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STRESS DISTRIBUTION BELOW PAVEMENTS UNDER TROLLEY BUS LOADINGS

BY

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STRESS DISTRIBUTION BELOW PAVEMENTS UNDER TROLLEY BUS LOADINGS

ROBERT M. HARDY, *Dean and Professor of Civil Engineering* AND P. J. RIVARD, *Instructor, University of Alberta*

SYNOPSIS

Incidental to an investigation of the causes of rapid deterioration of pavements under Trolley Bus Loadings in the City of Edmonton a comprehensive series of stress measurements in the sub-soil was undertaken. The project was commenced in 1948 in cooperation with the National Research Council of Canada and the City Engineer's Department.

The stress distribution below both rigid and flexible pavements under normal traffic loadings was investigated. The effect of dynamic forces was also assessed. Stresses were measured with U. S. Waterways Experiment Station pressure cells using automatic recording equipment.

The data indicate that the pressure distribution below the flexible pavement was in close agreement with that computed by the Boussinesq equations of the elastic theory. This is also true of the pressure distribution below the rigid pavement if the thickness of concrete pavement is replaced by an equivalent thickness of soil obtained by multiplying the concrete slab thickness by a constant factor. The effects of impact, braking and acceleration forces were small compared to the stresses produced by static loads.

Many cities have experienced rapid deterioration of pavements on arterial streets following loading by trolley bus traffic. The experience, since 1945, of the City of Edmonton, Alberta, Canada, is typical of a number of cities in Western Canada. Both rigid and flexible type pavements developed extensive failures within a few months, and frequently within only a few weeks, after being subjected to trolley bus traffic for the first time. In some cases the road surface was old but had given satisfactory service for many years, in others the surface was practically new.

Failures, in general, have been of the type indicative of inadequate pavement support, although some instability of the asphalt surface was noted, particularly at the bus stop points. In Edmonton, where the sub-soil is a clay, the initial failures invariably developed at the bus stop points.

An investigation of such failures was undertaken in 1948 in the City of Edmonton by the Civil Engineering Department of the University of Alberta with funds provided by the National Research Council of Canada and the City Engineer's Department of Edmonton.

Soil Characteristics—Soil characteristics were surveyed over a stretch of some thirty-five blocks on the most heavily travelled bus line. Subgrade strength determinations were made and the load carrying capacity of the pavement was checked with CBR design curves. Table 1 shows a summary of the soil properties. A comprehensive series of stress measurements in the subgrade at two route stop points was also undertaken. This paper deals primarily with the results of the stress measurements as these are somewhat more general in significance than the results derived from the study of the local soil properties and moisture conditions.

Stress Recording Equipment—Pressure cells of the type developed by the U. S. Waterways Experiment Station at Vicksburg (*1*)[1] were used for stress measurement. These cells gave satisfactory performance when properly built and carefully installed, although it took the best part of the first season's work to arrive at the stage where the cells were performing properly and an adequate technique was acquired for their installation. The cells were calibrated with dead weights with a sponge rubber pad placed above and below the cells. A typical calibration curve is shown on Figure 1.

The stresses were recorded using a Brush two channel oscillograph, model BL-202, and a Brush strain analyzer model BL-310. This equipment gives an instantaneous and continuous record of the stress produced on the cell. Typical records are shown in Figure 2. A total of about 2,000 readings were taken

TABLE 1. SOIL PROPERTIES

Liquid Limit	Maximum	83
	Minimum	56
	Average for 16 Locations	66
Plasticity Index	Maximum	59
	Minimum	30
	Average for 16 Locations	46
C.B.R.	Range of Field Determinations for 11 Locations—10.5 at 14.8 percent Moisture To 3.1 at 28.3 percent Moisture.	
	Range of Soaked Samples From 11 Locations—2.2 At 41 percent Moisture To 3.7 At 34 percent Moisture.	

with approximately equal numbers at each of the two sites investigated.

Soil Profiles—The profile at Location A consisted of 2½ in. of asphaltic concrete over an 8½-in. concrete slab laid directly on the natural subgrade soil. The bottom 2 in. of the concrete slab was badly deteriorated by alternate freezing and thawing or alkali action or a combination of both. For this reason the effective profile was considered to be 2½ in. of asphaltic concrete over a 6½-in. concrete slab lying on 2 in. of gravel base placed directly on the subgrade soil. The subgrade soil is a glacial deposit of fairly uniform inorganic clay with a liquid limit of 57 and a plasticity index of 32. The subgrade moisture content was about 30 percent during testing.

The pavement at Location A was regarded as a rigid pavement. The concrete slab and asphalt top were laid in 1946 and so were relatively new. Two thousand pound concrete with no air entrainment was used in the slab.

The profile at Location B consisted of 1½ in. of asphaltic concrete over a 7-in. concrete slab laid directly on the natural sub-soil. Black top soil to a depth of 4 to 6 in. existed immediately below the pavement. The subgrade material below this was a clay of the same type as at Location A. The pavement at this site had been down for more than twenty years. The asphalt top was badly cracked in a pattern typical of inadequate base support. The con-

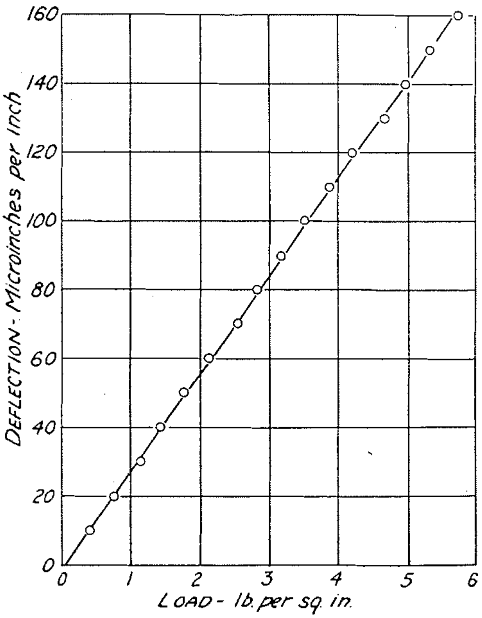

Figure 1. Calibration Curve—Cell No. 2—Att.20

crete slab was cracked into blocks with a maximum surface dimension of 4 to 6 in. and the bottom 1 in. was badly disintegrated. For these reasons the pavement at Location B was regarded as a flexible pavement with the broken and disintegrated concrete acting only as a gravel base course for the asphalt surface.

Pressure Cell Locations—At each location the pressure cells were placed in a pattern as shown in Figure 3. The installation was made from a hole dug outside the curb. A slot was cut into the soil below the pavement to take the pressure cell. After the cell was placed the soil

[1] Italicized figures in parentheses refer to the list of references at the end of the paper.

was backfilled into the slot and thoroughly tamped to a density exceeding that of the natural soil. The larger hole was also backfilled. A separate installation was made for each position of the pressure cell.

A three-foot square, centered over the particular cell upon which readings were to be taken, was then marked on the pavement and subdivided into 6-in. squares. Lines at one-foot intervals were also marked along the curb for a distance of 12 ft. on each side of the cell. These were used to locate the position of the

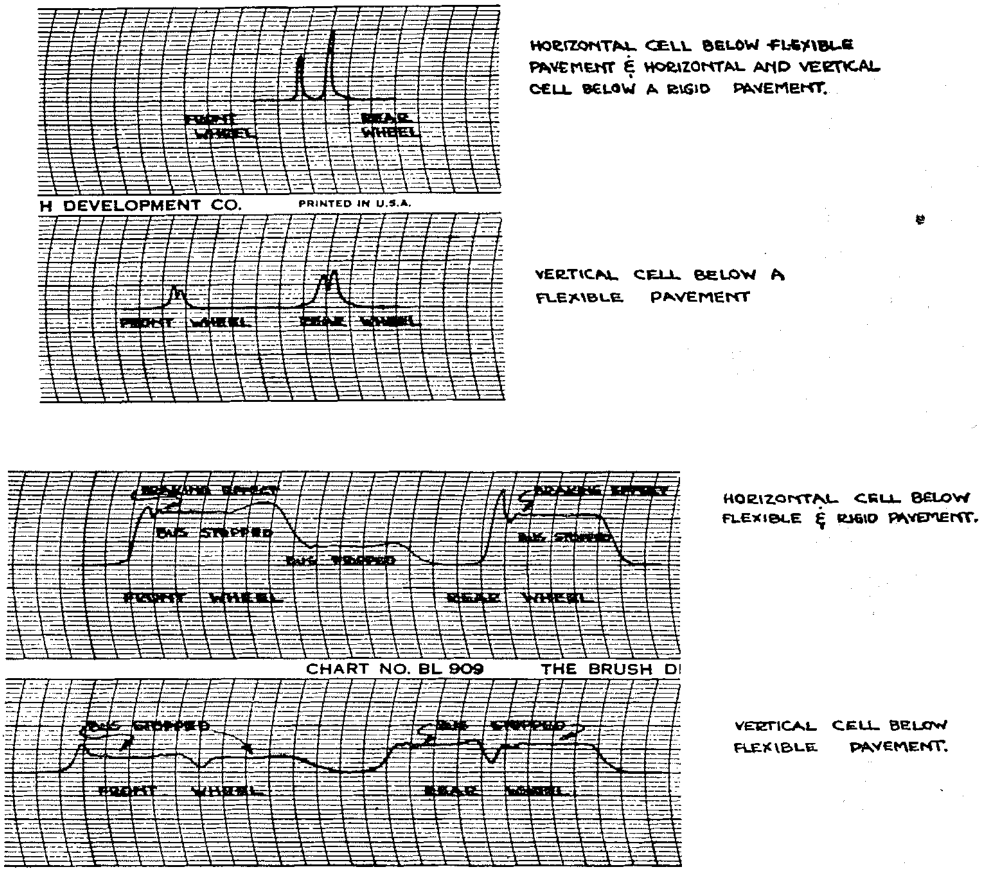

Figure 2. Typical Pressure Patterns

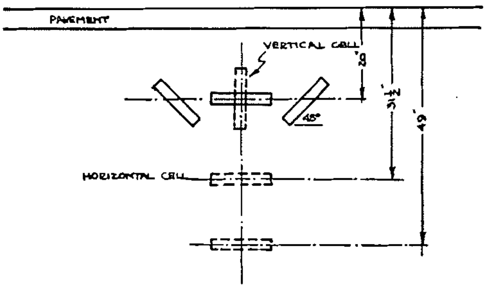

Figure 3. Cell Positions

bus wheels when stopping or starting or moving across the area. Loadings were recorded for the busses operating on their normal schedule. They moved across the area or were stopped and started on directions given to the drivers.

Trolley Bus Types—Three models of trolley bus were in operation on the route of the locations, A and B. These were designated types I, II, and III. Their dead weights were 18,700, 21,100 and 20,600 lb. respectively. The load distribution in each case was 35 percent on the front axle and 65 percent on the rear axle. In all cases the rear axles carried dual tires with a normal pressure of 65 psi. The front wheel normal tire pressures were 80 psi. All types of bus had a maximum live load capacity of 88 passengers. Capacity loading only occurred during the morning, noon and evening rush hours and during these periods pressure cell readings were not taken. The number of passengers on the bus at each reading was recorded. The average was about twenty.

Two series of readings were taken for each cell location. For the first set the bus travelled continuously across the cell. However, the vehicle in some cases was moving at a uniform speed and in others was accelerating or decelerating as the pressure recording was secured. For the second set the bus moved through the area of influence of the pressure cell in a series of stops and starts extending over a distance of 8 to 10 ft. on either side of the cell in the direction of travel. The purpose of the second series of readings was to assess the effect of braking and acceleration forces.

Flexible Pavement Results—Static Loads—The Boussinesq equations of the theoryof elasticity (*2*) express the stress conditions at a point within a semi-infinite, elastic, homogeneous and isotropic medium having a constant ratio between stress and strain, and loaded by a perpendicular point load applied to the surface. The pertinent equations are shown in Figure 4. The assumptions upon which the Boussinesq equations are based are of course not completely satisfied by a wheel load bearing upon a roadway structure. Nevertheless, it is reasonable as a first approach to compare the recorded stresses in the subgrade with the theoretical values computed from the Boussinesq theory.

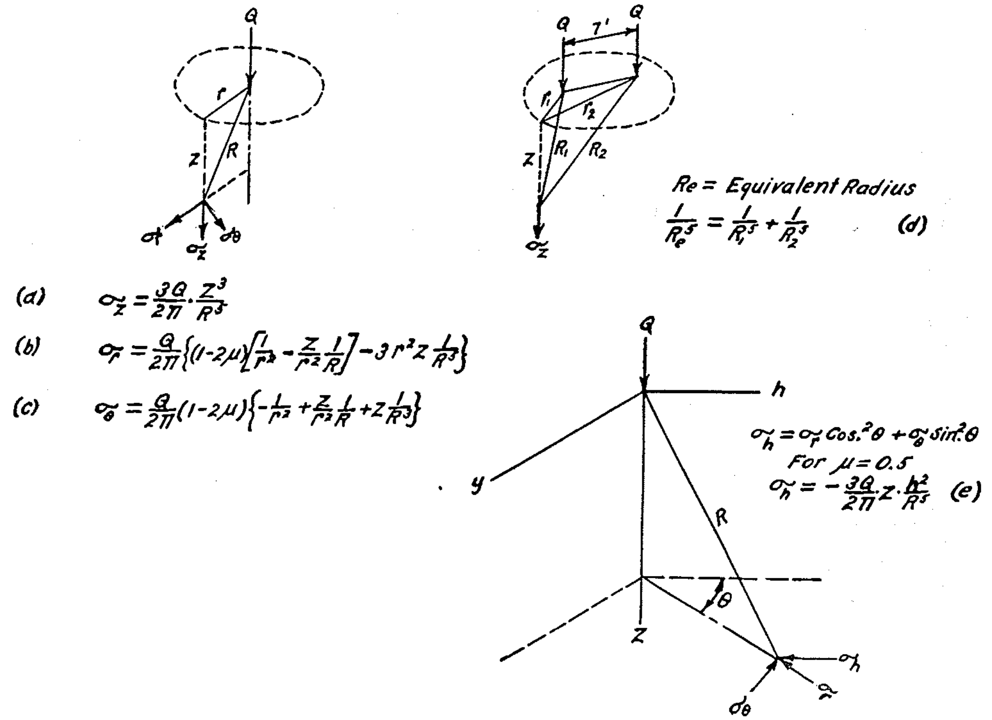

Figure 4

Figure 5 shows logarithmic plots of the recorded static vertical pressure against the corrected radial distance for the cell at depths of 20, 31.5, and 49 in. for front axle loadings at the flexible pavement site. The corrected radial distance is computed from equation d (Fig. 4) and is made to include the effect of the total axle load, because it was found that in some cases the far wheel produced a significant pressure on the cell in addition to that of the near wheel. The plotted pressures are the actual cell readings uncorrected for variation of type of bus and magnitude of live load. An analysis of the data showed that the corrections for these factors were smaller in magnitude than other experimental errors.

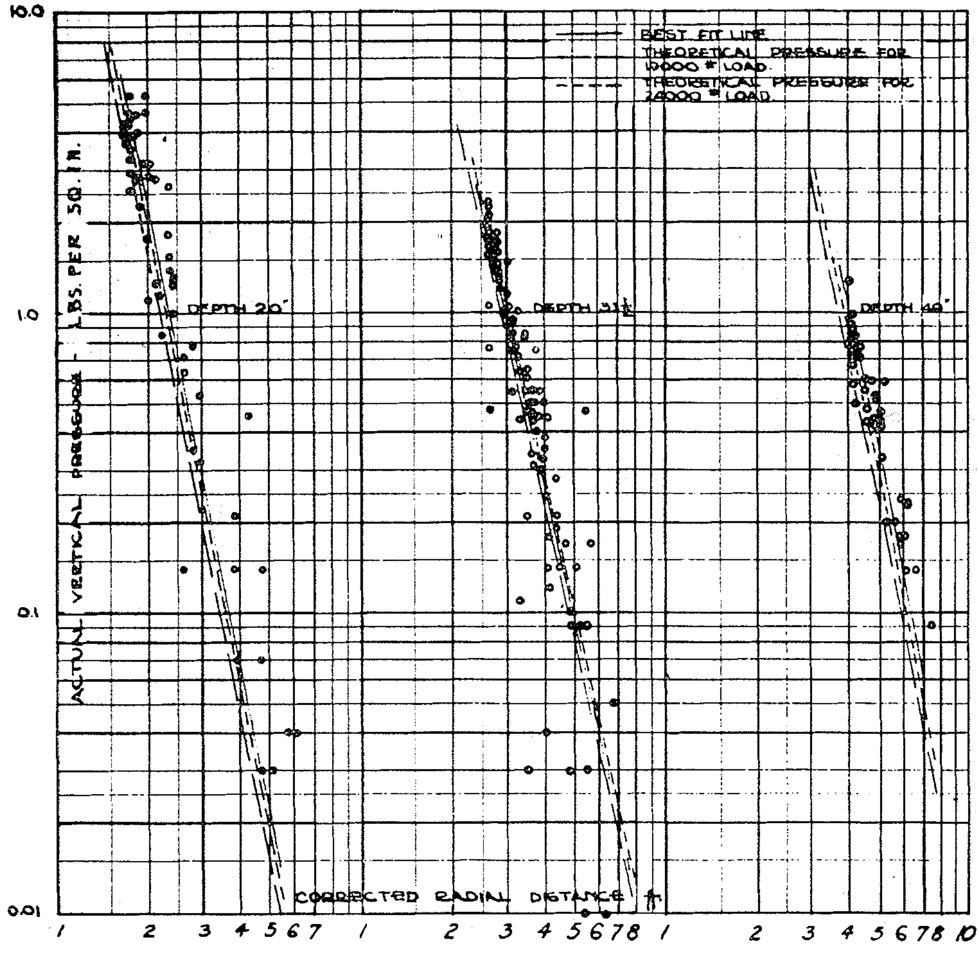

Figure 5. Actual Vertical Pressure Vs. Corrected Radial Distance—Static Load—Front Wheel —Flexible Pavement

If the experimental data satisfy equation a (Fig. 4) each of the plots of Figure 5 should establish a straight line, of slope −5 and each line should fall within the range of the corresponding plots of equation a (Fig. 4) for the probable range in Q values due to type of bus and actual live load. The best fit straight line for the data is produced as a full line on Figure 5. The extreme positions of the plot of equation a are also plotted as broken lines for minimum and maximum values of total bus weight of 19,000 and 24,000 lb. respectively.

Figure 6 shows similar plots for the experimental data for the rear axle loadings and Figure 7 is a plot for horizontal pressure. The theoretical curves on Figure 7 are computed from equation e (Fig. 4).

The data of the seven plots shown on Figure 5 to 7 are in agreement with the Boussinesq theory within the limits of experimental error. The conclusion is justified that for the flexible type pavement at Location B the subgrade soil pressures due to static loads are in accordance with the Boussinesq theory.

Rigid Pavement Results—Static Loads—For the rigid pavement site logarithmic plots of the

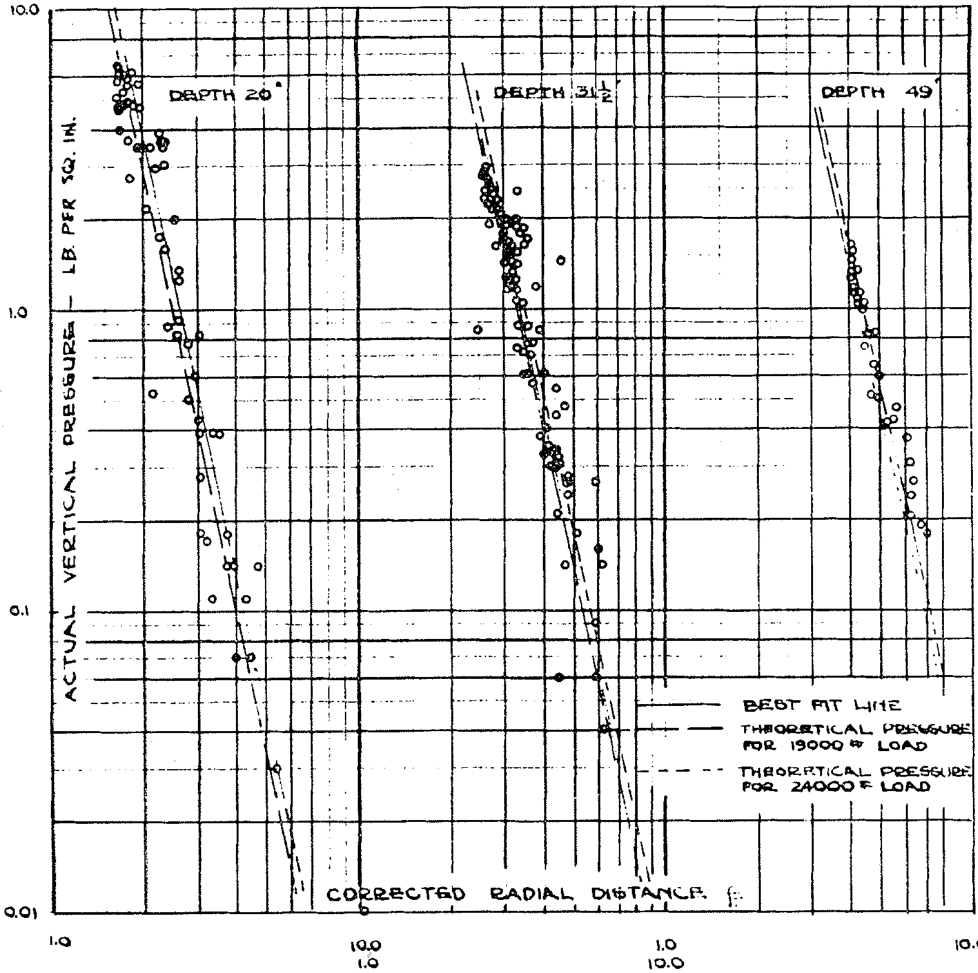

Figure 6. Actual Vertical Pressure Vs. Corrected Radial Distance—Static Load—Rear Wheel —Flexible Pavement

recorded static vertical pressure against the corrected radial distance defined curved lines typically shown in Figure 8. The effect of the rigid slab in reducing the unit soil pressure is clearly shown. It will be noted however that the plot approaches the theoretical Boussinesq curve as the radial distance increases.

It is possible to increase the depth to the cell by a constant amount to a new value C such that the logarithmic plot of recorded pressure against an equivalent radial distance computed for the C value is a straight line in close agreement with the Boussinesq theory. This is tantamount to replacing the thickness of rigid slab by an equivalent thickness of soil through which the stress will be distributed in accordance with the Boussinesq equations.

For each position of the pressure cell several values of the constant C were chosen and plots made of recorded pressure against equivalent radial distance as typically shown on Figure 9. For each C value a best fit straight line of slope −5 was then drawn through the plotted points. Each plot was then analyzed statistically and the C value determined for which the average root mean square deviation was a minimum for the best fit straight line of slope

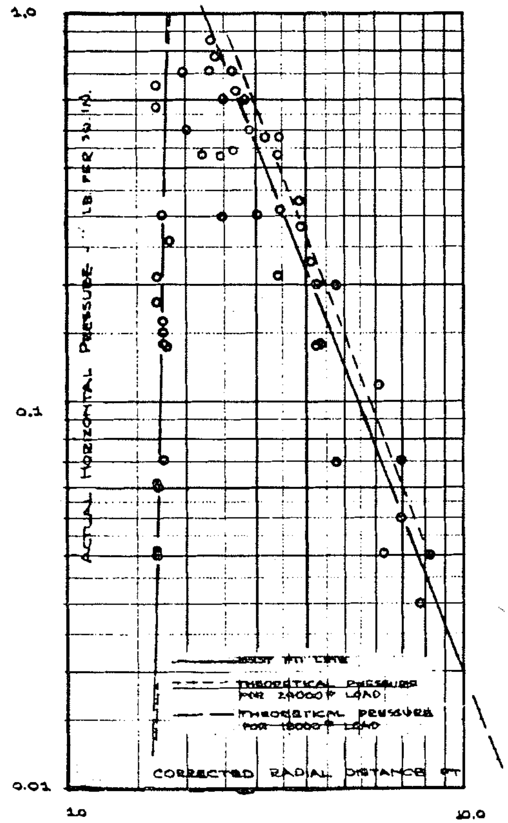

Figure 7. Actual Horizontal Pressure Vs. Corrected Radial Distance—Static Load—Vertical Cell-Depth 20 in.—Flexible Pavement

−5. This analysis gave values for equivalent thickness of the $6\frac{1}{2}$-in. concrete slab of 24, 23 and 25 in. for front wheel loading for the pressure cell at depths of 15, 19, and 31 in. respectively.

The extreme positions of the plot of equation a using the equivalent radial distance corresponding to a C value of 4.0 are plotted on Figure 9 as broken lines for minimum and maximum values of total bus weight of 19,000 and 24,000 lb. respectively. Figures 10 and 11 show similar plots for the experimental data for front and rear axle loadings and various positions of the pressure cell.

Corresponding analyses of the data from the pressure cells in the vertical and inclined positions are somewhat more difficult and results are not presented here. However, Figure 12 shows plots of the basic data from

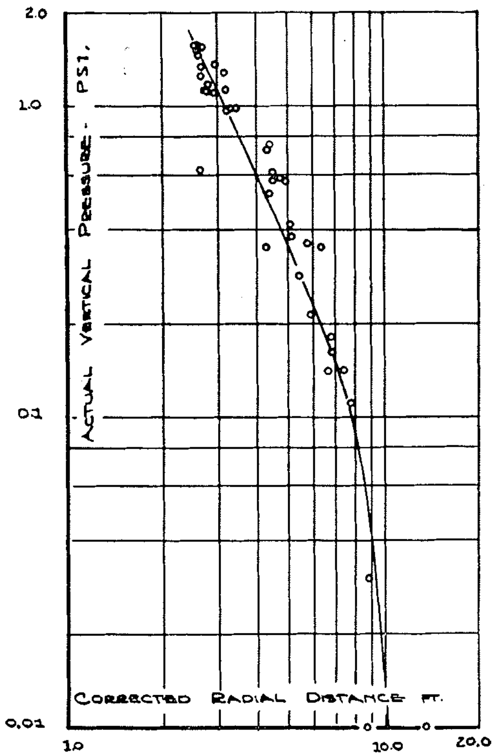

Figure 8. Actual Vertical Pressure Vs. Corrected Radial Distance—Static Load—Horizontal Cell—Rear Wheel—Rigid Pavement—Depth 31 in.

the cell in the horizontal position and also inclined at 45 deg. with its face perpendicular to the direction of traffic movement. It will be noted that these plots show the effect of the rigid slab similarly to the plots on Figure 9 for the cell horizontal.

An anomaly occurred consistently in the horizontal pressures measured by the cell below the rigid pavement. As will be noted on Figure 2 this stress did not show a reduction with the load directly above the cell. In accordance with the Boussinesq theory it should

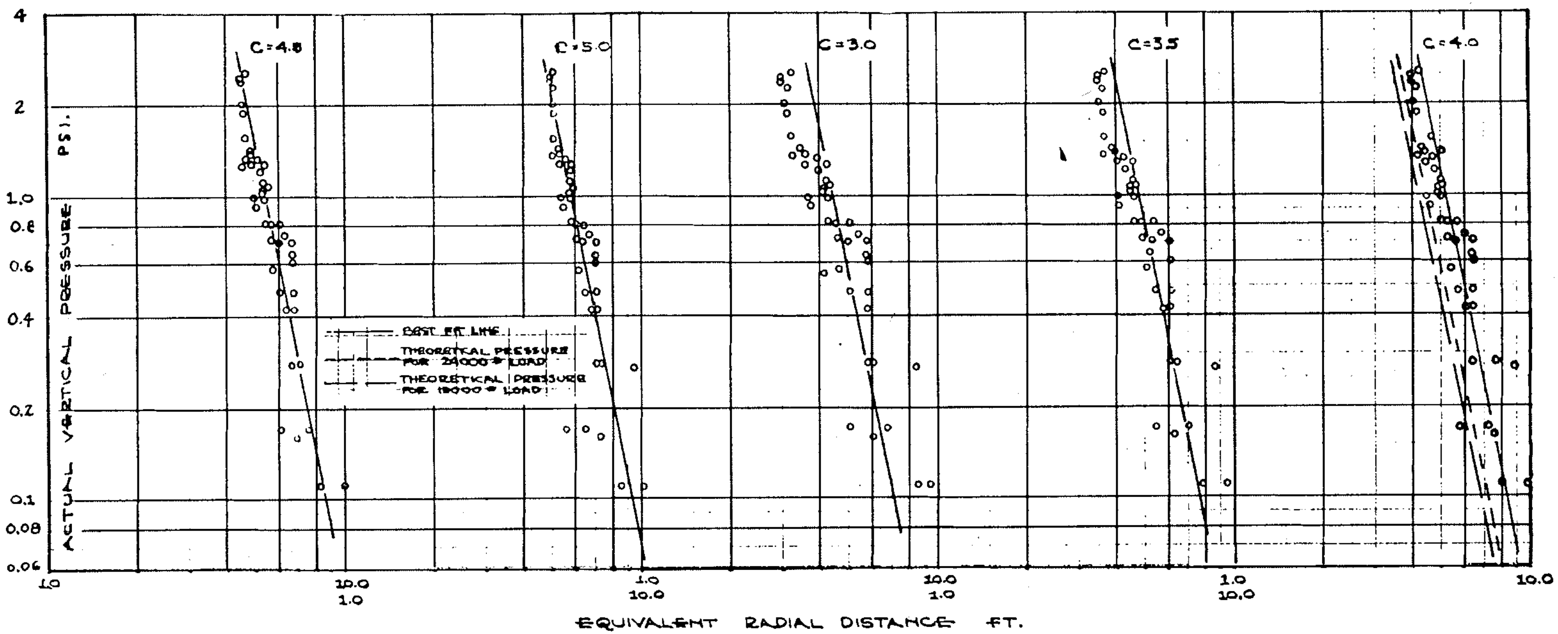

Figure 9. Actual Vertical Pressure Vs. Equivalent Radial Distance—Static Load—Horizontal Cell—Rear Wheel—Rigid Pavement—Depth 19 in.

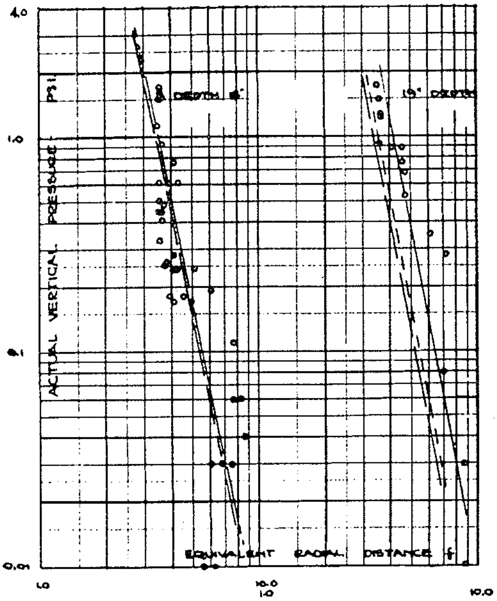

Figure 10. Actual Vertical Pressure Vs. Equivalent Radial Distance—Static Load—Rigid Pavement—Front Wheel—C = 3.5 ft.—See Figure 9 for Legend

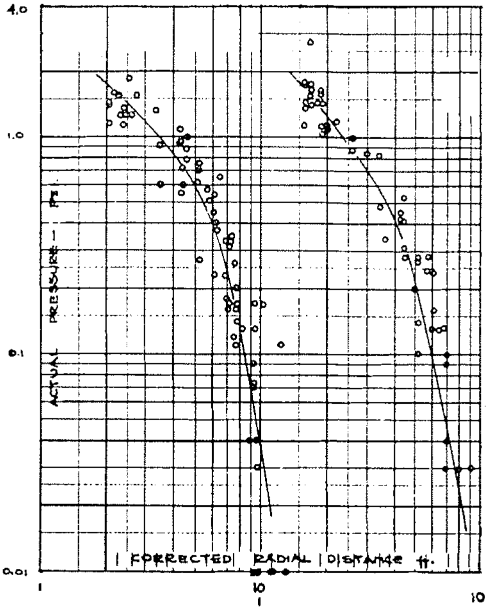

Figure 12. Right Hand Curve: Actual Horizontal Pressure Vs. Corrected Radial Distance—Rigid Pavement—Front Wheel—Depth 19 in. Left Hand Curve: Actual Pressure Vs. Corrected Radial Distance—Cell at 45 deg.—Rigid Pavement—Rear Wheel—Depth 19 in.

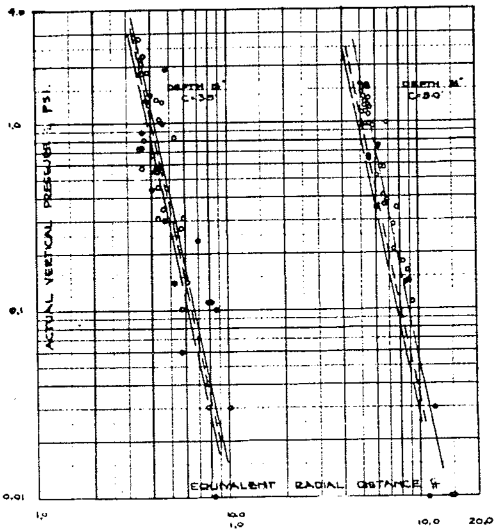

Figure 11. Actual Vertical Pressure Vs. Equivalent Radial Distance—Static Load—Rigid Pavement—Rear Wheel—See Fig. 9 for Legend

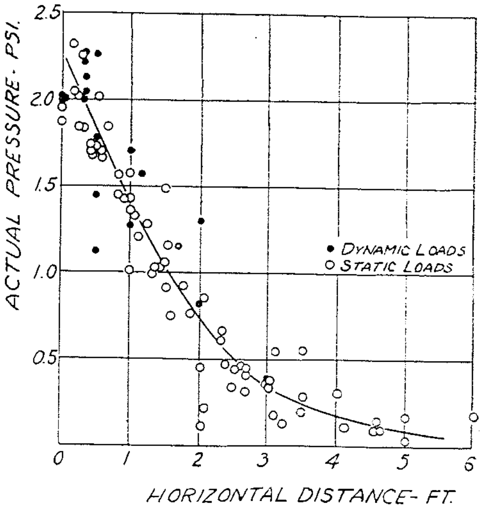

Figure 13. Actual Pressure Vs. Horizontal Distance for Dynamic and Static Pressure—Flexible Pavement—Horizontal Cell—Depth $31\frac{1}{2}$ in.

be zero for this loading. However, in general the data are in agreement with the Boussinesq theory within the limits of experimental error if the 6½-in. concrete slab is replaced by an equivalent thickness of about 24 in. of soil.

Dynamic Effects—Figure 13 shows a plot of recorded pressure against horizontal radial distance in which pressures are plotted both for wheels passing continuously across the cell and for static loads. No significant difference between the static and dynamic loadings is evident. Similar plots for other positions of the cell at Locations A and B also fail to show a significant difference.

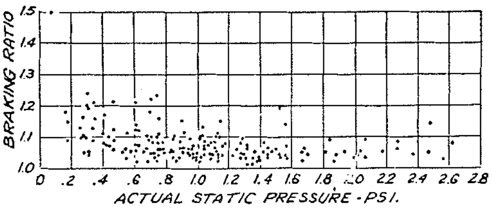

Figure 14. Braking Ratio Vs. Static Pressure —All Positions and Depths of Cell—Rigid Pavement—

Braking Ratio	Repetitions
1.0–1.1	149
1.1–1.2	283
1.2–1.2	7
1.3–1.4	0
1.4–1.5	1

Braking and Acceleration Effects—The pressure records showed no measurable effect due to forces of acceleration, but as shown on Figure 2 the effect of braking forces is evident. Figure 14 shows a plot of braking ratio against static pressure for the rigid pavement location. The braking ratio is the ratio the maximum pressure recorded during the time the bus was brought to a stop divided by the pressure recorded for the bus at rest. A similar plot is shown on Figure 15 for the flexible pavement location.

It will be noted from these plots that the average increase in stress due to braking forces is only about 5 percent for both rigid and flexible pavements.

However, it will also be noted that the percentage increase is somewhat larger at the lower unit pressures. This would appear to be the result of a shock wave being transmitted through the soil. The shock wave is somewhat more severe for the flexible than for the rigid pavement. However, in neither case is there evidence that the shock wave would cause stresses of a magnitude that could result in appreciable overloading of the soil.

Design Significance—The results of the investigation are negative to a certain extent from the point of view of solving the local problem in the City of Edmonton. Contrary to the local opinion braking and acceleration forces are not major factors in overloading the pavement.

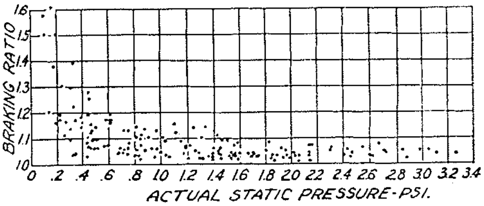

Figure 15. Braking Ratio Vs. Static Pressure —All Positions and Depths of Cell—Flexible Pavement

Braking Ratio	Repetitions
1.0–1.1	126
1.1–1.2	30
1.2–1.3	5
1.3–1.4	2
1.4–1.5	2
1.5–1.6	2

The trolley busses when loaded to capacity constitute a maximum loading exceeding by about 30 percent the gross load permitted on the highways in the Province of Alberta. The essential cause of the rapid deterioration of the pavement due to the busses appears therefore to be the heavier loading from the busses combined with a much larger frequency of loading as compared to normal heavy truck traffic using the streets. At the bus stops earlier breakdown results due to the fact that the repetition of load is confined to a comparatively small area.

The effect of the overloading by the trolley busses is well illustrated by the fact that using a "worst" C.B.R. value of 3 and design curves as developed by McLeod (*3*) for flexible pavements, the maximum weight of truck permitted on the provincial highways requires a thickness of granular base and pavement of 11 inches. On the same basis a trolley bus loading requires a thickness of 15 inches.

It is perhaps worthy of comment in conclusion that for these loadings essentially the same design of flexible pavement can be arrived at by selecting a thickness of granular base and pavement such that the maximum shearing stress in the subgrade as computed by the Boussinesq theory is less than an estimated maximum allowable shearing stress in the subgrade. This latter value can be arrived at with a fair degree of accuracy from a moisture content-strength curve determined by a series of unconfined compression tests.

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