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.

Acknowledgments—The complete cooperation of officials of the City Engineer's Department and the City Transit System of Edmonton greatly facilitated the progress of the field program. The valuable personal interest of Mr. R. F. Leggett, director, Division of Building Research, National Research Council of Canada is also acknowledged. The paper is published with the approval of the National Research Council of Canada.

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A STUDY OF THE VIBRATIONS PRODUCED IN STRUCTURES BY HEAVY VEHICLES

HUGH B. SUTHERLAND, *Lecturer in Civil Engineering, University of Glasgow, Scotland*

SYNOPSIS

The use of heavy vehicles in city streets in recent years in Canada has brought into prominence the question of the vibrations produced and the possibility of structural damage caused by these vibrations. In this paper, a series of experiments is described, whereby, using a seismograph, measurements were taken of the vibrations produced in a structure by the passage of a trolley bus and a gasoline bus. The relative effects on the amplitude and frequency of the vibrations of factors such as, (a) weight of vehicle, (b) speed of vehicle, (c) condition of road surface, (d) thickness of road bed, (e) underlying soil frozen and unfrozen were investigated. The vibrations measured are correlated with previously published reports of the vibrations necessary to cause damage to structures, and comments are made on the sensitivity of human beings to vibrations.

Since the introduction of trolley buses in Winnipeg, Manitoba, Canada, during the last few years, complaints of vibrations resulting from the buses have frequently been made. These complaints have been received by the Winnipeg Electric Company, who operate the vehicles, and by the City Engineer, who is responsible for the construction and maintenance of the roads and streets on which the vehicles run. Similar complaints, to lesser extent, have also been made of gasoline buses.

Various opinions had been expressed, with little or no evidence to substantiate them, as to the primary causes of the vibrations and as to methods of controlling and minimizing them.

It was arranged that the National Research Council of Canada should conduct an investigation of the vibrations resulting from heavy vehicles, this investigation to be carried out with the collaboration of the interested authorities in the City of Winnipeg.

The question of vibrations in buildings and other structures is one which is frequently encountered by engineers and architects. The question has been, and still is, the subject of much controversy as so many complicating factors, both physical and mental, enter into it. Data gathered from a large number of tests covering different conditions will assist in obtaining a better understanding of the problem of vibrations in structures. The data from the investigations in Winnipeg are presented in some detail in this paper.

SOIL AND FOUNDATION CONDITIONS IN WINNIPEG

During the Pleistocene or Glacial Period, the area on which the City of Winnipeg stands was inundated by a vast body of water called Lake Agassiz by the geologists. This water was retained by ice barriers and glacial deposits, and during its existence, successive layers of sedimentary deposits were laid down on the lake bottom. When these ice barriers melted, the impounded water was released.

The City of Winnipeg is built upon these sedimentary lake deposits. The strata from prairie level to bed rock, which is a distance of 60 to 70 ft. is approximately as follows, progressing from the surface down:[1]

A. 2 ft. of loam;
B. 3 ft. of silty clay;
C. 4 ft. of brown clay;
D. an average of 12 to 18 in. of "yellow" clay;
E. approximately 20 ft. of dense chocolate colored clay;
F. approximately 20 ft. of dense blue clay;
G. 2 ft. of boulders and ground-up limestone;
H. 2 ft. of semi hard-pan;
I. 5 to 10 ft. of hard-pan;
J. limestone bed rock.

During dry seasons, the surface soil dries out by evaporation and the clay is broken up by shrinkage cracks. When rain falls, the cracks fill with water, the clay swells, and heaving of the ground surface occurs. This depth of drying out extends to a depth of approximately 10 ft. in Winnipeg. However, these Winnipeg top soils have high shrinkage and expansion characteristics and considerable heaving of buildings occurs after a prolonged dry spell and subsequent rain. In addition, a building acts as a "cover" on the clay and loss of water in the underlying clay due to evaporation is reduced. Hence, the water content of the clay located beneath the covered areas increases with relation to the uncovered clay, and a resultant heave of the center part of the covered area occurs with respect to the outer boundaries of the area. The amount of heave is practically independent of the weight of the building but its effect on the building is very similar to that of unequal settlements. It leads to cracked basement floors, basement walls, partition walls and outside walls.

The foundations of heavy buildings in Winnipeg are generally built on bed rock by means of caissons. Medium size buildings have, as their foundations, spread footings extending to the layers of chocolate or blue clay, or these buildings may be carried on wooden or reinforced concrete piles driven to refusal at semi hard-pan. Foundations of heavy and medium size buildings are thus normally carried to depths unaffected by shrinkage with its resulting heaving action. This is not true of ordinary residential construction. With house construction, the foundation is not required to be greater than 4 ft. 6 in. below grade level in order to conform with the Winnipeg Building Code. The depth of drying and cracking of the soil is much greater than this. Thus the majority of houses in Winnipeg are subjected to considerable differential movements in their foundations after extended dry periods.

These movements can be seen by examination of houses in practically any district of the City, irrespective of the location of the house with respect to heavy traffic. It is the exception rather than the rule to find a house in Winnipeg free from cracks. These cracks appear to have been caused by differential movements in the foundations.

COMPLAINTS FROM PROPERTY OWNERS

Complaints were made to the Winnipeg Electric Company and to the City Engineer regarding the damage caused to property by the vibrations produced by trolley buses and also, to a minor degree, by gasoline buses. These complaints were fairly widespread throughout the City along the various trolley bus routes. The highest concentration of complaints came from one particular area and from property owners adjacent to one particular road. This road is a main trolley bus route. From a discussion with the complainants the following points emerged:

1. Before the introduction of trolley buses, street cars ran down the center strip of the

[1] From a report presented to the Executive Committee of the Winnipeg Branch of the Engineering Institute of Canada by the Committee on Foundations in August 1937.

road. This center strip is approximately 21 ft. wide. The construction and maintenance of the center strip was the responsibility of the Winnipeg Electric Company while the street cars were in operation. To accommodate the ties and rails and provide a suitable base, a total thickness of approximately 24 in. was provided in the center strip. Between this strip and the curbs on each side, the City of Winnipeg had provided a road approximately 10 in. thick. When the street cars stopped operating, the rails were removed and the complete width of carriage-way resurfaced with asphalt. A cross section of the roadway is shown in Figure 1, the 24-in. thickness being made up of 1-in. asphalt finish, 3-in. asphalt binder and a 20-in. concrete base, while the 10-in. thickness is made up of a similar asphalt finish and binder and a 6-in. concrete base.

2. No undue earth-borne vibrations resulted from the street cars while they were in operation though considerable nuisance resulted from air-borne vibrations or noise caused by these vehicles.

3. Since the introduction of the trolley buses, considerable vibration had been apparent in the property adjacent to the road. It was claimed by the majority of the complainants that their property was being damaged by these vibrations. Cracking and falling of plaster was reported in a number of cases. Cracking and fracture of basement walls and floors was reported in other cases. Damage to stucco facings was also the basis of some complaints. Some complainants stated that pictures on their walls moved, that crockery vibrated, and that the beds shook. Vibrations were worse upstairs than downstairs.

4. Various reasons and conditions were put forward by the complainants as being responsible for the vibrations. These are listed as follows:

a. The thickness of carriageway (10 in.) between the old street car tracks and the curb was stated as being inadequate. Little or no vibrations were felt when the trolley buses ran on the center strip, while considerable vibrations were experienced in the outer strips of lesser thickness. It was suggested that these outer strips should be increased in thickness to make them more in accord with the road thickness existing in the center strip and so reduce the vibrations.

b. Vibrations were more noticeable in winter when there were lumps of ice on the road surface. This problem is accentuated by the steam pipes from the district supply system. These pipes, in winter, impart heat to the road surface, melt snow, and produce irregularities in the road surface. Vehicles running over these irregularities produce considerable vibration.

c. Complainants were contradictory in their evidence as to whether the vibrations were greater when the buses were accelerating or decelerating.

d. All were agreed that increase in speed brought increased vibrations. Excessive speeds were very noticeable early in the morning and late at night.

e. Some relief from vibrations was provided when lighter vehicles were used.

INSPECTION OF DAMAGE TO PROPERTY

As the result of the discussion with the complainants a number of houses in that area from which complaints had been received were visited and inspected. These houses visited are situated directly on the road or closely adjacent to it.

Practically all of these houses inspected showed signs of cracking in either the basement floors, partition walls, basement walls or outside walls. A number of the owners stated that these cracks existed in their houses before the trolley buses were introduced. Others stated that the cracks appeared after the introduction of the trolley buses. In some new houses that had been built since the trolley buses started operating, cracks had appeared and were attributed to the vibrations caused by the trolley buses.

In one house which the owner had occupied for about one year, slight plaster cracks were attributed to vibrations. Inspection of the house showed fairly extensive cracking in the basement walls which had been repaired by the previous owner before the trolley buses were operating.

Houses in the same area, well removed from heavy traffic such as trolley buses, showed similar signs of cracking, sometimes much worse than those houses closer to the bus route.

As a result of the inspection, the following conclusions were reached

1 The vibrations, apart from any structural

damage they may cause, may constitute a definite nuisance, depending on the susceptibility of the occupier to vibrations.

2. Most houses inspected showed cracking. Contradictory opinions were expressed by property owners as to the cause of these cracks. While it is almost impossible by visual inspection to categorically state that the cracks are due to vibrations or heaving of the foundations, the cracks were characteristic of those produced in a building by the heave of the foundations.

FACTORS AFFECTING VIBRATIONS

In view of the conflicting opinions expressed as to the factors which produced the most severe vibrations a test program was evolved which as far as possible would measure the relative effect of each of these factors. A solution of this nature was desirable as the responsibility for the severity of the vibrations had been placed at various times on both the Winnipeg Electric Authority, who operate the vehicles and are responsible for the thicker center strip of roadway, and the Winnipeg Town Council, who construct and maintain the thinner outer strips of the roadway.

The various factors possibly affecting the vibrations may be listed as follows:

1. Weight of the vehicle,
2. Speed of the vehicle,
3. Braking and acceleration characteristics of the vehicle,
4. Condition of the road surface, that is, whether bumpy or smooth,
5. Thickness of the road bed,
6. Distance of vehicle from structure where vibrations are experienced,
7. Nature of the soil underlying the roadway.

The Winnipeg Electric Company kindly gave the use of two vehicles with which to conduct the tests. The first was a Trolley Bus No. 1682, of the type regularly in use. Complaints have been made of the vibrations caused by this vehicle. This trolley bus, of unloaded weight, 18,510 lb. was loaded with sand bags to bring it up to a total vehicle and passenger load of 25,000 lb. The second vehicle was a Gasoline Bus No. 717, of a type used in other transport routes operated by Company. The test weight of this vehicle was approximately 15,000 lb. The operation of these two vehicles at controlled speeds and under conditions of free running, braking and acceleration, enabled control to be exercised over the first three factors mentioned above.

It had been stated that vibrations were worst in winter when irregularities were formed on the road surface by ice. When the first set of observations were taken in July 1949 there were few bumps or pot holes in the road. Thus there were few opportunities of recording the vibrations from vehicles hitting bumps. To simulate the shocks to which the vehicles are subject in winter, a number of ramps were constructed. These ramps $1\frac{1}{8}$ in., $2\frac{1}{16}$ in., and $3\frac{1}{16}$ in., high were 12 in. long in the direction of motion of the vehicle and sloped at their back end to give little shock effect when the vehicles hit them. Their use helped control the fourth factor. One of these ramps can be seen in position in figure 2.

As mentioned previously the road is approximately 24 in. thick in the center strip, and approximately 10 in. thick in the outer strips. Running the vehicles on these various strips gave control over factor 5.

The distance of the vehicles causing vibrations from the observation points varied from 9 to 61.5 ft. Comparison of the vibrations produced over this range of distance gave control over factor 6.

A second set of observations with the same ramps, range of speeds, etc., was taken during February 1950 when the ground underlying the roadway was frozen. This afforded an opportunity of comparing the vibrations produced through soil in a frozen and unfrozen state and gave some control over factor 7. The tire pressure of the vehicles was kept constant at the normal operational value throughout the tests.

OBSERVATION POINTS

One of the house owners on the road kindly permitted the use of his house as an observation station. The house was ideally located for the purpose. It was of normal timber frame construction. The main observation station was downstairs on the floor of the room facing out to the road. A second observation point upstairs was established almost directly above the downstairs observation point. The majority of the observations were taken from these two points but a small number of observations were taken with the seismograph located on the road, the footpath and the grass verge between the footpath and the house. These observation points are shown in Figure 1.

The house is shown in Figure 2.

The seismograph was located accurately on the appropriate observation point each time it was used.

309 records. The road surface was cleared of snow for the February 1950 tests.

In each set the following tests were carried out:

Using the Trolley Bus 1682:

1. In each of the four strips, on the normal road surface and with each of the ramps in position in turn, two complete sets of tests were run over a range of speeds from 10 to 40 mph. at 6-mph. intervals. The observation point was downstairs.

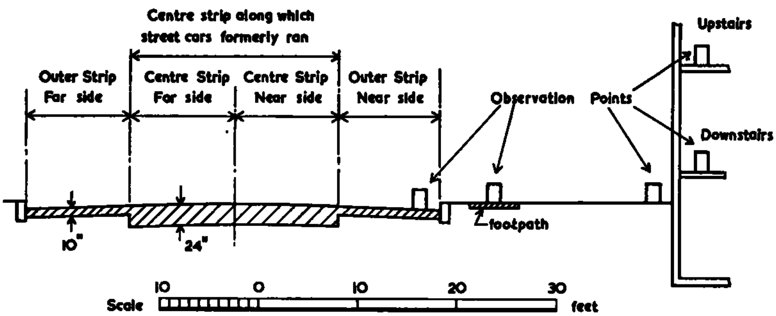

Figure 1. Cross Section of Roadway Showing Vehicle Running Tracks and Observation Points

Figure 2. House in Which Two Observation Points were Located.—Ramp can be seen in position.

TEST PROCEDURE

For purposes of testing, the road was divided into four strips as shown in Figure 1. The strips were described as; Outer strip, near side; Centre strip, near side; Centre strip, far side and Outer strip, far side.

Two separate sets of tests were carried out. The first set, in July 1949 consisted of 232 records. The second set, taken in February 1950 when the subsoil was frozen, consisted of

2. In the outer strip, near side alone, a set of readings similar to (1) above were taken to test the braking and acceleration characteristics of the vehicle. The observation point was downstairs.

Using the Gasoline Bus 717:

3. In the outer strip, near side, a set of readings similar to (1) above were taken, the observation point being downstairs.

During July 1949, records were taken of the vibrations produced, both upstairs and downstairs, by a person jumping on the floor.

During February 1950, records were taken with the seismograph set up on the roadway, on the concrete footpath, and on the grass between the footpath and the house, while the trolley bus was passing at different speeds over various ramps placed on the outer strip, near side.

RECORDING APPARATUS

The instrument used for measuring the vibrations was the Leet Seismograph (*1*).[2] This seismograph was designed and constructed primarily for the registration of vibrations from traffic, dynamic blasts, machinery, and general industrial sources. For vibrations of a frequency of 3 cycles per second or more, it gives a record directly proportional to displacement. The instrument records the longitudinal, vertical and transverse components of vibrations. These records have a magnification factor of 50 and with this factor full registration is given over a range from about .0002 in. to about .018 in.

The instrument is essentially a mechanical-optical system magnetically damped. The inertia elements are suspended by flat springs and have an undamped period of 1 second. These inertia elements have mirrors attached to them. Beams of light are focussed on these mirrors and in turn are directed to a moving roll of recording film. The movements of the mirrors, due to the vibrations, produce corresponding movements of the light beams on the film, and a record of the three components of vibration is obtained when the film is developed. A timing motor, working with a light beam and a perforated disc, places on the record 100 lines per second with every tenth line slightly wider than the others to facilitate counting. Tracings of the records obtained are shown in Figure 3, the 0.01-sec. timing lines being omitted.

[2] Italicized figures in parentheses refer to the references listed at the end of the paper.

TEST RESULTS

For all observations other than those measured at the upstairs observation point the amplitude of the vertical component is greatest, the longitudinal next and the transverse least. The amplitude is the displacement from the mid position. Record No. 1 on Figure 3 is a typical record measured downstairs and shows the relationship between the components of vibration. Accordingly, since the vertical compent of vibration is greatest and the frequency of transmission of the vibrations

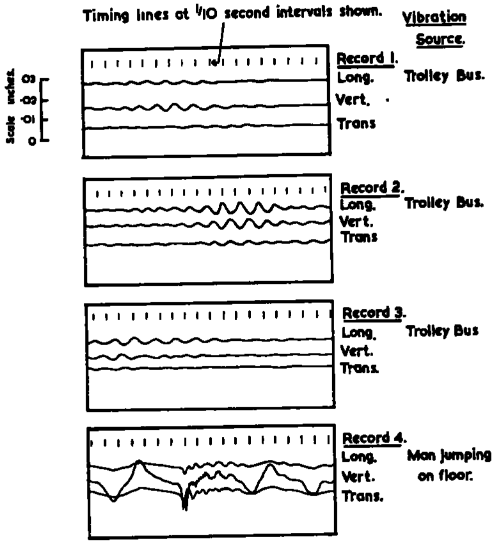

Figure 3. Typical Records from Leet Seismograph

is approximately the same for all components, this component has been used as the basis of comparison between all tests where observations were made downstairs.

When the upstairs observation point was used, the vertical and transverse components were approximately the same as those obtained from identical tests observed downstairs. The longitudinal component however had increased to become the strongest component. Record No. 2 on Figure 3 is a typical record measured upstairs. This increase in longitudinal component upstairs is probably due to lack of lateral stiffening in the frame of the building and accounts for the complaints that vibrations are more severe upstairs than downstairs.

From the records which were taken, a series of graphs were prepared for the various test conditions. From these graphs a few typical ones of which are reproduced in this paper, the following comments can be made regarding the various factors likely to affect the vibrations.

Effect of Weight of Vehicles—In Figure 4 is shown a comparison between the amplitude of the vertical components of vibrations resulting from the Trolley Bus 1682, weighing approximately 25,000 lb. and the Gasoline Bus 717, weighing approximately 15,000 lb.

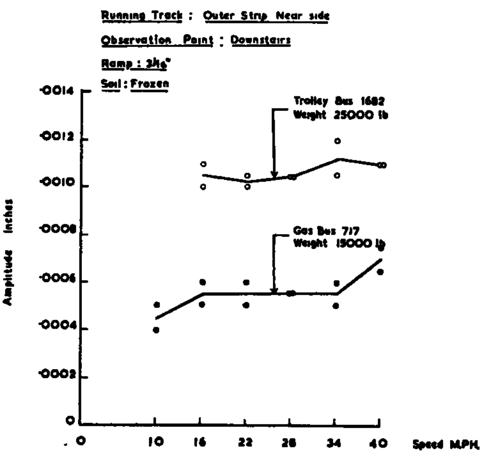

Figure 4. Comparison of Vertical Components of Vibrations from Vehicles of Different Weight

With no ramp on the roadway the amplitudes measured are approximately the same for each vehicle. When ramps are introduced differences in the amplitude become apparent and these differences become more pronounced as the ramps increase in size. With a $3\frac{1}{16}$-in. ramp the amplitudes from the Gasoline Bus are approximately one-half those obtained from the Trolley Bus.

Thus the heavier the vehicle the greater the amplitudes of the resulting vibrations.

Effect of Speed of Vehicles—Considering the amplitudes of the vertical components of the vibrations produced by running the vehicles at different speeds over the same ramp, there generally appears to be a slight increase in amplitude with speed. This is probably due to the fact that with increased speed the vehicle will rise higher off the ramp as it leaves it. There will thus be a slightly higher drop, a greater transmission of energy to the ground and an increased amplitude of vibration.

The effect of speed upon amplitude can be seen in Figures 4, 5, 6, 7, 9, and 10.

Effect of Braking and Acceleration—In the braking tests that were carried out with the Trolley Bus, the procedure was to approach the ramp at a controlled speed and then apply the total braking capacity of the vehicle when the rear wheels were just hitting the

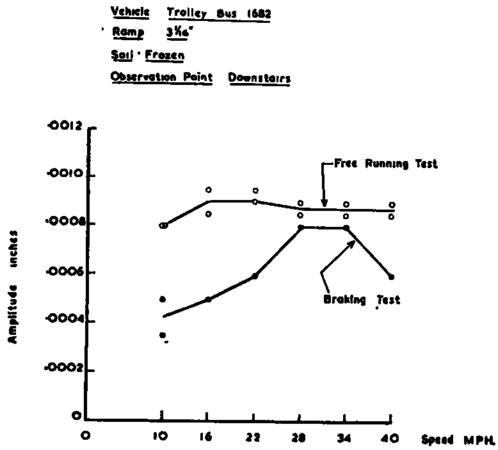

Figure 5. Comparison of Vertical Components of Vibrations from Free Running and Braking Tests

ramp. By applying the total braking the Trolley Bus could be stopped from 40 mph. in a distance of 109 ft. at a deceleration of 10.8 mph. per sec. which is a much more severe condition than encountered in the normal operation of the bus. The braking tests were carried out in July 1949 with the $3\frac{1}{16}$-in. ramp and also in February 1950 with the $3\frac{1}{16}$-in. and $2\frac{1}{16}$-in. ramps, the vehicle running track being the outer strip, near side. The observation point was downstairs.

As can be seen from a typical plot in Figure 5, the vibrations produced due to braking are not as severe as those encountered for free running at the same initial speed.

Acceleration tests were conducted by approaching the $3\frac{1}{16}$-in. ramp at a uniform speed and accelerating fully at 3.5 mph. per sec. as the ramp was reached. The vibrations resulting from this condition were very similar to those resulting from the free running condition.

Thus, compared with the vibrations resulting from the Trolley Bus running freely over a ramp, the vibrations from severe braking tests were much less, and the vibrations from acceleration tests were much the same for the same initial vehicle speed.

Effect of Condition of the Road Surface—Ramps were introduced on the roadway to simulate the irregularities which occur in the road surface, particularly in winter time. The ramps were held in position by sand bags placed at either end and if necessary, sand packing was put under the ramps to give them uniform bearing on the road surface.

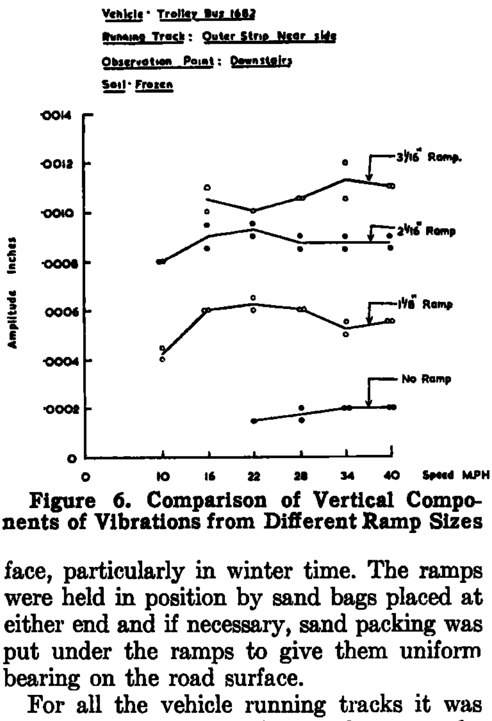

Figure 6. Comparison of Vertical Components of Vibrations from Different Ramp Sizes

For all the vehicle running tracks it was clearly shown that the higher the ramp the greater the vibrations. Figure 6 is a typical graph showing the effect of ramp size on the vertical components of the vibrations.

Effect of Thickness of Road Bed—The center strip of the road has a total thickness of approximately 24 in. while the outer strips have a total thickness of approximately 10 in. Figure 7 shows the vertical components of the vibrations produced by the Trolley Bus running in the various strips over one particular ramp. Similar results were obtained from the other ramps, the observation point being downstairs. Generally the vibrations produced in the outer strip, near side, that is the strip closest to the observation point are worst.

The vibrations from the outer strip, far side, which is also approximately 10 in. thick are generally almost equal to the vibrations from the two inner thicker lanes. This is despite the fact that these lanes are nearer the observation point.

The conclusion can be drawn that slightly less vibrations result from a greater thickness of road bed.

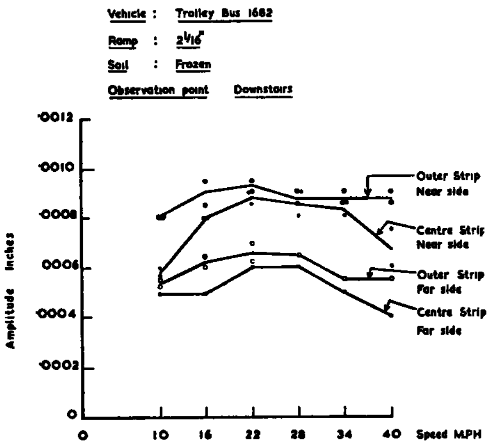

Figure 7. Comparison of Vertical Components of Vibrations from the Same Ramp in Different Vehicle Running Tracks

Effect of Distance of Vehicle from Observation Point—The center lines of the vehicle running tracks were 31, 41.5, 51 and 61.5 ft. from the downstairs observation point. Other observation points (in the positions shown in Fig. 1) were 9, 11 and 27 ft. from the center line of the vehicle which was the vibration source. Graphs of amplitude of vertical components of vibration against distance can be drawn for different ramps and vehicle speeds. One such typical graph is shown in Figure 8 and is for the Trolley Bus running over the $2\frac{1}{16}$-in. ramp at 34 mph. during the winter tests.

It can be seen that vibrations decreased in intensity as the distance of the vibration source from the observation point increased.

Effect of Nature of Soil Underlying the Roadway—Complaints had been received that the vibrations were greater in winter than in summer. This was attributed primarily to the lumps of ice which were formed on the roadway during winter, but it was also thought that the soil underlying the roadway when frozen might transmit the vibrations at a different frequency than when unfrozen. From the two sets of observations a comparison of the vibrations resulting from identical tests on frozen and unfrozen soil could be made.

The average air temperature when the February 1950 tests were made was −5 deg. F. and a trial pit dug showed the ground to be frozen to a depth of 3 ft. below the road surface despite the close proximity of a steam main from a district heating supply. At other locations away from the steam main the ground was frozen to a depth of 4.5 ft.

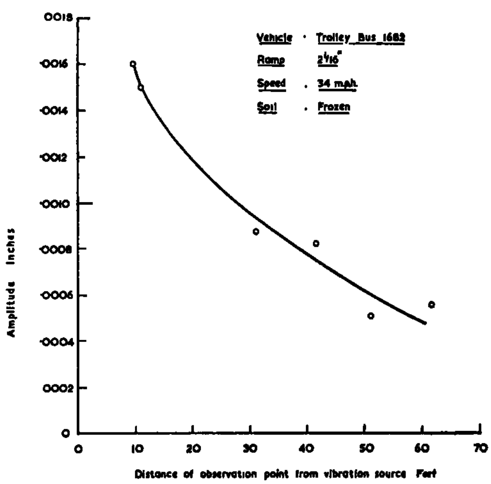

Figure 8. Variation of Vertical Component of Vibration with Distance of Observation Point from Center Line of Vehicle Causing Vibrations

Figure 9 shows a comparison of the amplitudes of the vertical components of vibration from the frozen and unfrozen tests. It can be seen that the amplitudes of the vibrations in winter with the soil frozen were much less than those obtained in identical tests carried out in the summer. This was true of all the tests carried out. There was a slight difference in the frequencies of the vibrations, the average for the vertical components of the vibrations produced in the summer being 7.3 cps. and the average frequency of the winter vibrations was 7.7 cps. This change of frequency with change of amplitude will be discussed later.

The decrease of amplitude in frozen soil was unexpected. As a result of this finding the Road Research Laboratory of the Department of Scientific and Industrial Research of Great Britain carried out vibration tests on saturated silty clay soil specimens before and after freezing. The resonance curves produced were not well defined in either case but the main indications were that damping was higher in the frozen specimens. If similar conditions prevail in the soil in situ in Winnipeg such an increase in damping would be in qualitative agreement with the records obtained in Winnipeg.

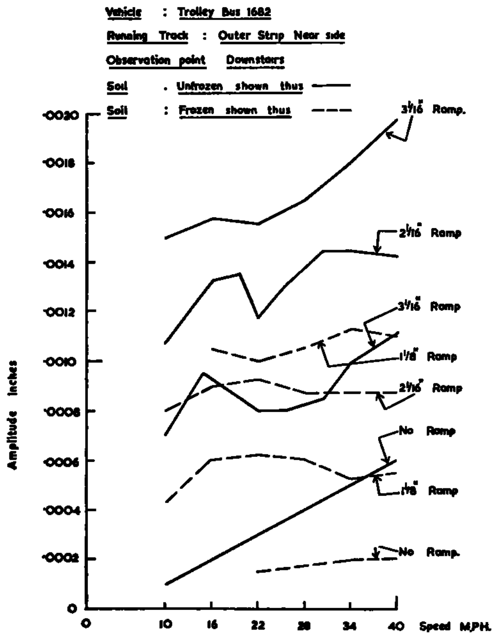

Figure 9. Comparison of Vertical Components of Vibrations from Identical Tests on Frozen and Unfrozen Soil

It can, therefore, be concluded that for a change of condition of the soil underlying the road surface from the unfrozen to the frozen state a decrease in the amplitude of vibrations occurs with an unchanged intensity of vibration source.

RELATIVE EFFECT OF THE VARIOUS FACTORS AFFECTING VIBRATIONS

The various factors affecting vibrations have been considered separately in the preceding notes. The comparative effect of these factors can be determined from a plot of the envelopes of influence of the various ramps as shown in Figure 10. In this diagram envelopes have been drawn around all the plots of vertical components of vibrations due to different speeds, different running tracks, different thicknesses of roadway and varying distances of the vehicles from the observation point.

From these envelopes it can be seen clearly that the most important factor affecting the vibrations produced by the Trolley Bus is irregularity of road surface (as simulated by the different ramps on the road surface). This irregularity of road surface has, within the range of tests conducted, a greater effect than any of the other factors concerned except the condition produced by the frozen soil.

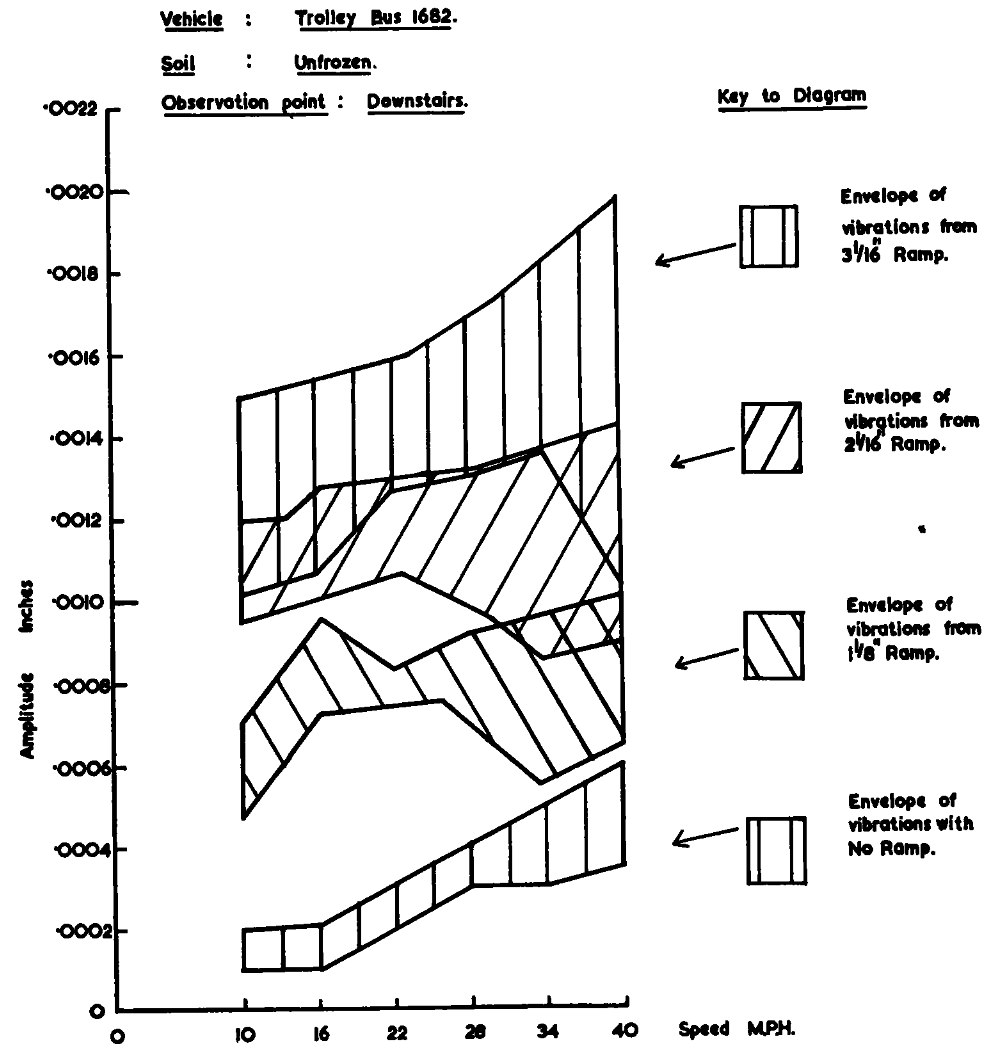

Figure 10. The Envelopes of Influence of the Various Ramps.—Each envelope encloses for any one ramp, the complete range of vertical components of vibrations due to different speeds, running tracks and thicknesses of roadway.

Figure 10 is an envelope of the test results obtained in July 1949. A similar diagram was obtained from the February 1950 results and from it the same conclusions can be drawn.

SENSITIVITY OF HUMANS TO VIBRATIONS

In 1931, at the Technical University of Stuttgart, Germany, H. Reiher and F. J. Meister (*2*) conducted an extensive research on the sensitivity and response of humans to vibrations. In this investigation, a number of people were subjected to vibrations of various ranges of amplitude and frequency and their reactions recorded. A number of graphs were plotted showing the reactions and sensitivity of these people to vibrations for different positions of their bodies. Figure 11 is a reproduction of one of these graphs. It deals with the reaction of people, when standing, to the

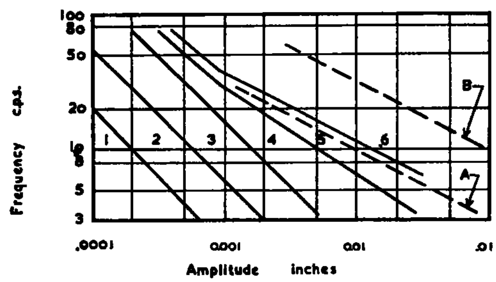

Figure 11. Combined Diagram from Reiher and Meister and U. S. Bureau of Mines Showing Zones of Response of Humans to Vibrations and Limits of Damage Due to Vibrations

Zone	Response
1	Not Perceptible
2	Slightly Perceptible
3	Distinctly Perceptible
4	Strongly Perceptible
5	Disturbing (may have detrimental effects, such as severe headaches, if of long duration)
6	Very Disturbing (may have detrimental effects if of short duration)

vertical components of vibrations. The authors, in their other graphs, show the reactions of humans to vertical components, (a) when lying down parallel to, and (b) lying down at right angles to the direction of the vibrations. When the subjects were standing, they were much more sensitive to vertical than horizontal vibrations. When lying down, the vertical vibrations were not as noticeable as the horizontal. Horizontal vibrations caused most disturbance when the subject was lying at right angles to the direction of the vibrations.

Some of the subjects were much more susceptible than others. One woman had violent reactions when other people did not suffer appreciably.

The investigations of Reiher and Meister and others in this field are based on sustained vibrations. Their results can be a useful guide with transient conditions, such as traffic vibrations, over the lower range of classifications namely, "slightly", "distinctly", and "strongly" perceptible. It is doubtful, however, if the results from sustained vibrations apply to transient conditions over the higher range of classifications (zones 5 and 6 in Fig. 11). Considering the vibrations produced in the Winnipeg tests the most severe vibrations fall into zone 4 (Fig. 11) that is "strongly perceptible". Under normal running conditions of the Trolley Buses no vibrations as severe as these would be experienced.

DAMAGE TO STRUCTURES FROM VIBRATIONS FROM HEAVY VEHICLES

The question arises as to whether the vibrations produced by heavy vehicles in Winnipeg in general and the trolley buses in particular are detrimental to structures.

A decision can be made from the vibrations observed, the researches of Reiher and Meister, and the investigations carried out by the U. S. Bureau of Mines. The U. S. Bureau of Mines (*3*) have published a Report entitled "Seismic Effects of Quarry Blasting". In this publication zones of damage due to vibrations, in terms of amplitude and frequency, are determined. These zones are defined by lines A and B which have been superimposed on Reiher and Meister's graph on Figure 11. Line A, which represents an acceleration of one-tenth that of gravity, indicates a caution stage, that is, beyond this line slight damage may occur. Between lines A and B there is likely to be some plaster damage due to vibrations. Beyond line B, which represents an acceleration of g, that of gravity, some structural damage will result. Acceleration cannot always be taken as a basis for comparison of damage likely to be caused by vibrations, since energy transmitted should be the sole criterion of judgement. However, for specific conditions, e.g. earthquakes, or for similar types of structures, standards of intensity, based on acceleration alone, can and have been set up.

Lines A and B from Bureau of Mines Bulletin 442 can therefore be adopted in this paper as a guide to damage from vibrations since they were determined for similar types of buildings to those with which this paper is concerned.

From Figure 11, it can be seen that people are aware of vibrations long before there is any possibility of damage to the structure. Vibrations which would cause extreme discomfort to a person would barely cause plaster damage to a structure.

The vibrations produced during the tests in Winnipeg were more severe than any likely to be encountered in the normal operation of the vehicles under any conditions, during any season of the year. No vehicle would withstand the regular jars and jolts produced when driving at high speed over the ramps, and could not be economically operated under such conditions. Even so, the worst effect produced in the tests, 0.003 in. at 8.2 cps., is a vibration "strongly perceptible" to humans but not damaging to structures.

Therefore, it can be concluded that the vibrations from heavy vehicles in Winnipeg do not produce harmful effects on the structures.

JUMPING ON FLOORS

At one house where complaints had been received of severe vibrations, a comparison was made of the vibrations produced by the trolley bus running at 40 mph. over the $3\frac{1}{16}$-in. ramp and by a person jumping on the floor of the room where the observations were being taken. The vehicle running track was approximately 90 ft. from the observation point which was upstairs in the house and above the garage. A comparison of the two records can be seen in Records 3 and 4 on Figure 3. As with the records taken upstairs in the main observation house and commented upon previously the longitudinal component of vibration is greater than the vertical component probably due to lack of lateral stiffening in the house.

The amplitude of all the components of vibration produced by a man jumping continuously on the floor can be seen from Record 4 on Figure 3 to exceed those produced by the trolley bus. The man was jumping at intervals of approximately 0.6 sec. Superimposed on the resulting impressed frequency are frequencied of approximately 50 cps. which appear to be the natural frequency of the floor system. The amplitudes of the vertical components produced by jumping are about four times the vertical components produced by the worst test running conditions of the trolley bus. Although the energy transmitted from the trolley bus is much greater than that from a man jumping, there is the possibility that the displacement produced in the latter case would be more liable to cause plaster damage to the ceilings below than would the vibrations from the trolley bus.

THE FREQUENCIES OF TRANSMISSION OF THE VIBRATIONS

A trial pit opened under the road surface and in line with the observation points and the ramps showed a yellow clay at a depth of 2.5 ft. below the surface.

TABLE 1
FREQUENCY OF VIBRATIONS

Vehicle	Time	Components of Vibrations		
		Longitudinal	Vertical	Transverse
		cps.	*cps.*	*cps.*
Trolley Bus	Summer		7.3	
	Winter	7 6	7.7	7.1
Ga Bus	Summer		7.4	
	Winter	7.5	7.9	6 8

TABLE 2
TRANSMISSION FREQUENCIES IN VARIOUS SOILS

Soil	Frequency
	cps.
Waterlogged estuarine silt	10
Very light soft clay	12
Light waterlogged sand	15
Medium sand	15
Loose fill	19.1
Limestone	30

Average values of the frequencies of the various components of the vibrations have been obtained for both the winter and summer tests. These are shown in Table 1.

The transmission frequencies measured in Winnipeg are low compared with the values normally encountered in soils as can be seen from some typical values given in Table 2.

The low transmission frequency of the Winnipeg soil means that there will be a much higher transmission of energy through it than is usually experienced with soils.

This, to some extent, accounts for the complaints of vibrations from heavy traffic in Winnipeg.

Average values of the frequency of trans-

TABLE 3
FREQUENCY RELATED TO RAMP HEIGHT

Time	Vibration Component	Ramp			
		None	$1\frac{3}{8}$ in.	$2\frac{1}{16}$ in.	$3\frac{1}{16}$ in.
		cps.	*cps.*	*cps.*	*cps.*
Summer	Vertical	7.7	7.5	7.4	7.0
Winter	Longitudinal		8.0	7.8	7.1
	Vertical	8.2	8.0	7.6	7.4

This change of frequency of transmission with amplitude agrees with the results discussed by Crockett and Hammond (*4*) who comment on similar observations by Degebo (*5*). It is due to the non-linear character of the load deflection relationship for the soil and results in a non-symmetrical resonance peak for the soil as distinct from the resonant peak symmetrical about a vertical axis ob-

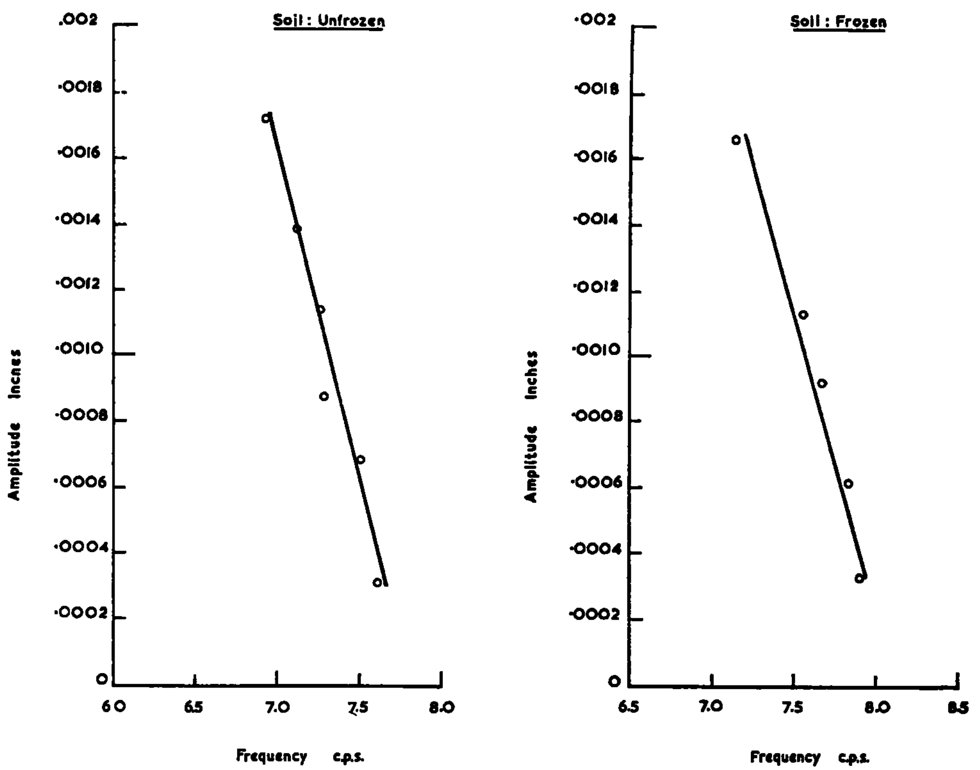

Figure 12. Variation of Frequency of Transmission of Vibrations with Variation in the Vertical Components of the Vibrations.

mission of the vibrations associated with each ramp are listed in Table 3.

As the ramp size increases, that is, as the amplitude of vibration increases, the frequency of transmission decreases. This observation led to plots being made of amplitude against frequency and these are shown for the frozen and unfrozen conditions in Figure 12. The points through which the sloping lines are drawn were obtained by taking the recorded amplitudes in ranges and finding the average frequency for each of these ranges.

tained for the linear condition. Crockett and Hammond state that the variation of transmission frequency is not more than 25 percent below the highest value obtained for small amplitude of movement. Degebo measured amplitude up to 0.06 cm., Crockett and Hammond measured amplitude up to 0.25 in. The maximum amplitude measured in the Winnipeg tests was 0.003 in. or 0.0076 cm.

GENERAL SURVEY OF THE INVESTIGATIONS

1. The frequency at which vibrations are transmitted through the Winnipeg soil is low

compared with other soils. This will result in more noticeable vibrations than would normally be encountered and had led to extensive complaints.

2. The subsoil in Winnipeg is one which is subject to high seasonal change of water content, to excessive shrinkage and subsequent expansion resulting in cracked basements, floors and walls in structures in which the foundations are not carried below the depth to which shrinkage occurs. This structural damage could be confused with damage resulting from vibrations from trolley buses and heavy vehicles. Human beings are extremely sensitive to vibrations. They are conscious of vibrations which are about one-hundredth of those which will cause only slight damage to structures. Vibrations which may have considerable nuisance value may be negligible from a structural damage point of view. The tests conducted produced more severe vibrations than will occur in the normal operation of the trolley buses. The worst vibrations produced in the tests are not sufficiently strong to cause any structural damage to buildings where these buildings are on a sound foundation. There is a possibility however that the vibrations might cause further damage where damage already existed due to other causes, such as heaving of the foundations.

3. The factor most influencing vibrations was the effect of irregularities on the road surface. For any one vehicle the ramps used in the roadway had a greater effect than all the other factors affecting vibration. Decrease in weight of vehicle produced decrease in vibrations.

4. Smaller vibrations were transmitted through frozen soil than through unfrozen soil possibly due to the greater damping properties of the latter.

5. The frequency of transmission of vibrations through frozen and unfrozen soil was approximately the same, but for both soil conditions, increase in amplitude produced decrease in frequency of transmission.

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