effect of construction equipment vibration on nearby buildings

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In recent years, large-scale construction work has been increasingly carried out in built-up metropolitan areas. This construction work has entailed blasting for tunnels, demolition of obsolete structures, and activity of heavy construction machinery. When this work is carried out in the vicinity of existing structures, the ground vibration produced becomes noticeable to the inhabitants of the adjacent buildings. The question is immediately raised as to the damaging effect of these vibrations to buildings.

The question of the effect of such construction activity on buildings in general and on homes in particular became a public matter in the metropolitan Toronto area when the reconstruction of Highway 401 was begun in 1963. The necessity for this reconstruction became urgent when the tremendous economic and population growth of metropolitan Toronto caused such increased traffic loads that congestion occurred on the highways. The functional report on the proposed reconstruction (January 1963) quoted a traffic volume at peak periods of 85,000 vehicles per day, whereas the practical capacity of the highway was 48,000 vehicles per day at 45- to 50-mph operating speed. The functional report recommended expanding the existing 4-lane facility to 10 to 14 lanes throughout the section between Islington Avenue and Highway 48 (Fig. 1). In the course of the 10 years that the highway had been opened, that entire section had become heavily residential, especially from Bathurst Street, west of Yonge Street, to Warden Avenue in the East.

The widening of the road brought heavy construction equipment into residential areas and an increasing anxiety in the minds of many homeowners that vibrations resulting from operation of the equipment was causing structural damage to their homes. That anxiety was not unexpected, for individuals can feel vibrations that are a hundredth of the level required to cause structural impairment. Consequently, homeowners quite naturally attributed previously unnoticed plaster and mortar cracks to the effects of construction activity.

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The questions then raised by those events were, What level of vibration is in fact detrimental to structures? What levels of vibration are caused by heavy construction equipment operated in the vicinity of structures? Earlier vibration studies in most of the literature have been primarily concerned with the effects of blasting.

In the beginning of 1964, the Department of Transportation and Communications (then the Department of Highways) sponsored vibration studies with a view to establishing the actual level of the vibration from construction equipment. This program ran until 1968 and was extended to include measurements of vibrations from blasting operations carried out during the excavation of storm sewers. Prior to 1964, the department had already sponsored a demonstration bridge demolition project in conjunction with the National Research Council and Ontario Research Foundation. That project resulted in a study to examine criteria previously used to establish a maximum safe level of vibration that would not cause structural damage to nearby buildings.

Knowledge of those criteria and a means of measuring the vibration have been important to contractors and consultants involved in litigation resulting from damage claims; an objective assessment can be made of the situation only if measurements of vibrations have been made and critical levels have been established. Consequently, the various criteria that have been used to evaluate damage will be summarized.

VIBRATION DAMAGE LEVEL CRITERIA

Establishing a value of ground vibration at which damage occurs to nearby structures is not entirely a simple matter because there are 3 distinct types of ground waves that are generated (Fig. 2): longitudinal or compression waves in which low frequencies predominate; vertical waves in which high frequencies predominate; and transverse or shear waves that begin with high frequencies and taper off to low frequencies. Furthermore, knowledge of which is the important vibration parameter—displacement, velocity, or acceleration—had to be determined.

The first major study to establish damage criteria for residential structures was carried out by the U. S. Bureau of Mines from 1935 to 1942 (2). A damage criterion was defined as the magnitude of one or more quantities associated with the vibration impinging on the structure and, if exceeded, would result in some degree of failure within the structure. The tests undertaken by the Bureau of Mines were of two types: quarry blasting and forced vibration of actual buildings with a mechanical vibrator.

One of the objectives of the latter test was to confirm or disprove a hypothesis that is frequently advanced with regard to building vibrations: A forcing vibration at or near the resonant frequency of a floor or wall panel can cause destructive vibrations to build up, even though the level of the external vibration was not destructive in itself. The tests carried out with the mechanical vibrator were especially suited to determine that point by bringing the vibrator up to maximum speed and then cutting off the motor and allowing it to coast down to rest while signals were recorded from vibration pickups located on various panels in the structure.

The data from those tests were divided into 3 classifications, which are still used: major damage (fall of plaster, serious cracking), minor damage (fine plaster cracks, opening of old cracks), and no damage. Results of the tests are discussed in detail in another report (1). The authors of the Bureau of Mines report concluded that damage occurred if the level of vibration exceeded 1 g. Later studies (2) indicated, however, that this was rather an arbitrary figure.

Following the pioneering work of the Bureau of Mines, the next major contribution was a paper by Crandell (4), who was directly concerned, at that time, in establishing blasting limits that would enable contractors to determine a safe charge of explosives used in excavation work so that no damage was caused to adjacent structures. Crandell notes that, because a contractor may be confronted with the damaging effects on as many as 1,000 buildings during the course of a long tunnel excavation, it is not practical to measure the vibration within each structure itself, as was done by the Bureau of Mines. In that situation, the intensity of the ground vibration would be much more useful as an indicator of structural damage.

The theoretical details of Crandell's work are discussed in an earlier report (1). Crandell developed an empirical formula that gave the amount of ground energy produced by a charge of dynamite in terms of a measure of vibration level called energy ratio (ER), given by the square of the maximum acceleration divided by the square of the minimum frequency, as determined from seismograph records (units of ER are in ft^2).

Crandell's energy ratio is still widely used by the construction industry for determining upper limits for vibration from all types of construction activity. Crandell found that damage can occur to prestressed structures when an ER of 3 is reached: hence, the practice is to limit the ER to 1.

A major difficulty in establishing the energy ratio is in determining the frequency because, as Figure 2 shows, the ground wave frequency varies with time. Also, because the maximum acceleration occurs at a different time from the minimum frequency, ER is not useful in determining gradations of damage.

The most recent definite work in establishing damage criteria was that covered in two studies by Edwards and Northwood (5, 6). The first was performed in 1958 during the demolition of a number of houses in connection with the forming of a head pond for the St. Lawrence power project. Controlled blasting was carried out in increasing charge weights to determine the threshold at which damage occurred. The aim of the investigators was to find a reasonably simple vibration measurement that would provide a dependable indication of damage risk.

In that study, measurements were made of displacement, velocity, and acceleration for increasing weight of charges until the threshold points of minor and major damage were established. The conclusions reached were that there was a well-defined threshold level of vibration above which damage could occur and that peak particle velocity gave the best indication of that threshold, which occurs between 4 and 5 in./sec. The authors recommended that a safe limit of 2 in./sec peak velocity be established and that the charge equation $C^{2/3}/D = 0.1$, where C = explosive charge in lb and D = distance in ft, be used for normal blasting operations.

The most recent work has established 2 in./sec as the maximum vibration level to be permitted during blasting so that no damage should occur to nearby buildings. There is a possibility, however, that continuous vibration such as that from construction equipment has a lower damage threshold; some results from the continuous vibrator tests in the U. S. Bureau of Mines report also point to that effect. The tests sponsored by the department were designed to establish the velocity level of vibration from different types of construction equipment and to determine how the vibration varies with distance. These data can be used to made quick estimates of the effect of operating equipment at any particular locality.

Figure 3 shows the layout of the test site, a partially completed interchange at Highway 401 and Victoria Park Avenue (Fig. 1). Velocity pickups were mounted in pairs on aluminum blocks (nonmagnetic), which were located at specific distances apart and oriented to pick up vertical and longitudinal vibrations (the transverse or shear wave has been found to be usually less than those two).

Various types of equipment (Fig. 4) were run on a test path perpendicular to the line of pickups, and oscillograph recordings were made of the resulting vibrations. The data curves from those tests are shown in Figures 5 to 33. The equipment was also run at various distances from a field house, and vibration levels were measured at different locations in the house. Reference to those data curves and records enables the prediction of approximate vibration levels for almost any situation. The tabulated house vibration levels and the method of using the data are given in another report (1).

Throughout the tests, no vibrations resulting from construction activity were measured that approximated in any way the recommended maximum safe level of 2 in./sec peak particle velocity. The most severe levels encountered were produced by the vibrating compactor operated beside the field-house wall, where a peak velocity of 0.63 in./sec at 22 Hz (the vibrating frequency) was measured. Although the vibration level was only a little more than a fourth of the safe level of 2 in./sec, it was felt by the personnel conducting the investigation to be extremely unpleasant. Vibration levels

Figure 1. Reconstruction area of Highway 401.

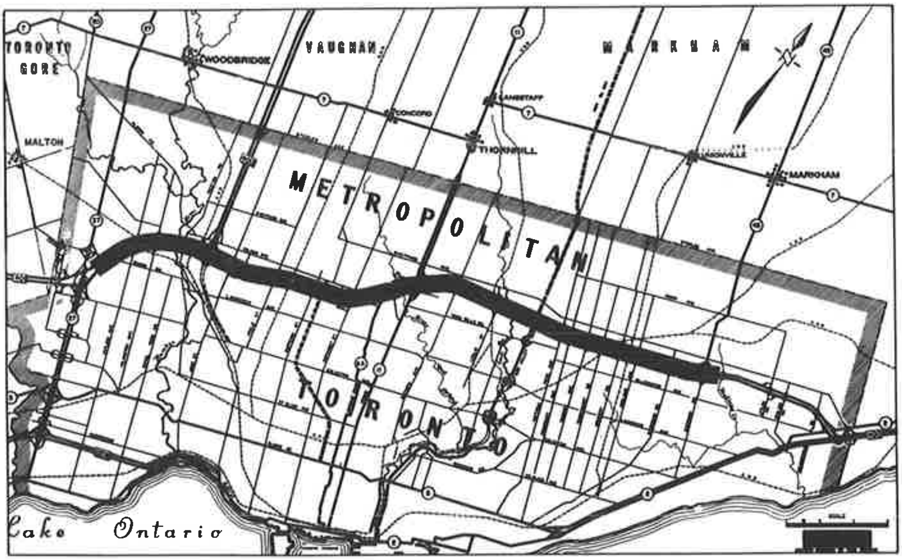


Figure 3. Field house and test area.

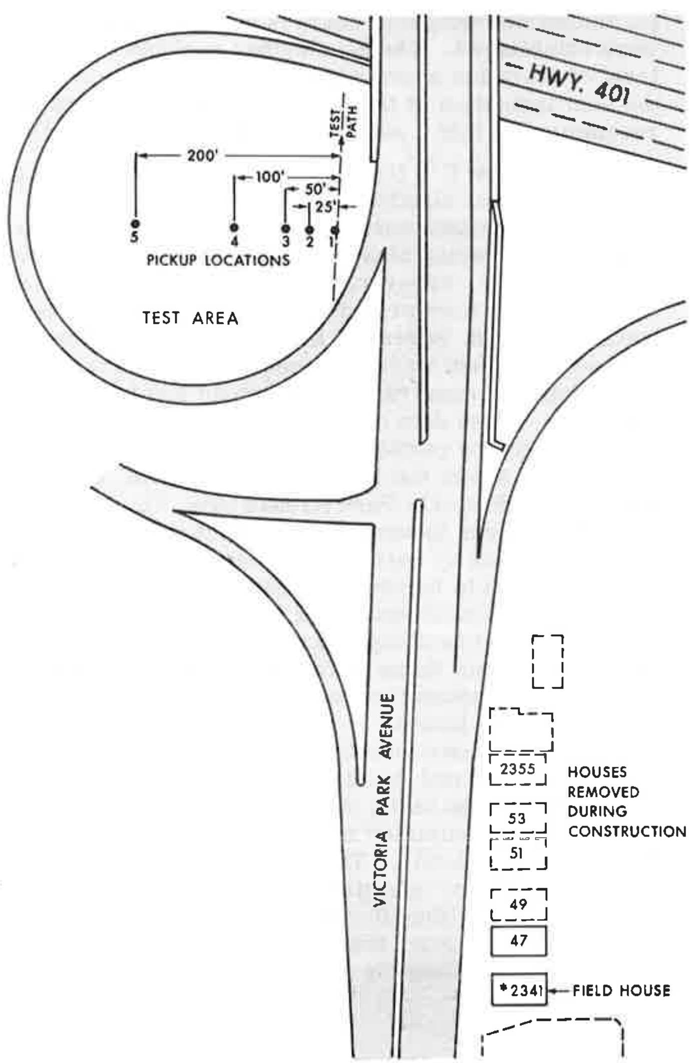


Figure 2. Ground waves resulting from vibrations and recorded simultaneously by seismograph.

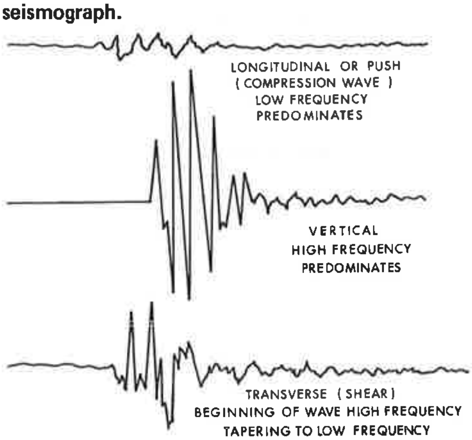


Figure 4. Construction vehicles used in vibration tests.

D8H Tractor (62,000 lb., G.W., 270 HP)

C6 Tractor (50,000 lb., G.W., 225 HP)

LW777 Grader (35,000 lb., 160 HP)

D4 Tractor and CF43 Vib., Sheepsfoot Compacto
(Tractor 18,000 lb., G.W., 65 HP)
(Compactor 12,000 lb., 1,400 to 1,600 vpm)

TS24 Earth Mover (91,000 lb., G.W., unloaded, 171,000 lb., loaded)
(Front engine 398 HP., rear engine 207 HP.)

Figure 5. Vertical vibrations of D8H tractor passing—test 1.

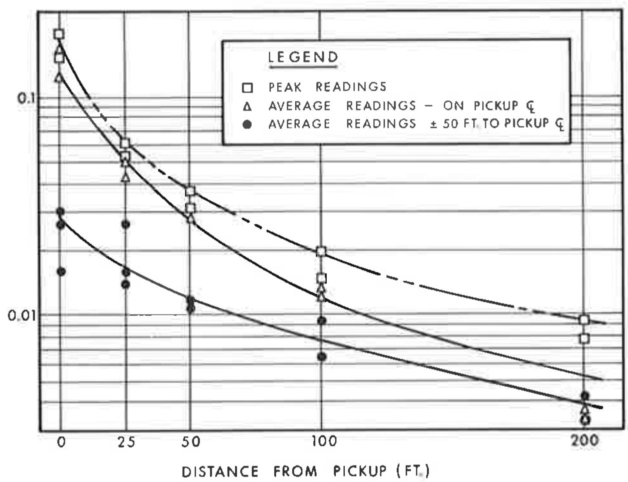


Figure 6. Longitudinal vibrations of D8H tractor passing—test 1.

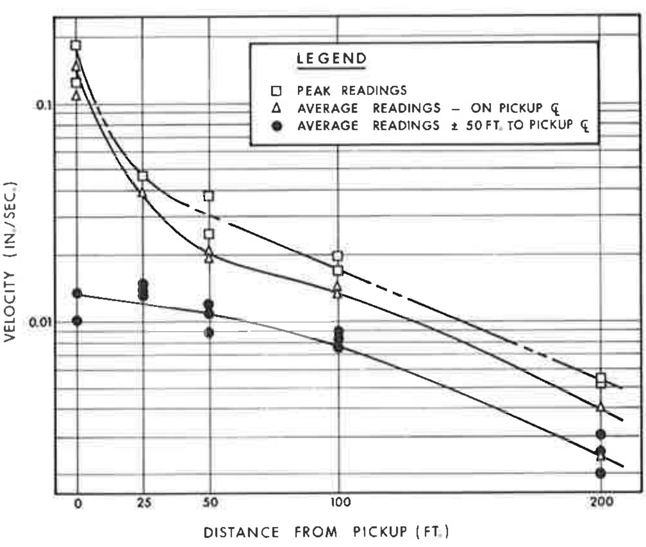


Figure 7. Vertical vibrations of TS24 earthmover slowly passing—test 2.

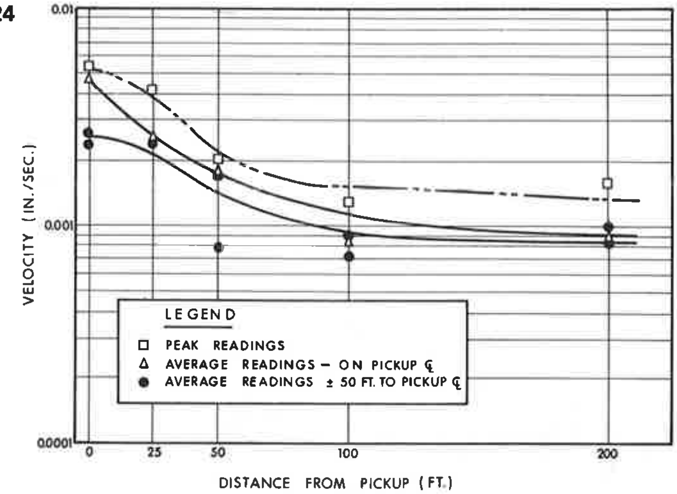


Figure 8. Longitudinal vibrations of TS24 earthmover slowly passing—test 2.

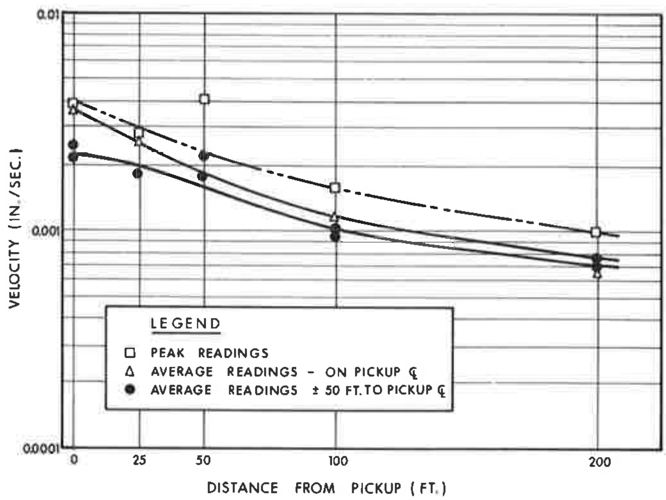


Figure 9. Vertical vibrations of TS24 earthmover rapidly passing—test 3.

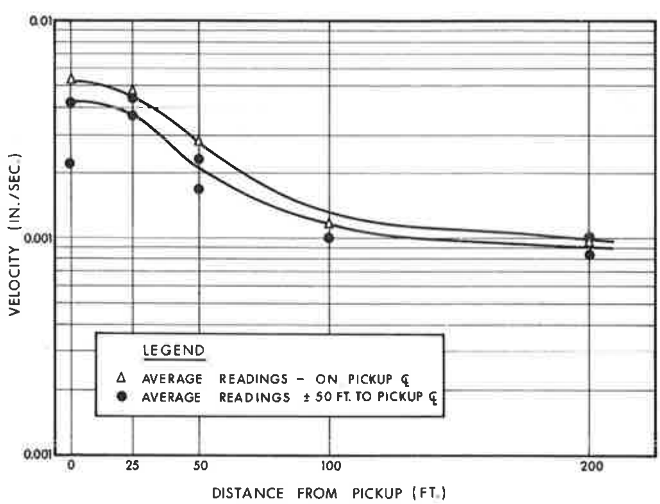


Figure 10. Longitudinal vibrations of TS24 earthmover rapidly passing—test 3.

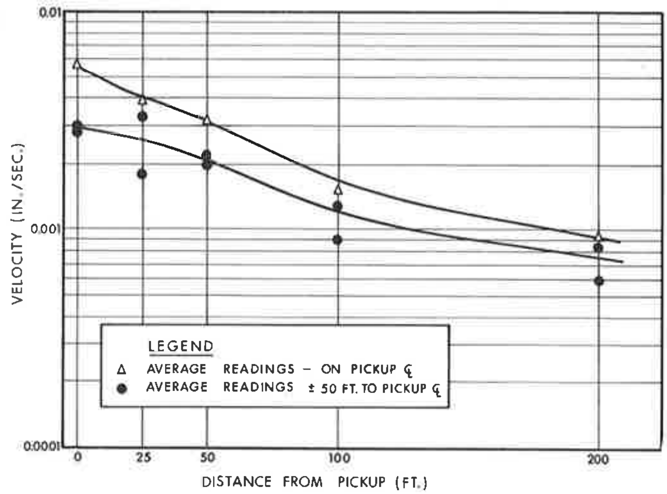


Figure 11. D8H tractor dropping blade to ground—test 4.

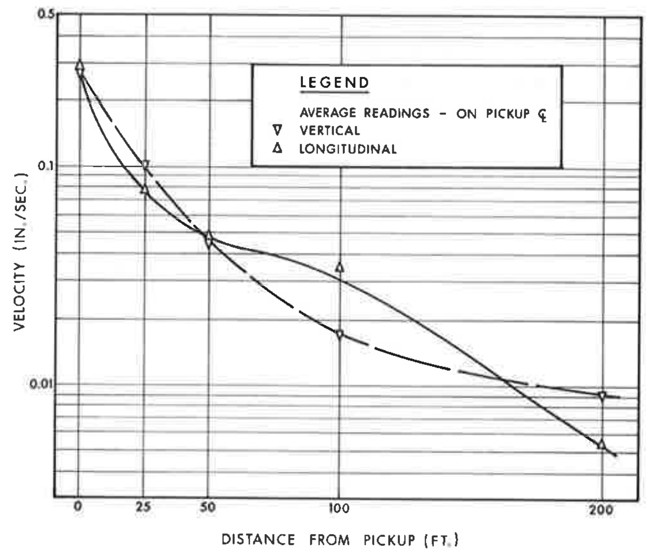


Figure 12. D8H tractor and TS24 earthmover passing but not in contact—test 5.

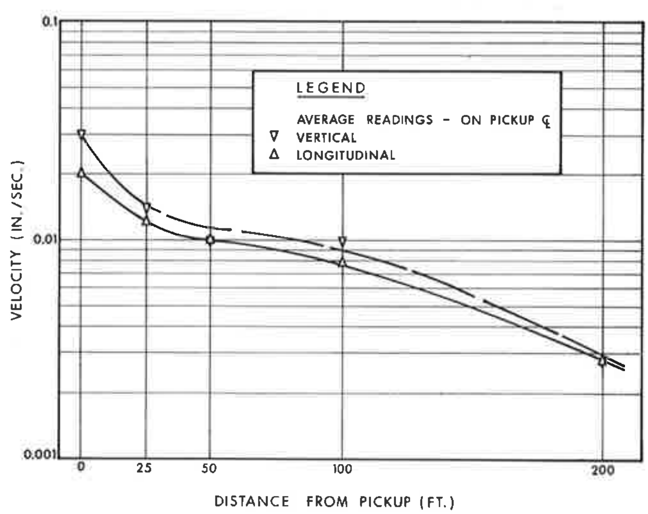


Figure 13. Vertical vibrations of D8H tractor not touching and TS24 earthmover scraping earth—test 6.

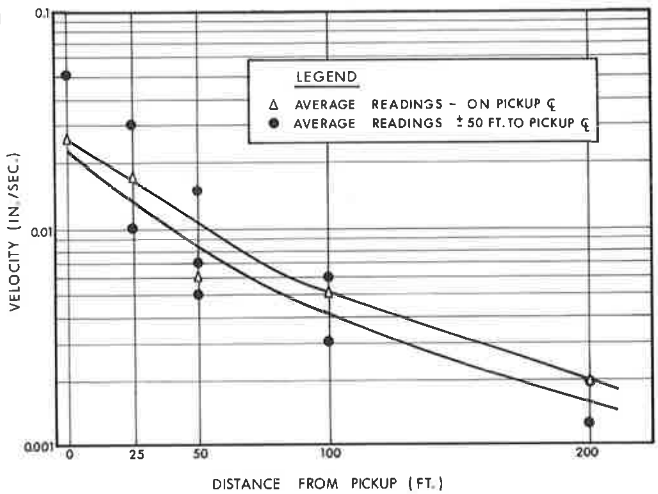


Figure 14. Longitudinal vibrations of D8H tractor not touching and TS24 earthmover scraping earth—test 6.

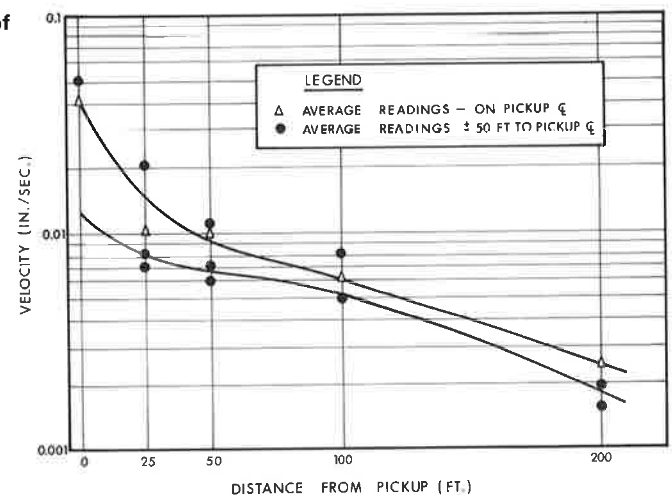


Figure 15. Vertical vibrations of LW777 passing in reverse and not cutting—test 7.

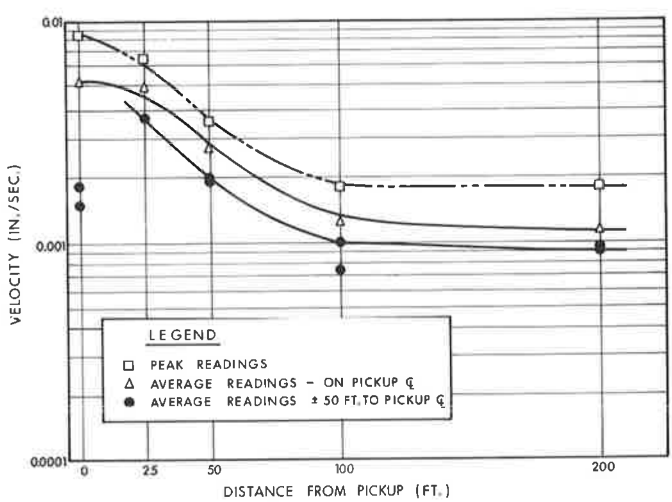


Figure 16. Longitudinal vibrations of LW777 grader passing in reverse and not cutting—test 7.

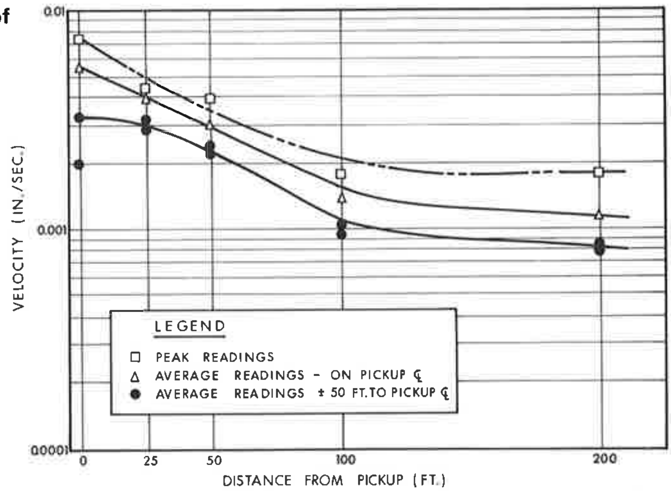


Figure 17. Vertical vibrations of LW777 passing forward and cutting—test 8.

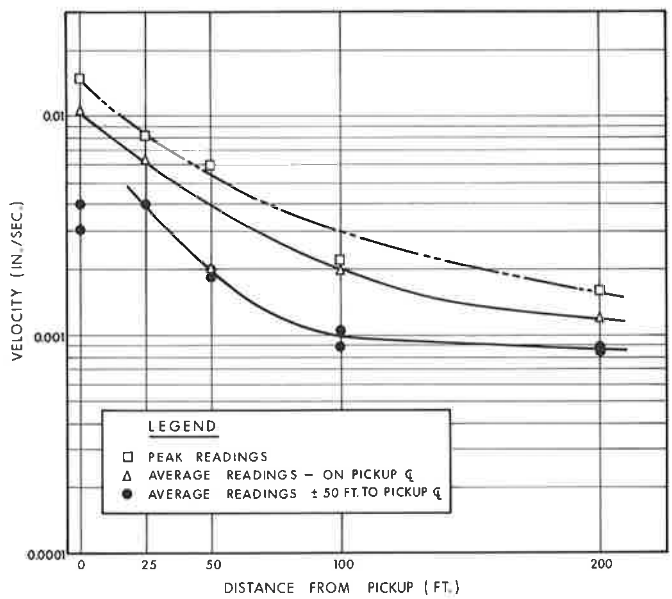


Figure 18. Longitudinal vibrations of LW777 passing forward and cutting—test 8.

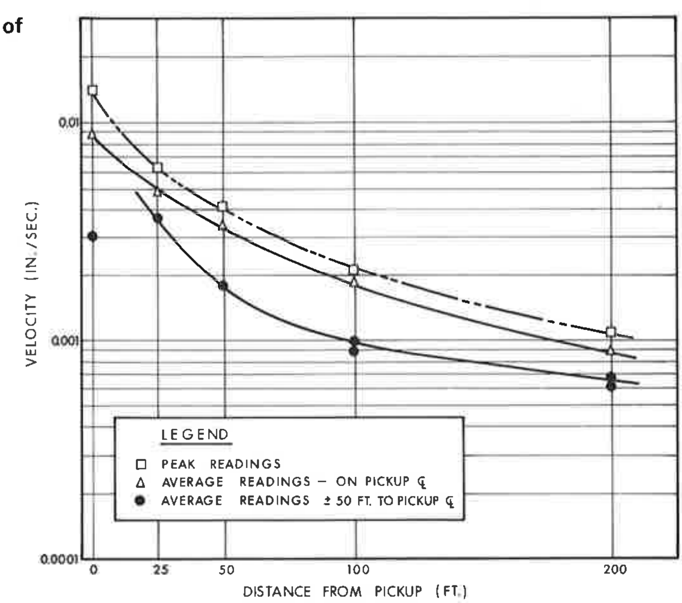


Figure 19. Vertical vibrations of C6 tractor pushing TS24 earthmover cutting earth—test 9.

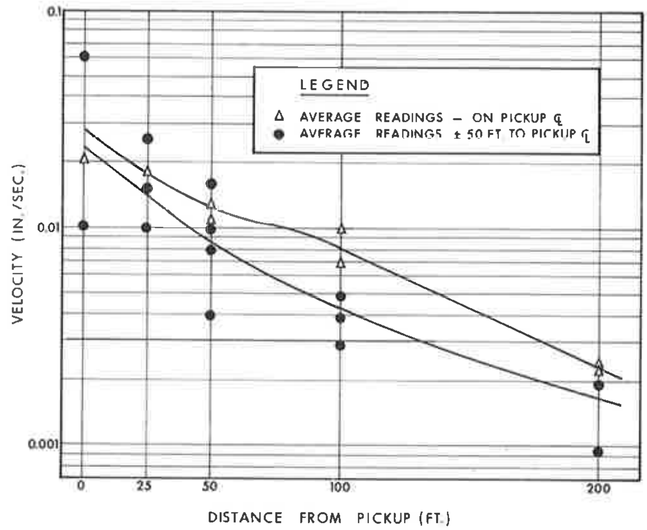


Figure 20. Longitudinal vibrations of C6 tractor pushing TS24 earthmover cutting earth—test 9.

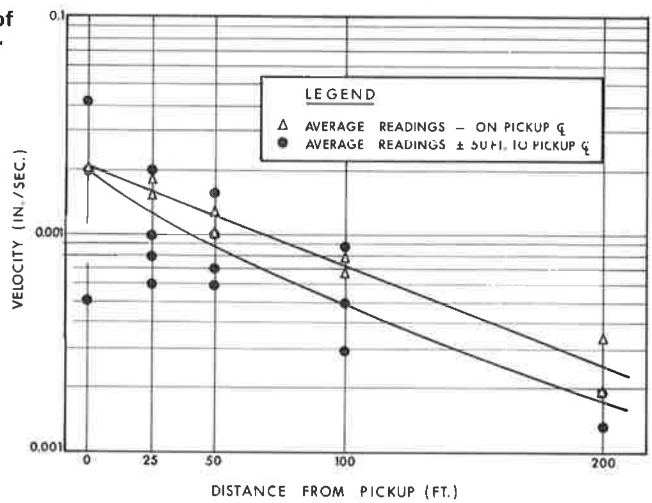


Figure 21. Vertical vibrations of C6 tractor slowly passing—test 10.

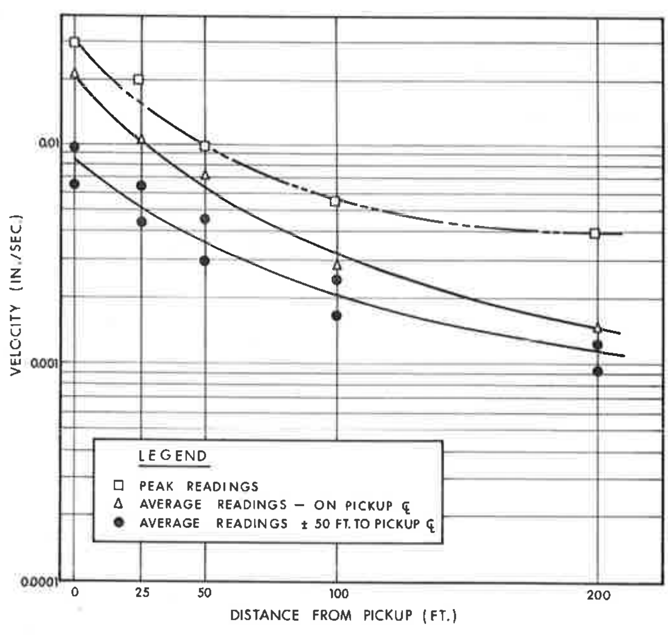


Figure 22. Longitudinal vibrations of C6 tractor slowly passing—test 10.

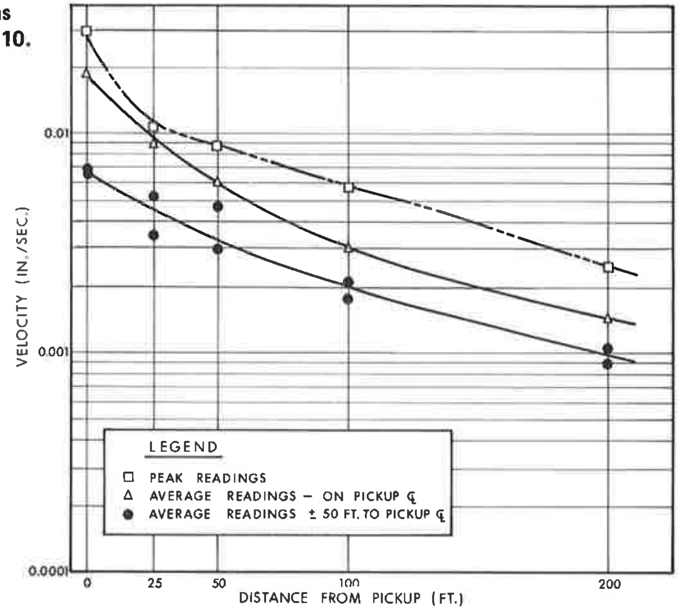


Figure 23. Vertical vibrations of C6 tractor rapidly passing—test 11.

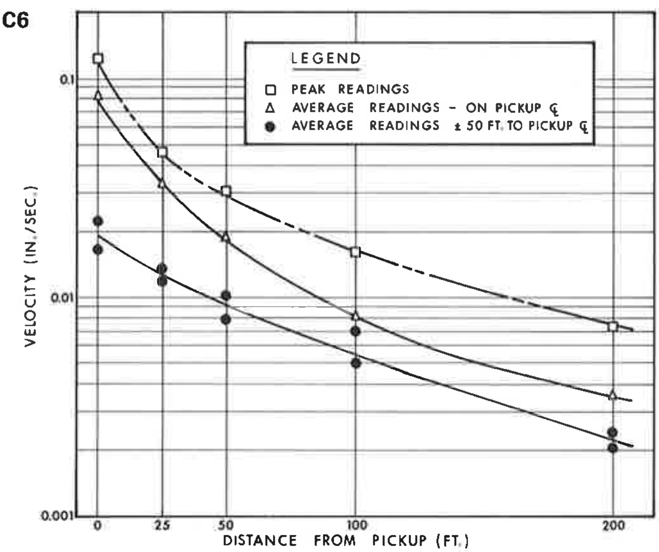


Figure 24. Longitudinal vibrations of C6 tractor rapidly passing—test 11.

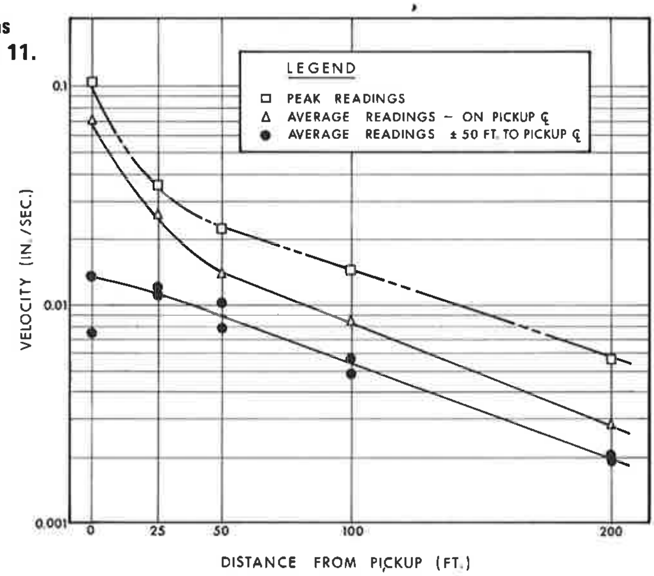


Figure 25. Vertical vibrations of D4 tractor with vibroplus sheepsfoot compactor not vibrating and slowly passing—test 12.

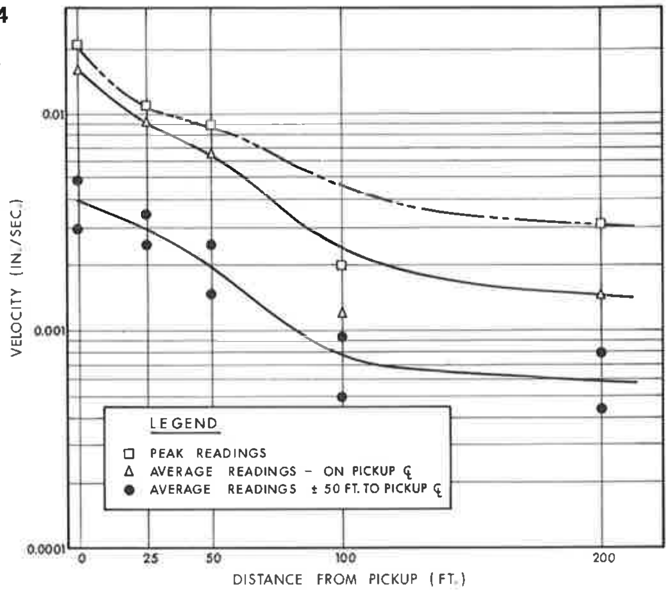


Figure 26. Longitudinal vibrations of D4 tractor with vibroplus sheepsfoot compactor not vibrating and slowly passing—test 12.

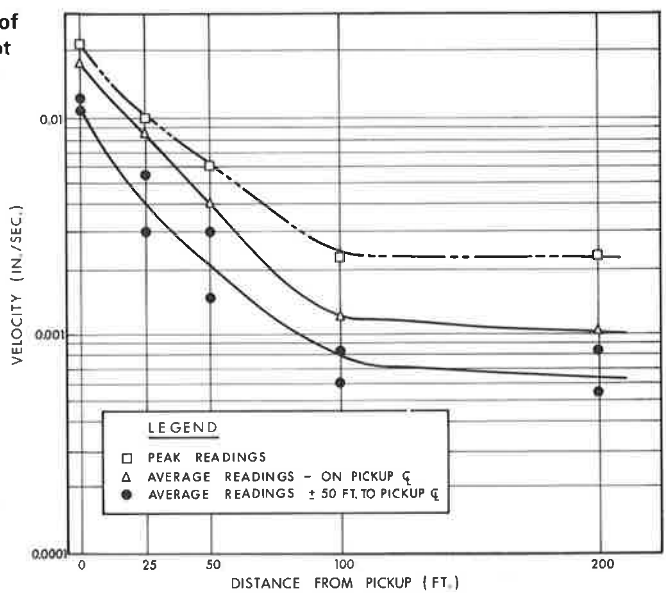


Figure 27. Vertical vibrations of D4 tractor with vibroplus sheepsfoot compactor vibrating—test 13.

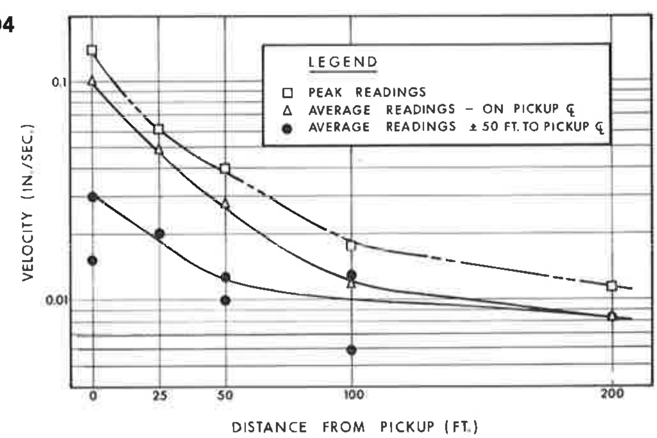


Figure 28. Longitudinal vibrations of D4 tractor with vibroplus sheepsfoot compactor vibrating—test 13.

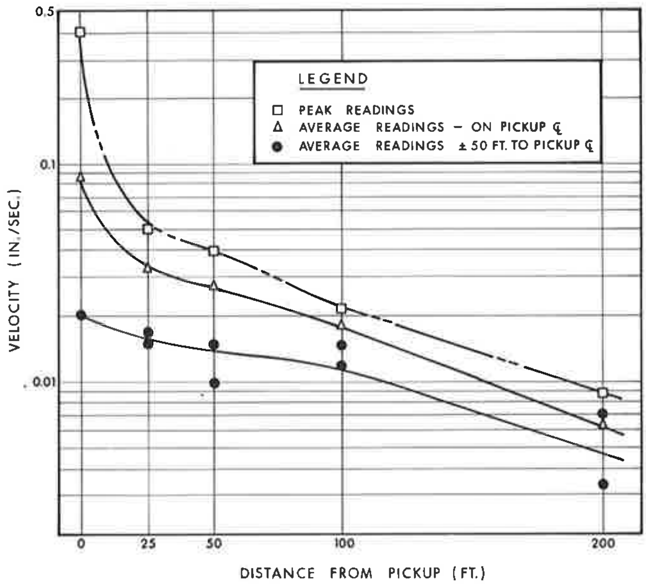


Figure 29. Stationary vibroplus sheepsfoot compactor operating opposite line of pickups—test 14.

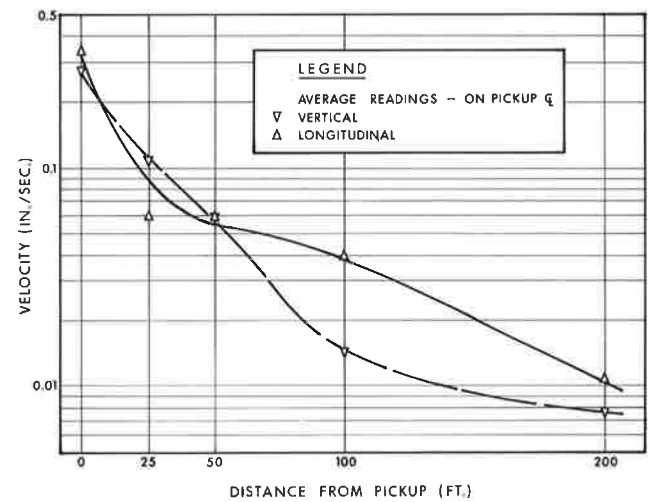


Figure 30. Vertical vibrations of D4 tractor slowly passing—test 15.

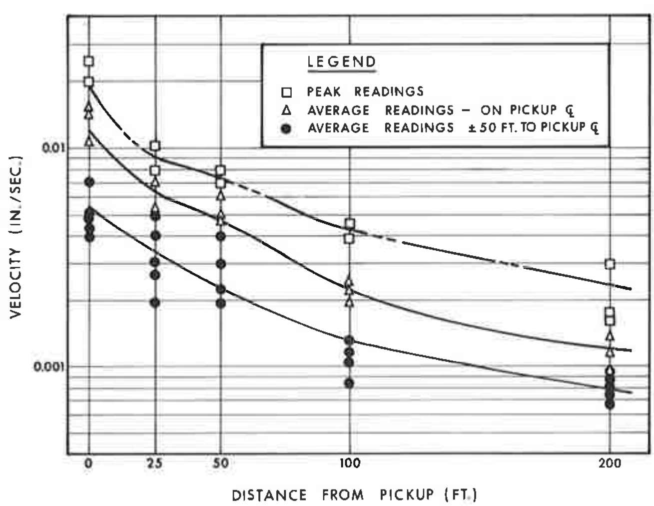


Figure 31. Longitudinal vibrations of D4 tractor slowly passing—test 15.

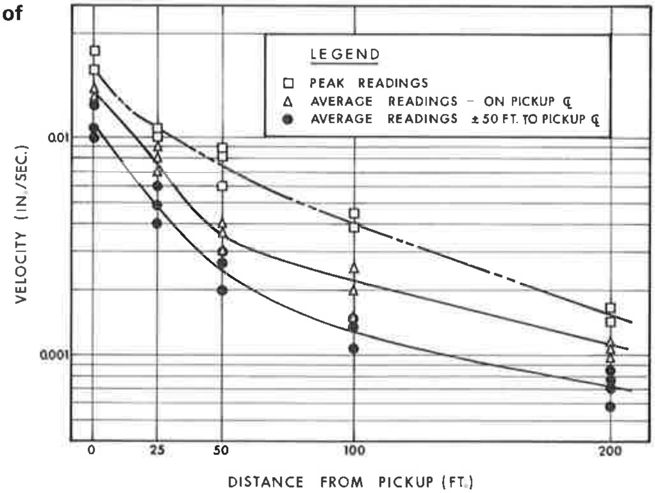


Figure 32. Vertical vibrations of D4 tractor rapidly passing—test 16.

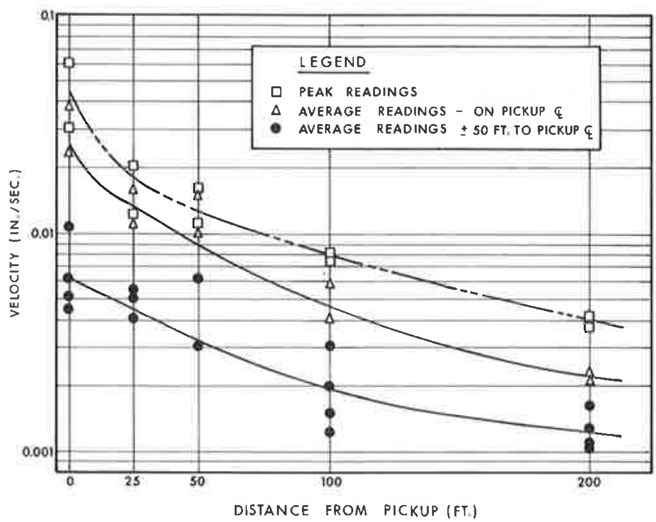
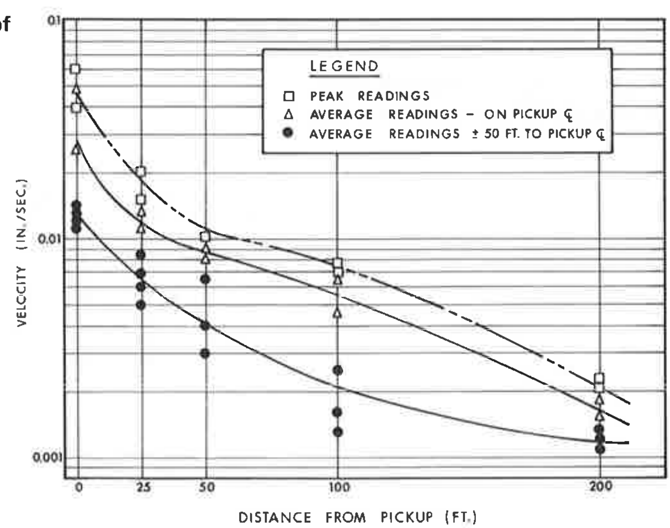


Figure 33. Longitudinal vibrations of D4 tractor rapidly passing—test 16.



from other equipment passes were all below 0.1 in./sec at 25 ft with frequencies between 20 and 30 Hz. Such vibrations were also subjectively very noticeable but much too small to cause any damage, according to the criteria reviewed.

With regard to blasting, however, the situation is very different. Blasting operations must be monitored by instrumentation, at least initially, to ensure that safe velocity levels are not exceeded. Details are given in the earlier report (1) on sewer blasting under a multilane expressway (the Queen Elizabeth Way) that caused fissures to develop in the road shoulder. Recordings established that the contractor was using charge weights that gave velocity levels of 22 in./sec. It is quite likely that, if blasting had proceeded under the roadbed with the same weight of charge, a cave-in could have resulted. Monitoring at this site was continued until the contractor was able to maintain a consistent velocity of approximately 5 in./sec, which, although high by residential criteria, appeared satisfactory for that operation.

Throughout those investigations, it was evident that a convenient, portable instrument for measuring velocity levels would be of value, and a portable velocity seismograph was developed at the Ontario Research Foundation to meet that need. Three-axes velocity signals are recorded on magnetic tape, and instant field readout is achieved by reducing the tape speed 10:1 and displaying the signals on a pen-chart recorder built into the instrument.

It was found that operation of construction equipment caused no damaging vibrations in nearby buildings, although the subjective effect of these vibrations could be unpleasant. With respect to blasting vibrations, it was found that theoretical values agreed reasonably well with actual measured values, using the formula developed by Edwards and Northwood (7). A need for portable instrumentation, suitable for operation by contractors and consultants, was found that embodied the velocity measurement principles used in the latest damage evaluation criteria.

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