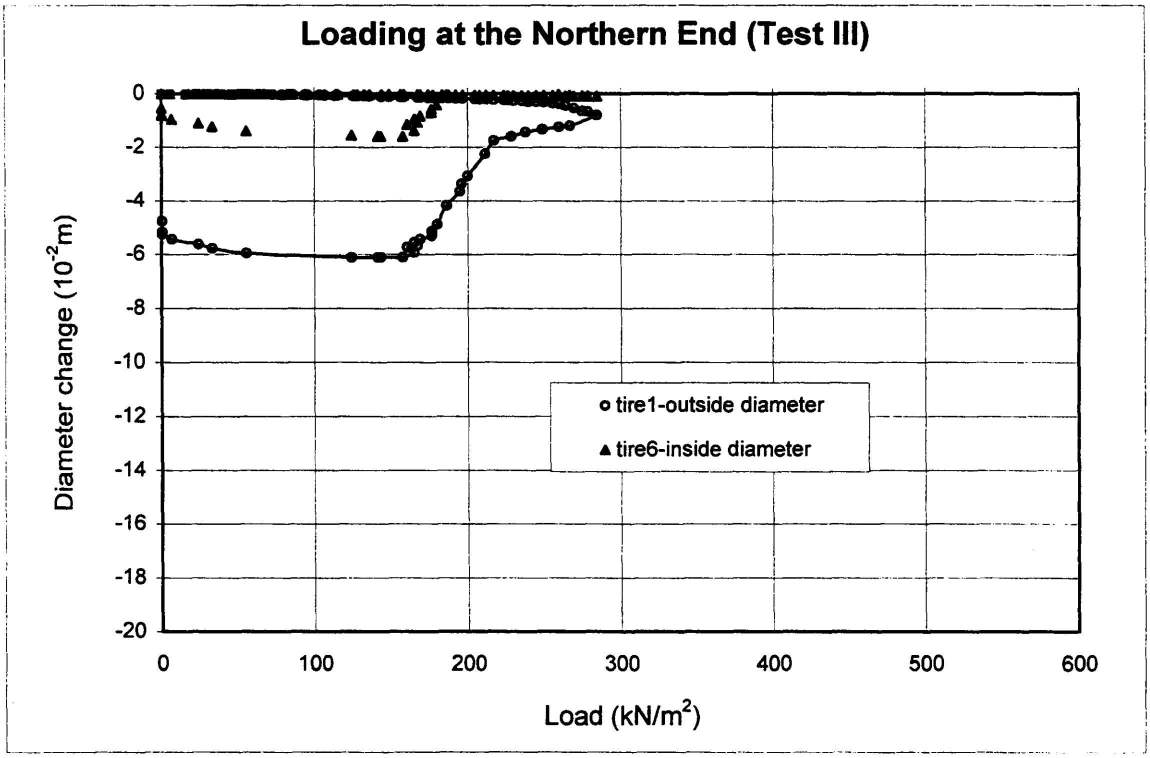


Figure 5.23. Diameter changes of tire 1 and tire 6 during the loading test at the northern end of the culvert for buried conduit test 3.

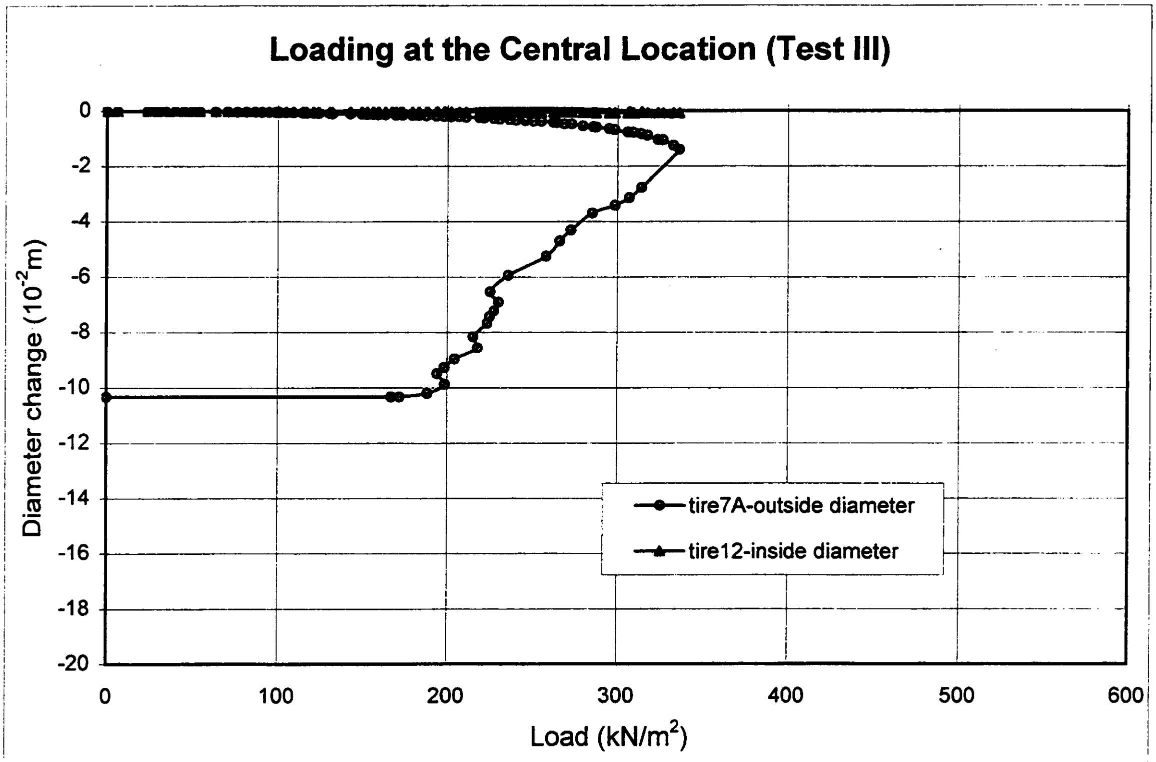


Figure 5.24. Diameter changes of tire 7a and tire 12 during the loading test at the central location of the culvert for buried conduit test 3.

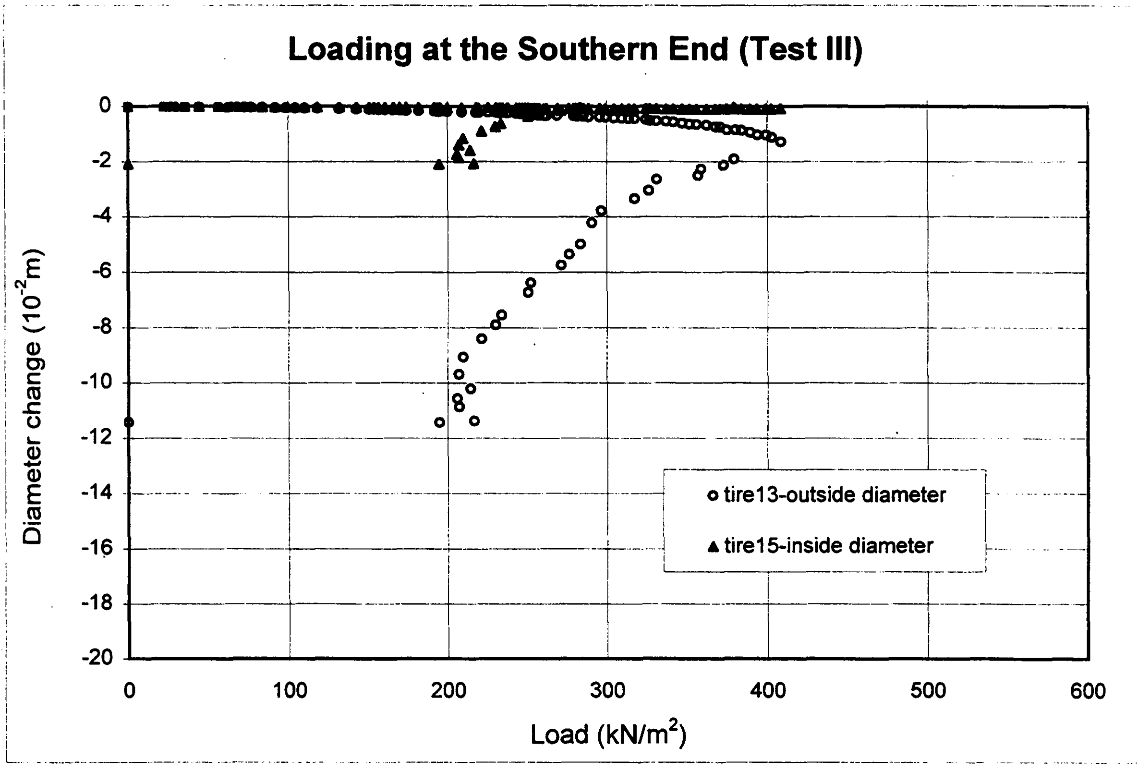


Figure 5.25. Diameter changes of tire 13 and tire 15 during the loading test at the southern end location of the culvert for buried conduit test 3.

6. Culvert Analyses and Design

6.1 Background and Objectives

The structural capacity of truck tire culverts must be sufficient to withstand the geostatic loads of the soil backfill and the superimposed loads from vehicles moving over the soil surface above the culvert. In situations where the culvert is constructed at shallow depths, the live loads from vehicles are greater than the loads resulting from the body force of the soil mass. As the depth of burial increases, the effect of surface loading is attenuated, and stresses imposed by the soil become greater. Elastic theory predicts that if the surface stress is applied over a contact area of about 0.1 m^2, the stress at a depth of 0.3 m will be about 10% of the surface stress. This indicates that the culvert should have a minimum depth of cover to reduce the effect of the surface loads and a maximum depth so that the soil mass will not excessively deform the pipe.

In order to define these limiting depths, CANDE (Culvert ANalysis and DEsign), a finite element computer program for structural design and analysis of underground culverts (Musser, 1989) was used to calculate the minimum and maximum soil depths to safely support backfill soil and standard AASHTO H-trucks. CANDE is two-dimensional, allowing calculations of deflection at a vertical section normal to the flow line of the pipe. The program considers soil-structure interaction, with three solution levels and six soil models corresponding to successively increased levels of analytical sophistication. Solution level and soil model are selected according to the specific situations such as pipe types, soil properties and the analytical strategies.

In this study, Solution level 2, which is a finite element approach with automated mesh generation, and the Duncan-Chang soil constitutive model were used. The limitations of this approach are the assumptions of small displacement, time independence and plane-strain effect.

6.2 Assumptions and Scope of Analysis

6.2.1 Determination of parameters

The parameters needed for CANDE analysis are the pipe diameter and wall thickness, material properties of the pipe including Young's modulus, Poisson's ratio and ultimate stress at rupture, and the properties of backfill and native, in situ soils. These parameters were obtained from laboratory test analyses or literature references.

More than 60 truck tires were measured and tested in this research. The outside diameter of the tires ranged from 0.99 m to 1.07 m with the most common value being 1.02 m; therefore 1.02 m is used as the pipe outside diameter. Determining a value for the pipe wall thickness presented a problem because of the complex tire cross sectional geometry. A nominal thickness concept was used in this analysis. This concept is based on the assumption that the cross section of the tires is rectangular and the weight, width and outside diameter of the tire are the measured values. Fig 6.1 is an illustration of how the nominal tire thickness was determined. The specific gravity of tires was determined previously to be 1.09-1.29, which includes truck tires and passenger car tires. The calculation of the nominal wall thickness of a truck tire, assuming a specific gravity of 1.25, is as follows.

$$\textit{Tire unit weight}: 9.81 \times 1.25 = 12.3\ kN/m^3$$
$$\textit{Tire weight}: 471.5\ N \quad (\textit{measured})$$
$$\textit{Tire width}: 0.21\ m \quad (\textit{measured})$$
$$\textit{Tire outside diameter}: 1.02\ m \quad (\textit{measured})$$
$$\textit{Tire volume}: 471.5 \times 10^{-3}\ kN / 12.3\ kN/m^3 = 0.0383\ m^3$$
$$\textit{Tire cross sectional area}: A = 0.0383\ m^3 / 0.21\ m = 0.18\ m^2$$
$$\textit{Tire cross sectional area}: A = \pi((OD + ID)/2)((OD + ID)/2)$$
$$\textit{Tire inside diameter}: ID = \sqrt{OD^2 - 4 \times A/\pi} = \sqrt{1.02^2 - 4 \times 0.18/\pi} = 0.90\ m$$
$$\textit{Tire thickness}: t = (OD - ID)/2 = (1.02 - 0.90)/2 = 0.06\ m$$

The nominal pipe thickness was estimated to be 0.06m; therefore, the average diameter of the tire pipe is 0.96m (The average radius, r, is 0.48m).

Because the cross sectional area was assumed to be rectangular, the moment of inertia (I) is equal to:

$I = t^3/12 = 0.06^3/12 = 1.8\times10^{-5} m^3$

Young's modulus, E, was determined from the results of the parallel plate tests reported in section 4. Tire stiffness (TS) values for deflections from 5% to 20% of the tire outside diameter ranged from 62 to 186 kN/m^2, with an average value of about 110 kN/m^2. The approximate relationship between EI and pipe stiffness (PS, or TS, in this case) is defined in ASTM D2412 as:

$EI = 0.149r^3(TS)$

So, therefore

$E = 0.149r^3(TS)/I = 0.149\times0.48^3\times110/(1.8\times10^{-5}) = 1.0\times10^5 = 100{,}000\,kN/m^2$

The upper and lower bound E values, calculated by using the maximum and minimum values of PS from the parallel plate tests are 170,000 and 56,000 KN/m^2, respectively. All three values of E were studied separately to analyze the sensitivity of the CANDE program results to the Young's modulus.

Tensile tests were used by Kumar and Bert (1982) to estimate the Poisson's ratio of a steel-rubber composite (having a cord volume fraction of 0.157) to be 0.39-0.40. A Poisson's ratio of 0.4 was used in the CANDE analysis.

No laboratory tests were done in this study to measure the ultimate stress at rupture of truck tires, and no data were found in the literature for this value. High-density polyethylene pipe research estimated the ultimate stress at rupture of the pipe material to be 23,400 kN/m^2. It is likely that tires have a lower value of ultimate stress at rupture than polyethylene pipe, so a value of 17,200 kN/m^2 was used. All of the truck tire culvert properties used in the CANDE analyses are summarized in Table 6.1.

Silty clay (CL), silty clayey sand (SM-SC) and silty sand (SM) soils were selected as representative backfill soil types for the CANDE analyses used in developing the design guidelines for truck tire culverts. Three degrees of compaction (45 %, 85% and 95% of the maximum AASHTO-T99 dry unit weight) were in turn used for the soils in the analyses. The soil compacted to 45% maximum AASHTO-T99 dry unit weight was to simulate uncontrolled or uncompacted backfill. The Duncan-Chang constitutive law soil parameters for all conditions were obtained from the CANDE data library and are listed in Table 6.2. These data are reasonably consistent with the laboratory triaxial test results from this study (reported in section 5), and, as will be discussed, provide conservative analytical results.

6.2.2 Simulation of vehicle loading

CANDE was originally designed to calculate pipe deflections under geostatic or backfill loads; therefore no modifications were needed to calculate maximum depths of backfill. The calculation of minimum depths of backfill to avoid excessive deflections from surface loading required modification of the basic program. Since CANDE is a plane-strain program, the three-dimensional vehicular loading on the surface of soil cannot be applied to the program directly. To simulate truck tire loads in two dimensions, a method proposed by Katona (1976) was used. For this method, an equivalent strip load, q, is calculated to represent a single concentrated point load, Q. This approach is based on the soil stress equivalence at the top of the pipe for the concentrated load and the strip load. The equivalent strip load, q, is expressed as:

$$q = \frac{3}{4}\left(\frac{Q}{L}\right) \text{ --------- } (1)$$

where L is the shortest distance from the point load to the top of the pipe.
In the CANDE analyses, the actual loads in the field conduit tests and the simulated H15-truck loads were treated as concentrated loads and converted to equivalent strip loads using equation (1). For analysis of the buried conduit tests, the magnitude of the

equivalent strip load was adjusted for the penetration of the loading plate into the backfill by adjusting L in equation (1) accordingly.

6.3 Results of Analysis

6.3.1 Comparison of CANDE solutions with experimental data

Three buried conduit field tests were conducted, as described in section 5. For Test I the backfill soil was dumped in the trench with no compaction. As discussed in section 5, soil dry unit weights corresponding to about 80% of maximum AASHTO-T99 dry unit weight were measured near the backfill surface with a nuclear densometer. It is highly likely, however, that a significant portion of the backfill in Test 1 had a relative compaction closer to 50% than to the 80% shown by our in situ tests. The higher value was likely due to compaction of the surface of the fill by installation activities.

In Test II and Test III the backfill soil was compacted to >95% of the maximum AASHTO-T99 dry unit weight. The culvert for Test III was placed in a 1.2 m wide by 1.2 m deep trench that was excavated in precompacted glacial till soil while the culvert for Test II was placed in a wide trench. The results of these tests in relation to the degree of compaction were discussed in section 5. It was shown that tire culverts buried in stiffer or more dense backfill deflected less than culverts buried in less dense backfill under equivalent loading conditions. This section will address comparisons of the computer model with those field tests.

Data from buried conduit Test II are compared with a CANDE analysis using the soil stiffness parameters interpreted from the triaxial tests conducted in this study and a CANDE analysis using the soil stiffness parameters of a soil with the same classification from the CANDE library (see Table 5.2) in Fig 6.2. Inspection of these curves shows that both of the analytical results tend to slightly over-estimate deflections that were measured in the field tests. The triaxial test data, however, provide analytical results that are closer to the experimental deflections and the library data predict larger deflections for equivalent loads. This comparison indicates that, at least for this soil type, the parameters from the CANDE library provide more conservative analytical results. For this reason, the library data were used in the analyses for developing the design standards.

A comparison of CANDE analysis deflections with measured deflections for the three buried conduit tests are shown in Figs 6.3, 6.4,and 6.5. Soil parameters from the CANDE library are used for these CANDE analyses. For test 1 (Fig 6.3), CANDE analyses were carried out for soil parameters corresponding to both 45% compaction and 80% compaction. As expected, the CANDE analysis for the 45% compaction parameters gives larger deflections than the analysis for 80% compaction parameters. The deflections measured in the test tend to agree with the 80% curve earlier in the test, and with the 45% curve as the maximum mobilized stress is approached. This tends to support the hypothesis that the backfill was compacted close to 80% near the surface, with lower unit weights below. The comparisons for tests 2 and 3 show slightly greater analytical deflections than measured deflections, but the agreement in all cases is relatively good. As indicated by Fig 6.2 for test 2, CANDE analysis deflections would likely have been smaller and agreement better if the triaxial test parameters had been used for test 3 instead of the CANDE library parameters. These comparisons provide some confidence that the recommendations of minimum and maximum cover based on the CANDE analysis using the library soil parameters are reliable, albeit conservative.

6.3.2 CANDE sensitivity analyses

Recall that there is a half order of magnitude difference between the upper bound and lower bound tire stiffness values determined from the parallel plate tests (i.e. from 62 to 186 kN/m^2). The average value of 110 kN/m^2 was used for calculating the tire pipe Young's modulus for the CANDE analyses. Recall also that the total width of tire tread in contact with the platens was used to calculate tire stiffness rather than the gross width of the tire or tire section. Using the gross width would decrease the tire stiffness values by about 25%. It could be argued, however, that the spaces between the edges of the treads of adjacent tires in a truck tire culvert would be filled with compacted soil that would be stiffer than the tire tread portion of the tire. In any case, an assumption had to be made to simplify the problem for numerical analysis and development of the design standards. The potential impact of the tire stiffness (and hence Young's modulus) variability and assumptions made in tire stiffness calculation were assessed through parameter sensitivity analyses with CANDE.

The sensitivity of the calculated maximum tire deflection to the tire pipe Young's modulus was examined for a variety of backfill conditions with CL, SM-SC and SM soils in Figs 6.6, 6.7 and 6.8, respectively. The CANDE library soil parameters for 85% relative compaction were used for all analyses. As expected, the highest tire pipe Young's modulus gives the lowest deflections for each of the analyses. The most significant difference in maximum deflection between using the upper bound and lower bound tire pipe Young's modulus values is for the case of 0.61 m of backfill cover and H-15 truck loading applied. Even in these cases, however, the deflections only change by about 0.01 to 0.015 m. Moreover, reducing the tire pipe Young's modulus from the average value to the lower bound value (about a factor of two or by about 50%), increases maximum deflections by about 0.005 to 0.01 m.

The effect of varying Poisson's ratio is shown in Fig 6.9. These results indicate that the CANDE analyses are very insensitive to this parameter.

These sensitivity analyses have shown that the maximum deflections are relatively insensitive to tire pipe Young's modulus and essentially insensitive to tire pipe Poisson's ratio. Variations in tire stiffness and assumptions made in calculating the tire pipe stiffness should, therefore, have minimal impact on truck tire culvert design and performance.

6.3.3 Minimum and maximum backfill from CANDE program

In order to determine the minimum and maximum allowable backfill covers, it is necessary to select some limiting vertical truck tire culvert strain. No published data exist on maximum allowable strains for truck tire culverts, however the parallel plate test data from this study indicate that truck tires buckle or completely fail at deflections of about 13% of the tire outside diameter. Based on these data, for design purposes, the maximum allowable strain of the top of tires under backfill soil and surface loading is 5% of the outside tire diameter. This is a limiting deflection of 0.05 m. This low allowable strain is also justified because tires have potential creep development.

With the constraint of pipe deflection less than 5% of the outside diameter, the minimum and maximum soil covers for the soils and degrees of compaction were obtained using the CANDE program. The results of these calculations are in Table 6.3 and Table 6.4, respectively. The minimum soil covers listed in Table 6.3 were estimated under both soil load and H15-truck load. The maximum soil covers listed in Table 6.4 were estimated under geostatic load only because the effect of surface load for deep trenches is negligible.

Table 6.1. Pipe parameters used in CANDE analysis

Average diameter (m)	Average Thickness (m)	Moment of inertia ($10^{-5} m^3$)	Poisson's Ratio	Young's Modulus (kN/m^2)	Ultimate stress at rupture (kN/m^2)
0.96	0.06	1.8	0.4	100,000	17,200

Table 6.2. Soil types and Duncan power law parameters in CANDE analyses

Unified classification	Degree of compaction (standard AASHTO)	Total unit weight γ_m (kN/m^3)	Initial friction angle Φ_o (degree)	Reduction in friction angle for a 10-fold increase in confining pressure $\Delta\Phi$ (degree)	Cohesion intercept C (kN/m^2)	Modulus number K	Modulus exponent n	Failure ratio R_f	Bulk modulus number K_b	Bulk modulus exponent m
Silty clay (CL)	45	9.7	23	11	0	16	0.95	0.75	15	1.02
	85	18.9	30	0	4.8	60	0.45	0.7	50	0.2
	95	20.4	15	4	62.0	120	0.45	1.0	80	0.2
	100	21.2	30	0	19.3	150	0.45	0.7	140	0.2
Silty clayey sand (SM-SC)	45	11.0	23	0	0	16	0.95	0.55	15	0.94
	85	18.9	33	0	9.7	100	0.6	0.7	50	0.5
	95	20.4	33	0	20.7	250	0.6	0.7	125	0.5
	100	21.2	33	0	24.1	400	0.6	0.7	200	0.5
Silty sand (SM)	45	11.0	23	0	0	16	0.95	0.55	15	0.94
	85	18.9	30	2	0	150	0.25	0.7	150	0
	95	20.4	34	6	0	450	0.25	0.7	350	0
	100	21.2	36	8	0	600	0.25	0.7	450	0

Table 6.3. Recommended minimum soil covers under H15-truck load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides are well compacted	1.2	0.6	0.6	0.6	0.5	0.5	0.3
Sides are poorly compacted (45%)	1.2	1.2	0.9	0.9	0.9	0.9	0.9

Table 6.4. Recommended maximum soil covers under geostatic load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides are well compacted	13	19	18.5	22	26	41.5	47.5
Sides are poorly compacted (45%)	13	4.5	5.5	6	7.5	10.5	16

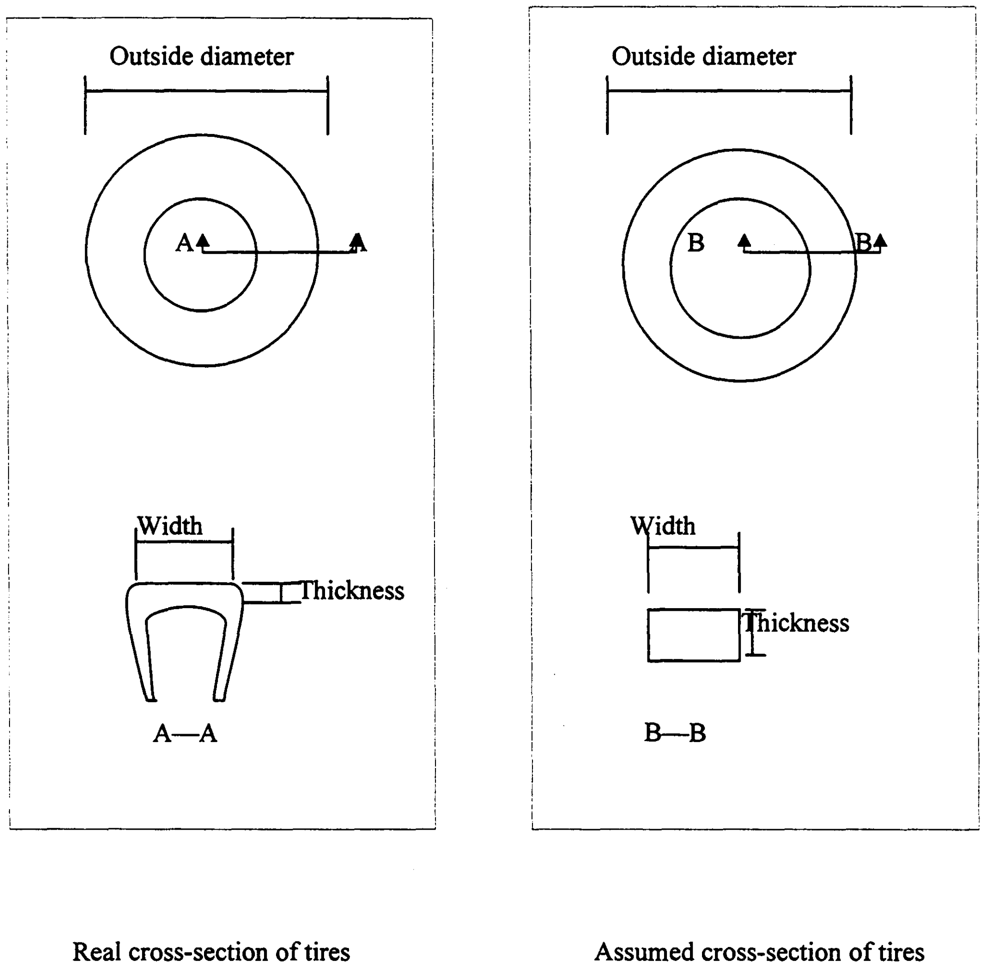


Figure 6.1. Determination of the tire pipe thickness.

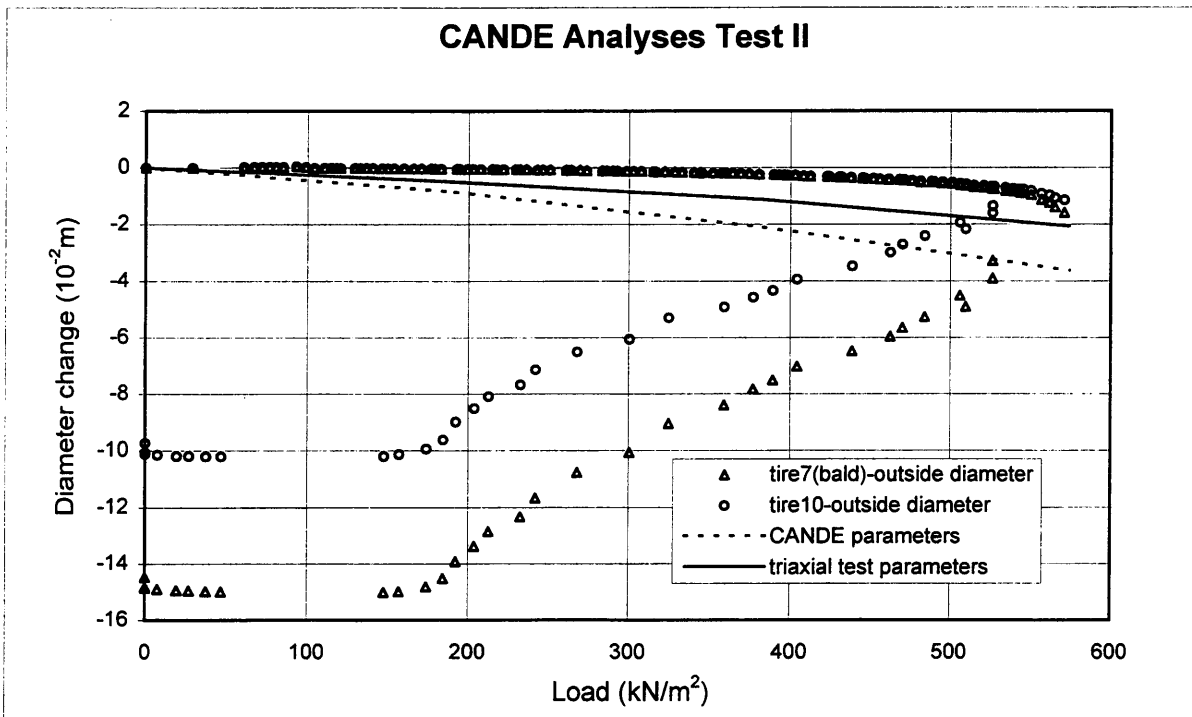


Figure 6.2. CANDE analyses for buried conduit test 2: triaxial test versus CANDE library soil parameters.

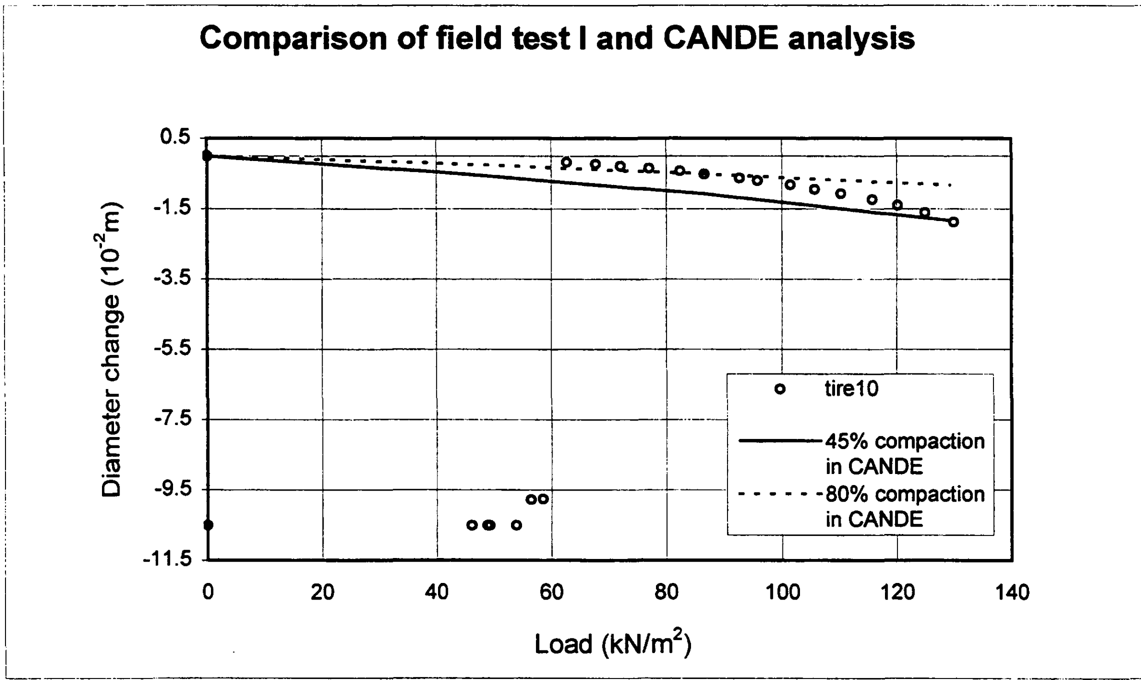


Figure 6.3. CANDE analyses for buried conduit test 1.

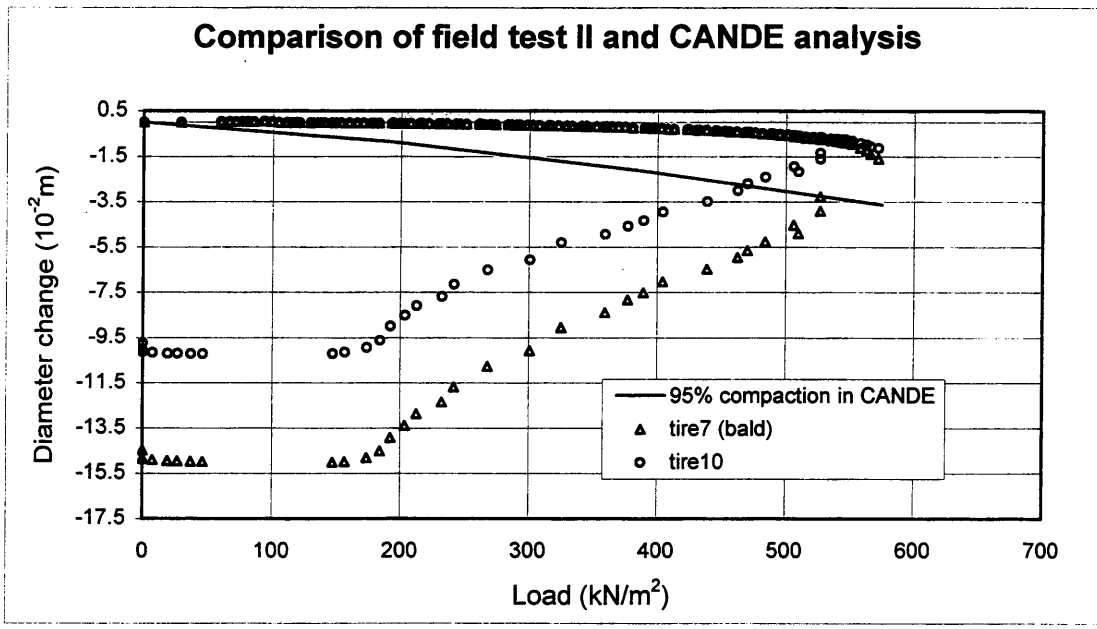


Figure 6.4. CANDE analysis for buried conduit test 2.

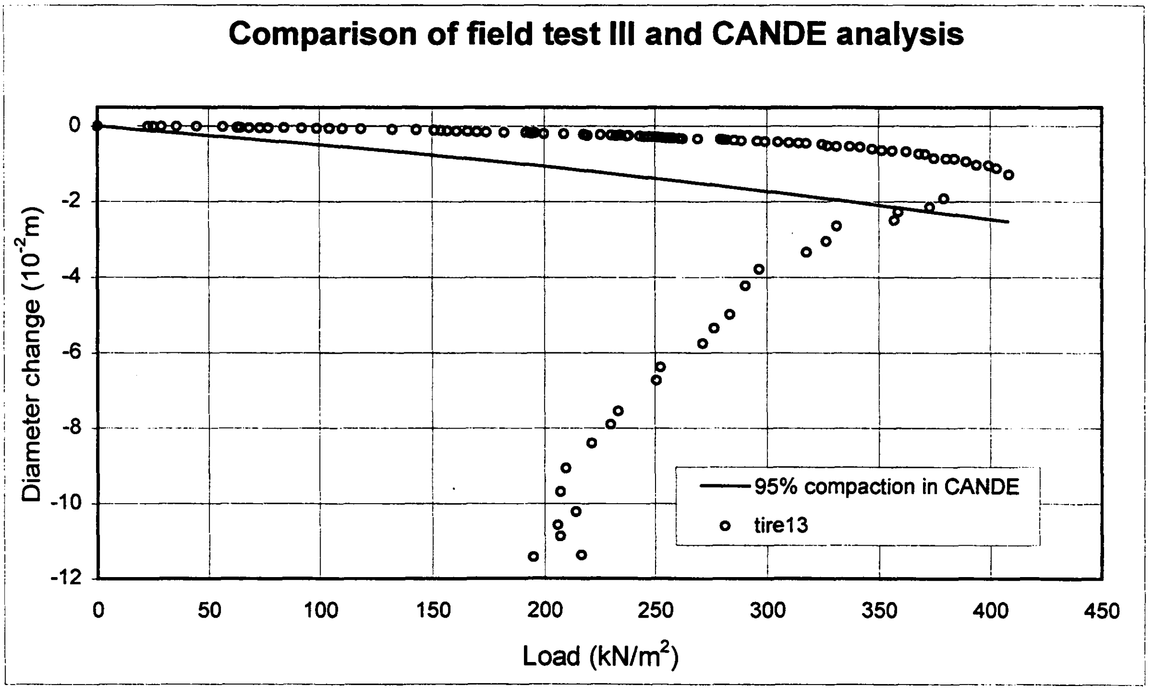


Figure 6.5. CANDE analysis for buried conduit test 3.

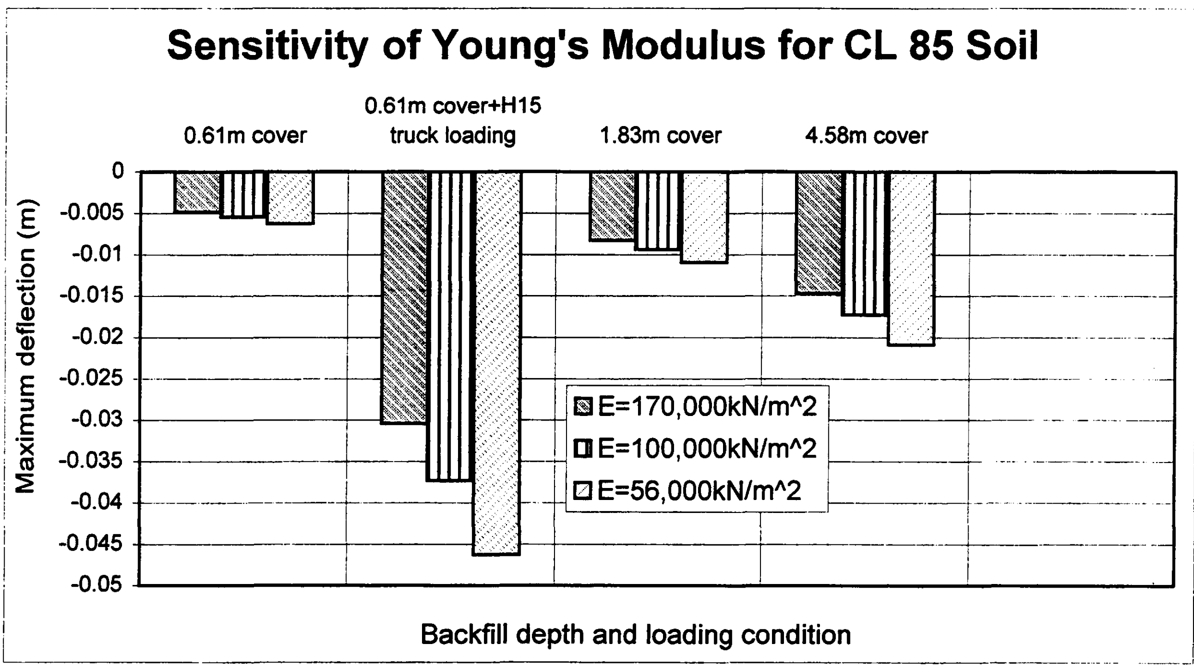


Figure 6.6. Sensitivity of CANDE analysis to tire pipe Young's modulus for CL soil with 85% compaction CANDE library soil parameters.

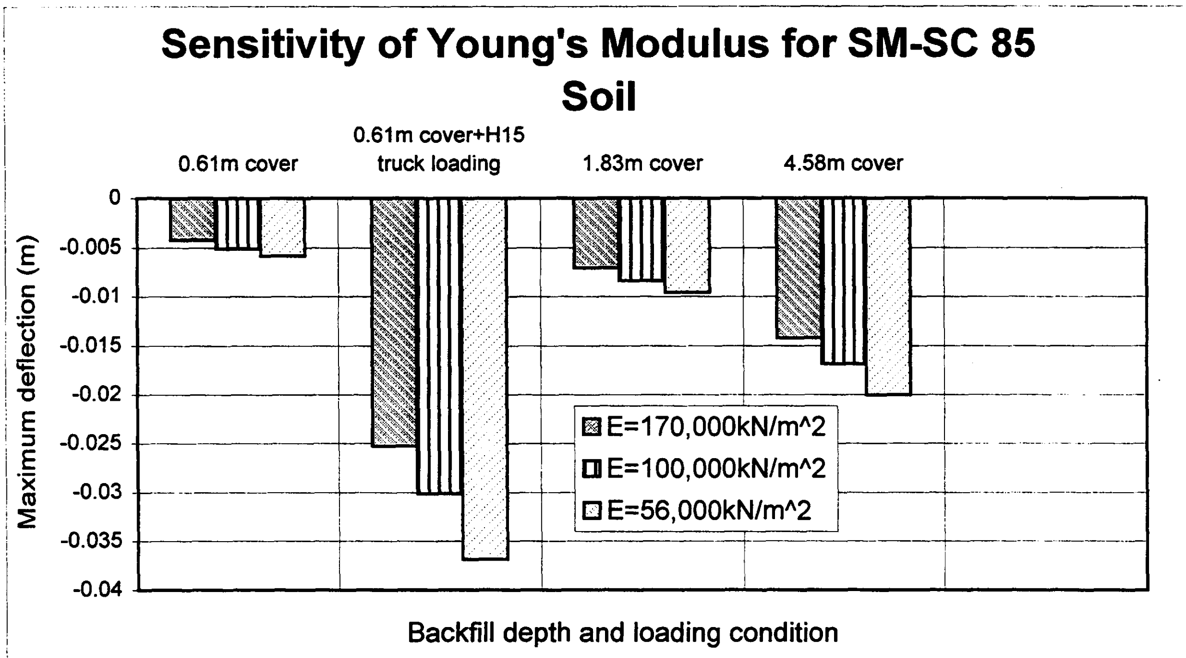


Figure 6.7. Sensitivity of CANDE analysis to tire pipe Young's modulus for SM-SC soil with 85% compaction CANDE library soil parameters.

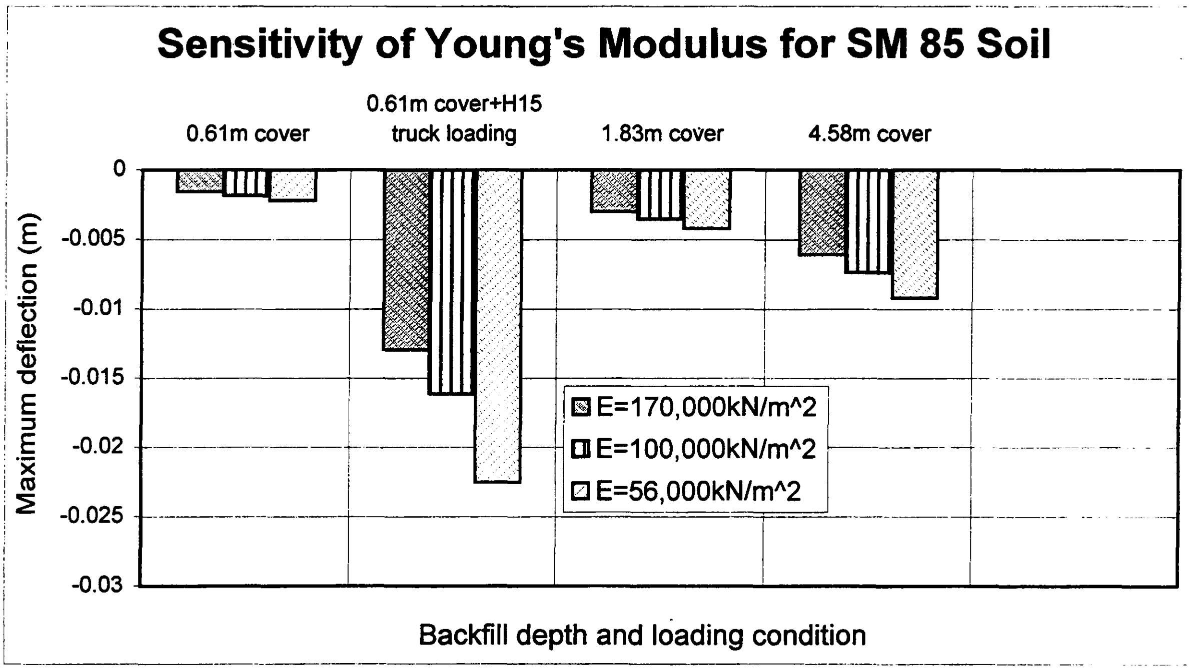


Figure 6.8. Sensitivity of CANDE analysis to tire pipe Young's modulus for SM soil with 85% compaction CANDE library soil parameters.

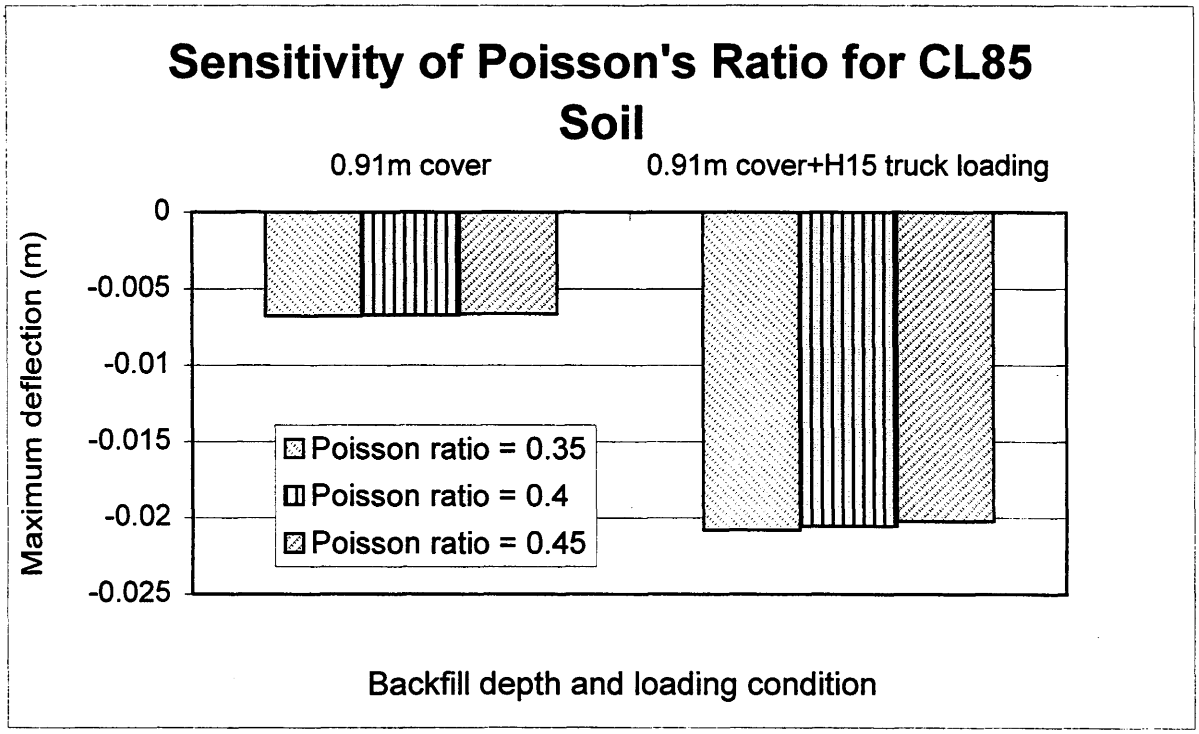


Figure 6.9. Sensitivity of CANDE analysis to tire pipe Poisson's ratio for CL soil with 85% compaction CANDE library soil parameters.

7 Design Guidelines for Truck Tire Culvert

7.1 Introduction

A truck tire culvert, an underground conduit built with whole scrap truck tires, is an economical alternative to a conventional underground culvert in situations where the water flow rate will be low to moderate. The structural and hydraulic characteristics of truck tire culverts have been evaluated through field tests, laboratory experiments, and theoretical analyses. These design guidelines are based on those test results and analyses.

7.2 Assumptions, criteria and limitations

Design assumptions, criteria and limitations set forth in the narrative are used to insure the constructability and performance of the structure. The assumptions, criteria and limitations are:

- Truck Tire Culvert (Pipe) Diameters:
  More than 60 whole scrap truck tires were measured and tested in this research. The truck tire inside diameter for conducting water ranges from 0.53m to 0.60m. The smallest diameter (0.53m) is used as the pipe diameter in the hydraulic calculations. The outside diameters range from 0.99m to 1.07m with the most common being 1.02m; therefore it is used as the pipe outside diameter.

- Roughness coefficient:
  The roughness coefficient is an important parameter for hydraulic analyses, however no tests were carried out to measure the roughness coefficient of the truck tire culvert. A roughness coefficient value of 0.05 was estimated from empirical equations. This value corresponds to a condition with sand ballast

placed in the bottom of the tires (the sand ballast is discussed further below). As it turns out, the value of 0.05 is two times the roughness coefficient of a corrugated metal pipe.

- Maximum water depth:
  A truck tire culvert is designed for partial flow only due to the high roughness coefficient and to avoid buoyancy effects associated with air trapped in the top of the tires. The maximum water depth inside the pipe is limited to 75% of the pipe diameter (0.4m).

- Maximum pipe deflection:
  From previous studies, the design strain for HDPE pipes ranges from 4% to 8% of the pipe diameter. Tires strain more than HDPE pipes and have potential creep development; therefore, the maximum deflection of the top of tires under backfill soil and surface loading is limited to 5% of the outside diameter (0.05m).

- Minimum and maximum soil covers:
  The range of soil depths over the tires is limited by the allowable pipe deflection, which is determined by the type and degree of compaction of the backfill soil, and the surface load. With the constraint of pipe deflection less than 5% of the outside diameter, the minimum and maximum soil covers for three soils at different degrees of compaction were obtained using the CANDE program.

  Important properties of the soils used in the CANDE analyses are listed in Table 7.1. The minimum soil covers listed in Table 7.2 were estimated under both soil load and H15-truck load. The maximum soil covers listed in Table 7.3 were estimated under geostatic load only because the effect of surface load for deep trenches is negligible.

- Tire selection:

  From the testing of more than 60 randomly selected scrap truck tires, most of the tires are adequate for culvert construction. Tires without treads (bald tires), excessively worn tires and tires with damaged sidewalls were observed to have the lowest load bearing capacity in parallel plate tests and should not be used for a truck tire culvert.

- Tire installation:

  The most convenient way to place truck tires in the trench is using sections of three banded tires. Tires are more stable and can be installed faster when banded. Sections of four or more banded tires are difficult to handle and are not recommended. In addition, it is recommended that sand ballast be placed in the bottom portion of the tires up to the top of the sidewall. This will significantly reduce the amount of water that could stagnate in this portion of the tires and also provide additional resistance to potential buoyancy effects. To further mitigate potential uplift buoyancy problems, the truck tire culverts should not be installed below the highest groundwater table position in the surrounding soil.

- Factor of safety:

  No factor of safety is applied within the design process. This is left up to the designer to determine for specific situations. However, the assumptions and limitations used here are based on conservative considerations.

7.3 Design process

Following the design flowchart, Figure 7.1, the first step in the design process is to gather all pertinent data about the project site. The information should include a plan view of the site, the drainage area, culvert alignment, ground surface elevations, elevations at the inlet and outlet, tailwater level, soil types, trench depth and backfill method, and types and magnitudes of surface loads.

Profile drawings using the elevation data will help the designer visualize the project and determine the gradient of the proposed tire culvert. The discharge to the culvert is proportional to the drainage area and can be determined using a runoff chart, as described below. The length and slope of the culvert determine the flow conditions and hence the hydraulic capacity of the culvert. Soil types, trench depth and degree of compaction are parameters needed for determining the pipe deflection under geostatic load and surface load.

- Hydraulic design

The hydraulic capacity of the proposed truck tire culvert should be estimated first. The specific method of estimating design discharge, Q_{design}, is left to the designer. The design discharge, which is a storm runoff at a certain frequency, can be determined from the drainage area. Equations and charts that relate the drainage areas and runoffs can be obtained from hydraulic handbooks or the Iowa Department of Transportation. As an example, Figure 7.2 is a runoff chart for Iowa. The relationship between drainage area and peak rate of runoff shown on this chart is for a storm frequency of 50 years and very hilly land with mixed cover terrain. Factors may be applied for different storm frequencies (called frequency factor – FF) and for different land descriptions and uses (called land use factor – LF).

After the design discharge, Q_{design}, length of the culvert, L, and slope of the culvert, S_o are defined, Figure 7.3 can be used to determine if the truck tire culvert has enough hydraulic capacity. Figure 7.3 indicates the relationship between the hydraulic capacity and the length and slope of the truck tire culvert when the tailwater is lower than the critical depth. It was established through hydraulic analyses. To use Figure 7.3, find Q_{design} on the ordinate and draw a horizontal line to the line representing the length of the culvert (interpolate if necessary); from there draw a vertical line and obtain the slope on the abscissa. This slope is the minimum slope required for conducting the design discharge within the maximum water level requirement and is called S_{min}. If the slope of the truck tire culvert is equal or greater than S_{min}, a truck tire culvert can be used for this project.

Figure 7.3 indicates that for slopes equal to or greater than 0.11, the hydraulic capacity is no longer a function of the length and slope of the culvert. This is because 0.11 is the critical slope at which flow changes from outlet control to inlet control. For the flow with inlet control, the hydraulic capacity of the culvert is independent of the length and slope of the culvert.

- Structural design

Once the hydraulic capacity of the truck tire culvert is found to be adequate for the project, the next step is structural analysis. This analysis is to assure that the maximum pipe deflection of the culvert is less than 5% of the outside diameter after the culvert is put into use.

The recommended minimum and maximum soil covers of a truck tire culvert for three soils at different degrees of compaction are shown in Tables 7.2 and Table 7.3. Table 7.2 can be used to determine the minimum soil cover and Table 7.3 can be used to determine the maximum soil cover over the truck tire culvert. As indicated on the flowchart, if the soil cover at the proposed compactive effort falls between the minimum and maximum values, a truck tire culvert can be used.

If both the hydraulic and structural criteria are met during the design process, then construction of the truck tire culvert may proceed.

Table 7.1. Soil type information for CANDE analyses

Unified classification	Degree of compaction (standard AASHTO)	Total unit weight γ_m (kN/m^3)	Initial friction angle Φ_o (degree)	Reduction in friction angle for a 10-fold increase in confining pressure $\Delta\Phi$ (degree)	Cohesion intercept C (kN/m^2)	Modulus number K	Modulus exponent n	Failure ratio R_f	Bulk modulus number K_b	Bulk modulus exponent m
Silty clay (CL)	45	9.7	23	11	0	16	0.95	0.75	15	1.02
	85	18.9	30	0	4.8	60	0.45	0.7	50	0.2
	95	20.4	15	4	62.0	120	0.45	1.0	80	0.2
	100	21.2	30	0	19.3	150	0.45	0.7	140	0.2
Silty clayey sand (SM-SC)	45	11.0	23	0	0	16	0.95	0.55	15	0.94
	85	18.9	33	0	9.7	100	0.6	0.7	50	0.5
	95	20.4	33	0	20.7	250	0.6	0.7	125	0.5
	100	21.2	33	0	24.1	400	0.6	0.7	200	0.5
Silty sand (SM)	45	11.0	23	0	0	16	0.95	0.55	15	0.94
	85	18.9	30	2	0	150	0.25	0.7	150	0
	95	20.4	34	6	0	450	0.25	0.7	350	0
	100	21.2	36	8	0	600	0.25	0.7	450	0

Table 7.2. Recommended minimum soil covers under H15-truck load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides compacted the same as the cover	1.2	0.6	0.6	0.6	0.5	0.5	0.3
Sides are poorly compacted (45%)	1.2	1.2	0.9	0.9	0.9	0.9	0.9

Table 7.3. Recommended maximum soil covers under geostatic load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides compacted the same as the cover	13	19	18.5	22	26	41.5	47.5
Sides are poorly compacted (45%)	13	4.5	5.5	6	7.5	10.5	16

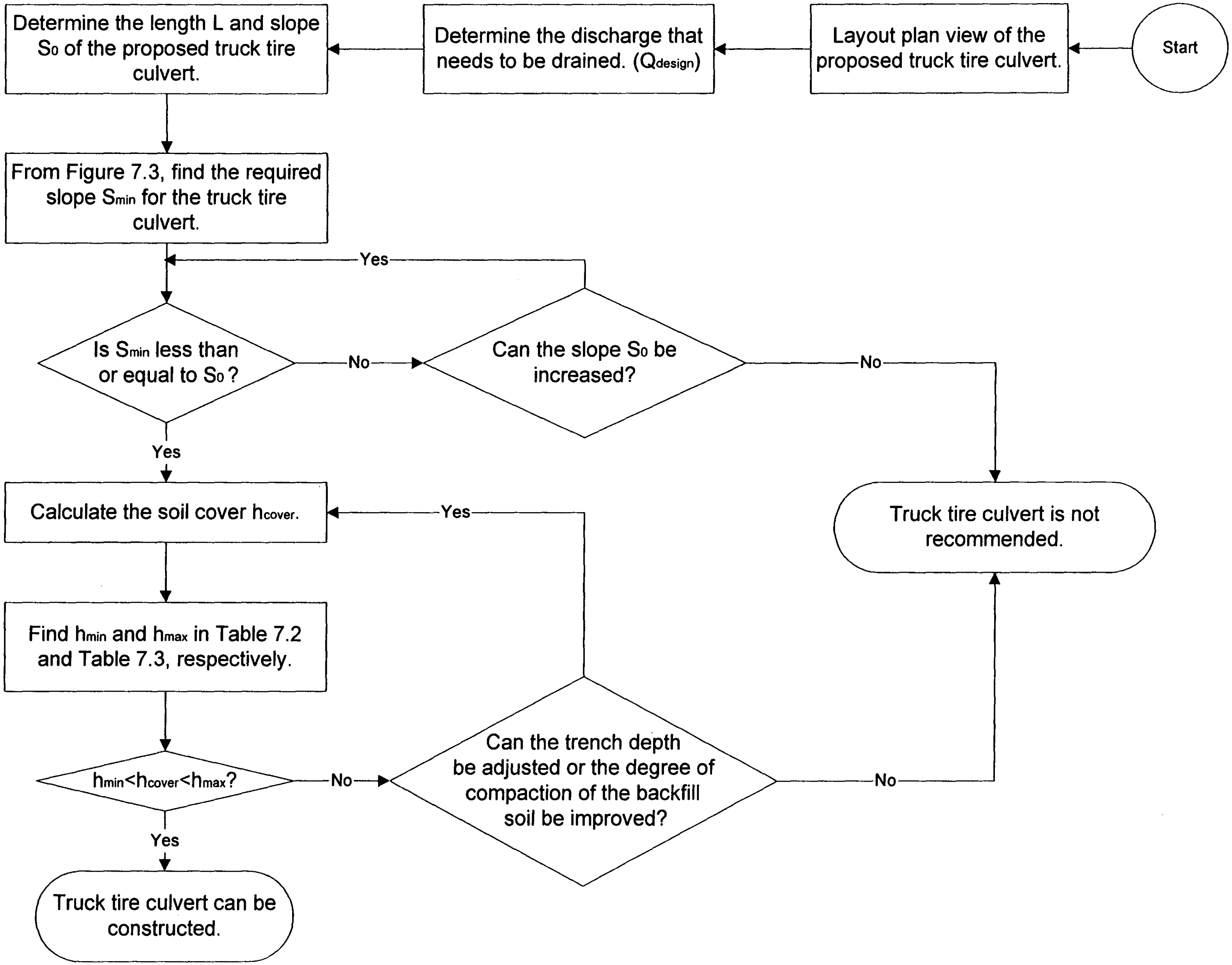


Figure 7.1 Design flowchart for truck tire culvert.

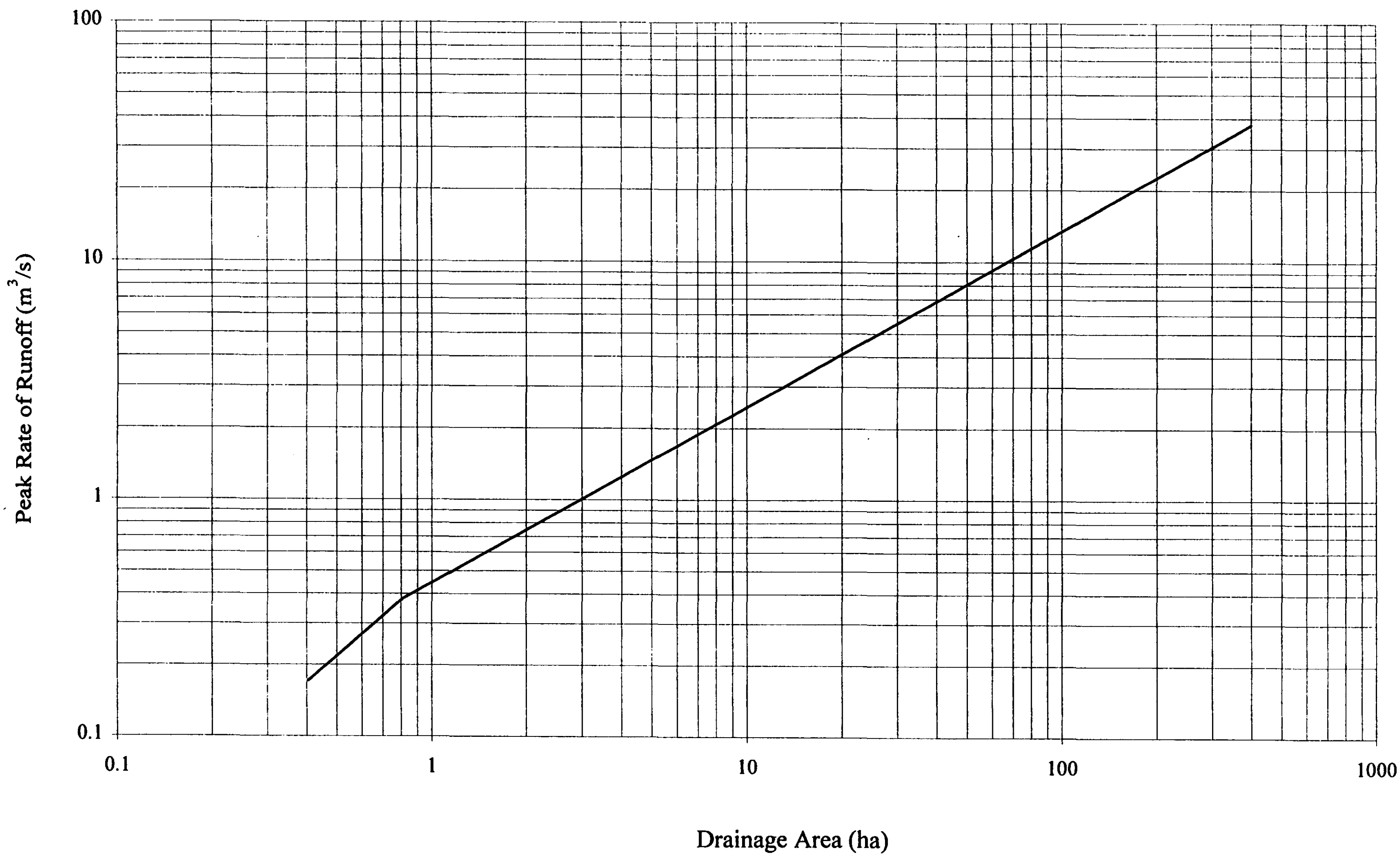


Figure 7.2 Iowa Runoff Chart (Frequency of 50 years, mixed cover on very hilly slope).

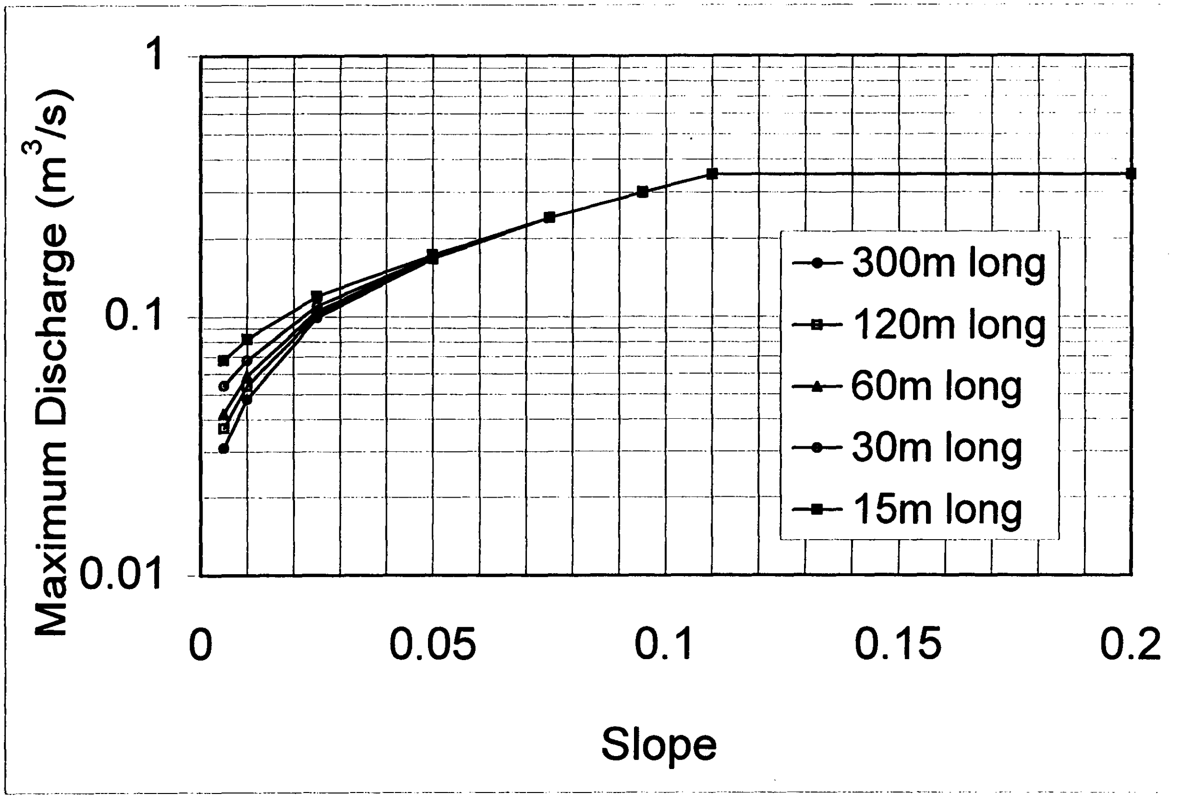


Figure 7.3 Hydraulic capacity of truck tire culvert (tailwater depth less than 0.2d).

7.4 Truck Tire Culvert - Design Example

Given:

The area to be drained is 2 hectares (5 acres) with mixed cover and rolling slope. The required length of the culvert is 60m and it can be placed at a slope of 0.08. The native soil is silty clay and the trench depth is limited to 1.7 m. It is assumed that the backfill soil will be compacted to 85% of the AASHTO standard and the soil beside the culvert in the trench will be well compacted. The maximum surface load corresponds to H-15 truck loading (gross weight of 133 kN or 30,000 lbs). Assume the frequency of the design flow is 5 years and the tailwater level at the end of the culvert is very low.

Solution:

Design parameters for the culvert: L=60m, So=0.08, Htrench=1.7m, Drainage Area=2 hectares

1. Following the design flowchart Figure 7.1, Determine the design discharge Q_{design}.

From the Iowa runoff equation:

$$Q_{design} = LF \times FF \times Q - - - - - (1)$$

Where: LF is the land use factor, FF is the frequency factor and Q may be determined from the Iowa Runoff Chart Figure 7.2 or calculated as

$$Q = 0.446 A^{0.740} - - - - - (2)$$

Note that equation (2) is for drainage areas between 1 and 400 hectares.

For a frequency factor FF of 0.5 (corresponding to a frequency of 5 years) and a land use factor LF of 0.6 (corresponding to mixed cover and rolling terrain) the design discharge is:

$Q_{design} = 0.22\ m^3/s$

2. Check the required slope

Using the relationship between the design discharge, length of the culvert and slope of the culvert on Figure 7.3, locate the design discharge of 0.22 m^3/s on the ordinate, draw a horizontal line to the curve corresponding to a length of 60 m (note that at this design discharge the curves have already coalesced) and from there draw a vertical line to the abscissa and find the minimum slope.

$S_{min} = 0.07$.

Because $S_{min} < S_o$, the hydraulic requirements are met and the truck tire culvert can be used to drain the surface water for that drainage area.

3. Check the soil cover.

   Since the outside diameter of the tires is 1.02m, the cover of backfill soil is calculated as

$h_c = 1.7m - 1.02m = 0.7m$

From Table 7.2 find the minimum soil cover for silty clay soil at 85% compaction with the soil beside the culvert in the trench well compacted.

$h_{min} = 0.6m$

From Table 7.3 find the maximum soil cover for silty clay soil at 85% compaction with the soil beside the culvert in the trench well compacted.

h_{max} = 19m

Since $h_{min} < hc < h_{max}$, truck tire culvert can be constructed.

4. Conclusion

For the proposed truck tire culvert, both the hydraulic and structural criteria are met, so the construction of the truck tire culvert may proceed.

8. Conclusions and Recommendations

8.1 Conclusions

There are several distinct advantages to using whole truck tires for subsurface drainage structures. The internal steel belts will not be directly exposed to the leaching action of water and the costs of grinding, shredding or shearing tires to produce chips are eliminated. Truck tires, in particular, are difficult to grind and process because of the heavy bead wire. Recognizing this problem with the recycling of truck tires, Dodger Enterprises of Fort Dodge, Iowa, constructed an innovative 330 m long culvert system using whole truck tires on previously undisturbed land near Fort Dodge. The culvert system was constructed during the summer of 1995 to reduce the groundwater level and to divert surface water runoff away from its buildings. While the Dodger Enterprises culvert drainage structure has performed satisfactorily and has demonstrated an innovative reuse of scrap truck tires, the key engineering properties of the whole truck tires and the design and performance aspects of this type of structure have not been quantified to allow use of the designs by other parties.

The specific objectives of this research were to:

1) Characterize and quantify the key engineering properties of whole truck tires as drainage culverts.
2) Quantify the performance of whole truck tire culvert sections when installed in a trench under various bedding conditions.
3) Develop recommendations for design and construction of culverts with scrap truck tires.
4) Disseminate the design recommendations to the public through publication of the results, open houses, workshops, seminars and/or short courses.

The following conclusions are based on the results and analyses conducted for this research project. These conclusions are based on a limited number of laboratory and field test results over a limited period of time. Generalizations of these conclusions for other situations and cases may not, in some conditions, be valid.

1. Dimensional measurements of truck tires used in this research program indicate that the inside diameter for conducting water ranges from 0.53 m to 0.60 m, with an average of 0.55 m. The smallest diameter (0.53 m) is used as the pipe diameter in the hydraulic calculations. The outside diameter ranged from 0.99 m to 1.07 m with the most common value being 1.02 m. The widths of the truck tire tread ranges from 0.18 m to 0.24 m with an average value of 0.21 m. The gross width of the tire is larger than the tread width by about 0.05 m.

2. Given the relatively small hydraulic pipe diameter of a whole truck tire culvert (0.53 m), the maximum discharge capacity of a truck tire culvert was determined to be about 0.35 m^3/s. This analysis used an estimated roughness coefficient of 0.05 and limited the maximum water level in the pipe to 75% of the pipe diameter. Given these design parameters and constraints, our analyses have shown that the truck tire culvert could be effectively applied to drain water from small drainage basins up to several hectares, depending on the frequency and land use factors.

3. Parallel plate tests on whole truck tires indicate that the load-diameter change curves for three truck tire banded sections (tire sections) are essentially an average response of the three individual tires making up the section. These tests indicate that the load- diameter change response of a tire section is adequately defined by testing single tires. This testing also indicates that the change in the inside, water-conducting diameter of the truck tires is only about 15% of the change in outside diameter and that tires without treads are not as stiff as the tires with treads.

4. Repetitive parallel plate tests on single truck tires indicate that the load bearing capability of the truck tires is not significantly impacted through six cycles of unloading and reloading. In practical terms, this indicates that repetitive loading, such as from traffic, should not cause excessive deformation of truck tire culverts.

5. Short duration parallel plate creep tests (up to a maximum time of two hours) indicate that at least 90% of the total tire compression takes place in the first 5 to 10 minutes. However, compression continues to increase, albeit at a relatively low rate, within the entire period of the tests. While there is continuing compression with time, it should not significantly impact the long term performance of the truck tire culvert system. Recall that the change in the inside, water conducting diameter of the truck tire is only about 15% of the change in outside diameter and the truck tires will have lateral structural support from the compacted backfill soil in the field; the tires in the creep tests were not supported laterally. It is recommended, however, that since rubber is a material that is highly prone to long term creep, further tests of a longer duration should be carried out to confirm potential long term impacts to truck tire culvert performance.

6. The results of buried conduit tests for shallow trench configurations (i.e. about 0.6 m of fill above the top of the tires) with different backfill conditions have shown that the load carrying capacity of a truck tire culvert is very dependent on the strength and stiffness of the surrounding backfill (i.e. moisture content and degree of compaction). Well compacted backfill with a higher strength and stiffness yielded higher maximum mobilized stresses. The load carrying capacity also depends on the location of the loading along the length of the culvert. Lower maximum mobilized stresses generally occur at the ends of the culvert relative to the center. In addition, the results indicate that maximum diameter changes recorded for the inside diameter are typically much smaller than for the outside diameter of the neighboring tire for tests near the midlength of the culvert. These results imply that

while the outside diameter may be undergoing relatively large deflections, the inside, water conducting diameter may not be significantly affected.

7. The maximum and minimum depths of backfill overlying a truck tire culvert were computed using the Culvert ANalysis and DEsign or CANDE program. A maximum allowable culvert deflection of 5% of its outside diameter was used in these analyses. Minimum soil covers, for the soils and degrees of compaction investigated, varied from 0.3 m to 1.2 m. These values were estimated under both soil load and H15-truck load. The maximum soil covers, for the soils and degrees of compaction investigated, varied from 4.5 m to 47.5 m. These values were estimated under geostatic load only because the effect of surface load for deep trenches is negligible. To meet the structural performance requirements, a truck tire culvert would need to have a depth of backfill between the two limits.

8. The CANDE analyses to evaluate the maximum and minimum depths of backfill were carried out using an average Young' modulus value that was calculated from the average tire stiffness value from the parallel plate tests. CANDE analyses were carried out to examine the sensitivity of the calculated maximum tire deflection to the tire pipe Young's modulus; lower bound and upper bound Young's modulus values were calculated from the upper and lower bound tire stiffness values, respectively. In addition, the effect of varying Poisson's ratio on the calculated maximum tire deflection was also examined. The results of these sensitivity analyses show that the maximum deflections are relatively insensitive to tire pipe Young's modulus and essentially insensitive to tire pipe Poisson's ratio.

9. The most convenient way to place truck tires in the trench is using sections of three banded tires. Tires are more stable and can be installed faster when banded. Sections of four or more banded tires are difficult to handle and are not recommended. In addition, it is recommended that sand ballast be placed in the

bottom portion of the tires up to the top of the sidewall. This will significantly reduce the amount of water that could stagnate in this portion of the tires and also provide additional resistance to potential buoyancy effects. To further mitigate potential uplift buoyancy problems, the truck tire culverts should not be installed below the highest groundwater table position in the surrounding soil. In addition, tires without treads (bald tires), excessively worn tires and tires with damaged sidewalls should not be used for a truck tire culvert.

8.2 Recommendations

Significant progress on defining relevant engineering properties and design guidelines for using large sized shredded and whole truck tires as drainage structures has been made; however, it is recommended that further research be carried out. In particular, a demonstration truck tire culvert should be constructed following the design guidelines and specifications set forth in this report. The structure should be carefully monitored during construction and for a period of about three years after construction. Monitoring should include as a minimum: precipitation amounts and frequencies, groundwater table elevations near the structure, deformation of the truck tire culvert and the hydraulic capacity. The latter monitoring would involve recording the levels of water impounded at the structure inlet and water flow rates through the culvert. In addition, a water quality impact monitoring program should be carried out with this demonstration structure.

In addition, further experimental work is recommended. The truck tire culvert roughness coefficient was estimated for the hydraulic analyses. While it is believed that a conservative estimate of this coefficient was used, the hydraulic analyses are sensitive to this coefficient. It is recommended that tests be carried out to measure values of roughness coefficient for truck tire culverts. It is also recommended that creep tests of a longer duration than this project be carried out to assess potential long term impacts to truck tire culvert performance.

9. Acknowledgments

This study was funded by a grant from the Recycling and Reuse Technology Transfer Center of the University of Northern Iowa. The authors are grateful to Mr. Don Grell and Mr. Ernest Kersten of Dodger Enterprises for their insightful collaboration and provision of the truck tires and truck tire culvert sections for testing. In addition, it was Mr. Don Grell's prototype culvert structure that developed the interest in and formed the basis of this work. A special thanks is also extended to the numerous undergraduate students who assisted with this investigation.

10. References

Ahmed, I. and Lovell, C.W. 1992. "Use of rubber tires in highway construction" in *Utilization of Waste Materials in Highway Construction*, Proc. of sessions sponsored by Materials Div. of Am. Soc. of Civil Engrs., H.I.Inyang and K.L.Bergeson (Eds.), pp 166-179.

Anonymous, 1990. "Tire fill stabilizes roadway, embankment" *Public Works*,Oct.:68.

AASHTO. Guidelines for Hydraulic Design of Culverts. *Highway Drainage Guidelines*. Vol. IV, 1992.

ASTM D2412 – 93, "Standard test method for determination of external loading characteristics of plastic pipe by parallel-plate loading".

Bauer, G.E. and Zhao, Y., 1993. "Shear strength tests for coarse granualr backfill and reinforced soils", ASTM *Geotechnical Testing Journal*, pp 115-119.

Benson, C.H., 1995. "Using shredded scrap tires in civil and environmental construction", *Resource Recycling*, October, 1995, pp 71-74.

Bosscher, P.J.; Edil, T.B. and Eldin, N.N. 1992. "Construction and performance of a shredded waste tire Test Embankment", *Transportation Research Record*, 1345, pp 44-52.

Chalmers, P., 1995. "Tackling tire and frost problems simultaneously" *Waste Age*, Jan.:67-70.

Chen, L., and Humphrey, D.N. 1997. "Use of tire chips/soil mixtures to limit frost heave and pavement damage of paved roads," A Study for the New England

Transportation Consortium, Department of Civil Engineering, University of Maine, Orono, ME,.

Das, B.M. 1998. *Principles of Geotechnical Engineering, 4th Edition*, PWS Publishing Co., Boston, MA.

Edil, T.B. and Bosscher, P.J., "Engineering properties of tire chips and soil mixtures," ASTM *Geotechnical Testing Journal,* Vol. 17, No. 4, December 1994, pp. 453-464.

Fetter, C.W., *Applied Hydrogeology, 3rd Edition*, Macmillian College Publishing Company, Inc., New York, 1994, pp. 86, 98.

Foose, G.J., Benson, C.H., and Bosscher, P.J., 1996. "Sand reinforced with shredded waste tires", ASCE *Journal of Geotechnical Engineering*, Vol. 122, No. 9, Sept. 1996, pp760-767.

Fung, Ping Kan, "Loess soil as highway material," MS Thesis, Iowa State University, Ames, Iowa, 1945.

Gupta, R. S. Hydrology & Hydraulic Systems. Waveland Press, Inc., Prospect Heights, Illinois, 1995.

Hall, T.J., 1990. "Reuse of shredded waste tire material for leachate collection systems at municipal solid waste landfills," for Iowa Department of Natural Resources Waste Management and Authority Division, by Shrive-Hattery Engineers and Architects, Inc.

Hendrickson, J.G., Jr, 1964, "*Hydraulics of Culverts*", American Concrete Pipe Association, Chicago.

Humphrey, D.N., “Civil Engineering Applications of Chipped Tires,” Nebraska DEQ Seminar, Omaha, Nebraska, Nov. 15, 1995.

Humphrey, D.N., Sandford, T.C., Cribbs, M.M., Gharegrat, H., and Manion, W.P., 1992 . “Tire chips as lightweight backfill for retaining walls - Phase I,” A Study for the New England Transportation Consortium, Department of Civil Engineering, University of Maine, Orono, ME,.

Humphrey, D.N., Sandford, T.C., Cribbs, M.M., Gharegrat, H., and Manion, W.P., 1993. “Shear strength and compressibility of tire chips for use as retaining wall backfill,” *Transportation Research Record No. 1422*, Transportation Research Board,.

Katona, M. G., 1976, “CANDE: A modern approach for the structural design and analysis of buried culvert,” FHWA, Report FHWA-RD-77-5, U.S.

Keller, G.R., 1988. "Retaining forest roads", *Civil Engineering*, 60 (12):50-53.

Kersten, E., Dodger Enterprises, Fort Dodge, Iowa. Personal Correspondence, October 6, 1997.

Kumar, M. and Bert, C. W., 1982, “Experimental characterization of mechanical behavior of cord-rubber composites,” *Tire Science and Technology*, Vol. 10, Nos. 1-4, Jan.-Dec. 1982.

Klaiber, F. W., Lohnes, R. A., Wipf, T. J., and Phares, B. M., “Investigation of high density polyethylene pipe for highway application”, ISU-ERI-Ames 96407, Engineering Research Institute, Iowa State University.

Manion, W.P. and Humphrey, D.N.,. 1992. "Use of tire chips as lightweight and conventional embankmentf fill, phase I - laboratory," *Technical Paper 91-1*, Technical Services Division, Maine Department of Transportation, Augusta, ME

Ng, Kam Weng, 1997. "Field tests and analyses of high density polyethylene pipes for highway applications," MS Thesis, Iowa State University, Ames, Iowa,
Petroff, L. J., 1993, "Ring bending stiffness and the design of flexible pipe," *Structural Performance of Pipes*, Sargand, Mitchell & Hurd (eds.).

Poh, P.S.H. and B.B. Broms, 1995. "Slope stabilization using old rubber tires and geotextiles", *Jour. of Performance of Constructed Facilities*, 9 (1):pp. 76-79.

Roe, H.B., and Ayres, Q.C., *Engineering for Agricultural Drainage*, McGraw-Hill Book Company, 1954, pp. 249-251.

Shackelford, C.D. and Javad, F., 1991. "Large scale laboratory permeability testing of a compacted clay soil," ASTM *Geotechnical Testing Journal*, Vol. 14, No. 2, June 1991, pp. 171-179.

Spangler, M.G. and Handy, R.L. 1982. *Soil Engineering, 4th Edition,* Harper and Row Publishers, New York.

Straub, L. G. and H. M. Morris. Hydraulic Data Comparison of Concrete and Corrugated Metal Culvert Pipes. *Technical Paper*, No. 3, Series B. Minnesota University St. Anthony Falls Hydraulic Laboratory, 1950.

Townsend, F. C., Shiau, Jih-Min, and Pietrus, T. J., "Piping susceptibility and filter criteria for sands," *Engineering Aspects of Soil Erosion, Dispersive Clays and* Loess, Proceedings of a Symposium sponsored by the Soil Properties

Committee of the American Society of Civil Engineers in conjunction with the ASCE *Convention in Atlantic City, New Jersey*, *Ed. C. W. Lovell, April 29, 1987,* pp. 46-66.

Tsai, Chin-Ta, 1991. "Constant head pumping tests in oxidized glacial till," M.S. Thesis, Iowa State University, Ames, Iowa,.

USEPA, 1991. "Markets for scrap tires", EPA/530-SW-90-074A, USEPA, Office of Solid Waste, Washington D.C. 115pp.

Zimmerman, P. 1997. "Compressibility, hydraulic conductivity and soil infiltration testing of tire shreds and field testing of a shredded tire horizontal drain", MS Thesis, Iowa State University, Ames, Iowa.