29 Apr 1981, 9:00 am - 12:30 pm

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Proceedings: First International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 26 - May 3, 1981, St. Louis, Missouri

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SYNOPSIS Different types of model pavements were subjected to forced vertical vibration with a view to studying the attenuation properties of Rayleigh Waves. The effect of the road base materials is studied along with the effect of the change in the thickness of the wearing course. The effect of different corner angles at the edge of the road is also investigated. The characteristics of geometric and material damping are discussed in relation to transmission and attenuation of vibration.

INTRODUCTION

The problem of noise and ground-borne vibration caused by the heavy vehicular traffic travelling often on poorly maintained roads accompanies the big urban and industrial development in the third world nations. This problem is severe for the houses flanking the roads in metropolitan cities like Delhi, India. A survey conducted to assess the problem indicated that most of the residents were ready to spend a little amount to get rid of the nuisance, if a remedy could be suggested to them. Noise, the airborne vibration is not the subject of this study. This deals with the groundborne vibrations. Quite often, vibrations produced by the movement of heavy vehicular traffic on the road are much higher than the tolerance limit of a normal human being. Due to geometrical damping and attenuation, these vibrations die down to a certain level and diminish as they travel, but still fall in the category of "severe to persons" based on response spectra for vibration limits (Richart et al 1970). It is generally desirable to minimize the vibrations produced by heavy vehicular traffic to at least a level of "barely noticeable to persons" or even less, if possible. A systematic approach to the solution of the problem requires, firstly, the determination of the frequency and amplitude, velocity or acceleration of the vibration at the source by actual measurement or calculation; secondly, the establishment of criteria for an acceptable level of vibration for various types of buildings; and thirdly, the reduction of vibration level in the building to the acceptable level.

LITERATURE REVIEW

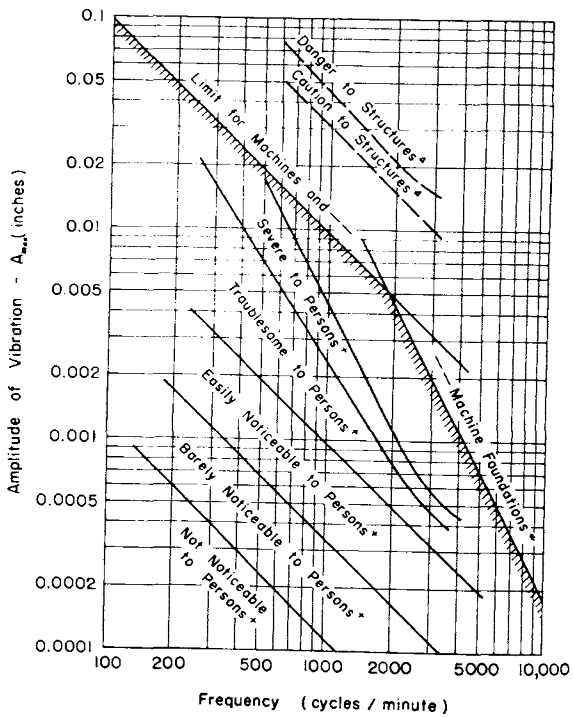
The methods used to reduce the vibration to within desirable limit can be employed in one of the following ways: (i) at the source (active isolation), (ii) during transfer, in the intermediate area and/or (iii) at the receiving end (passive isolation). The solutions suggested at (ii) and (iii) have a vast scope for investigation and are not dealt with extensively. Some work has been reported on isolation. The effect of sheet-piling and trenches for isolation has been studied in detail for machine foundations by Barkan (1962), Dolling (1965) and in much detail by Woods (1968) for both active and passive isolation.

The active isolation includes pavement structure and automobile performance; the role played by the former is the subject of this project. Apart from the weight, speed and acceleration characteristics of the vehicle, the the condition of road surface, the thickness of roadbed, the type of subgrade and the distance of vehicles from the structure are amongst the factors which affect the vibration. Additional factors like the type of binding material in the roadbase, the thickness of surfacing, and the corner angle of road edge (the angle of interface) are also vital in affecting the magnitude of vibrations and their characteristics. Sutherland (1950) studied the effect of various factors on the vibrations produced in the road pavement and their effect on the nearby structures. Irregularity of the road surface appeared as a prominent factor amongst those studied. Steffens (1952) reported from his observations that the groundborne vibrations due to traffic were in the range of 10 to 26 cycles per second, and their amplitude varied so that they fell within just perceptible to clearly perceptible range. The frequency of vibration depends more on geological conditions than on the separation of the source and the observer. Transmission frequencies ranging between 4 to 10 cycles per second for silty soils and 30 cycles per second for limestone were reported by Sutherland (1950).

Tolerance Limit of Vibration

A particular criteria of vibration for buildings or other structures cannot be laid down very rigidly as many physical and mental factors govern the limit. The limit of tolerance varies from person to person. Persons feel disturbed by the vibrations which are generated and are not in their interest, which they, otherwise, would not have perceived.

Richart (1962) defines general limits of displacement amplitude for a particular frequency of vibration or a limiting value of peak velocity or peak acceleration in developing design criteria in relation to the dynamic response of the foundation. He indicates five zones for different sensitivities of response by persons, ranging from "not noticeable" to "severe". Sensitivity is based on a person standing and being subjected to vertical vibrations. Peak velocities for the boundaries between various zones are defined. In presenting the allowable amplitude to frequency relation as in Figure (1), Richart (1962) shows that the vibrations causing even the slightest damage to structures are much greater than the vibrations which are severe to persons. Richart et al (1970) conclude that people expect the new foundation system or road construction to perform better than the old system, when rebuilt, in reducing vibration transmission.



(After Richart 1962)

Fig. 1 Allowable Vertical Vibration Amplitude for a Particular Frequency of Vibration

Rayleigh Waves (R-Waves)

The effect of vertical oscillations on the surface of a half space is to generate body and surface waves. The surface waves generated, which are known as Rayleigh waves, carry about 70% of the total energy emitted. They propagate near the surface. Hence these are of primary interest to the safety and behavior of structures founded on relatively shallow depths. Most residential buildings in the area under consideration are founded on shallow depths. It is mainly the vertical component of such waves which causes discomfort to the residents and may even lead to structural damage of buildings. Observations were, therefore, recorded only for the vertical component of R-waves in the evaluation of wave transmission properties The reduction in the vertical component of R-waves is influenced by geometric damping and material damping. Mathematically the reduced amplitude of vibration is expressed as follows:

$$w = w_1\sqrt{r_1/r}\ \exp\{-\alpha(r-r_1)\}\ \ldots\ \ldots \qquad (1)$$

where

r_1 = distance from source to point of known amplitude

r = distance from source to point in question

w_1 = amplitude of the vertical component of R-wave at a distance r from source

α = coeff. of attenuation having units 1/distance

The coefficient of attenuation is a function of the media through which the waves propagate. The behavior of propagation of the R-waves in a media and the mechanism which controlls the transmission of R-waves when it meets an interface of different materials having different densities and velocities of transmission is relevant to the situation. At the junction of road surface and ground, an incident R-wave may be partitioned into the following waves: (1) a reflected R-wave, (2) a reflected body wave, (3) transmitted R-wave, (4) a refracted body wave, and (5) an interface wave. The distribution of energy among these waves is a function of the material properties and the angles of interface and corner angles. The ratio of reflected-R-wave energy to incident-R-wave energy as a function of corner angle is reported by three investigators using model studies (Viktorov, 1958; deBremaecker, 1958; Plant et al, 1964). These studies though not directly applicable provide a basis for a qualitative estimate.

Damping Mechanism

Damping mechanism in cementitious materials is a complex phenomenon. The damping occurs partly in the form of elastic deformation, the degree of which varies depending on the elastic property of the binding material and partly through energy dissipated at surface cracks, which are generally observed in concrete pavements due to shrinkage. Viscous, solid and frictional damping are present to varying degrees in different types of road bases. The amplitude of vibrations dies down exponentially in viscous and material damping. In case of frictional damping it dies linearly (Swami, 1971).

EXPERIMENTAL APPROACH AND TEST PROCEDURE

From a practical standpoint an extensive series of full scale tests on different kinds of pavement structures did not seem feasible. Therefore the model approach was investigated. The model approach has been extensively used in seismological studies. In the present study three model pits each of 90 cm x 90 cm x 13 cm depth were prepared representing different pavement structures. The size of the pit was decided on the basis of an assumption that the nearest distance to road edge, at which traffic frequently moves, would be about 45 cm. To keep the same distance from the edge of road to vibrator, when kept at the center of pit, would require an area of 90 cm x 90 cm. The interfacial edges of each pit were kept at different inclinations, though same for corresponding sides of the pits.

The inclination of the interface (between the pavement structure and the confining soil) with the vertical has been termed as angle of interface. Different angles were chosen to be able to study the effect of inclination of the interface on the transmissibility of the surface wave across it. The angles chosen for the purpose were -10^o, 0^o, $+10^o$, and $+20^o$. Positive sign indicates the pavement structure resting on the confining soil.

The effect of the pavement structure on attenuation properties of the surface waves was judged by preparing the pits with three commonly used materials of construction. The pavement structures studied were coated macadam, dry bound macadam, and concrete roadbases. 4 cm nominal size of the crushed stone aggregate mixed with the relevant binding materials was used to fill the pits. These materials made the roadbases for the test pits. The wearing course was placed over the base in two layers of 2.5 cm thickness each. It consisted of 1 cm single size, crushed stone chips with 5% asphalt added by weight.

For attenuation properties, three sets of observation were taken at three different levels of acceleration emitted at the source ie. the vibrator. The observations were recorded with distance for wearing course thicknesses of 2.5 cm and 5.0 cm.

Transmissibility of the wave energy across the interface was measured in terms of the amplitude reduction. It was observed along each edge with its characteristic interfacial angle and for wearing course thicknesses of 0 cm, 2.5 cm and 5.0 cm. Level of input acceleration was kept constant.

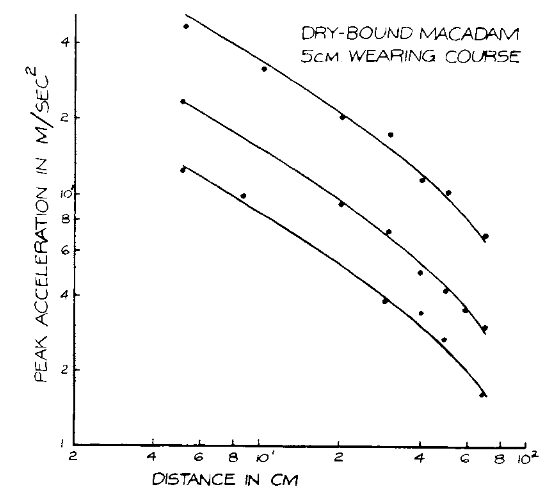


Fig. 2 Change of Acceleration Over Distance with Change in Frequency of Vibration

RESULTS

Figure (2) shows the decay in amplitude of peak acceleration with distance from the vibrator for the 5 cm wearing course constructed on dry bound macadam. The curves are parallel to one another, which clearly indicates that the level of acceleration has no effect on the attenuation properties of such a system. This may be true as the amplitudes of vibration generated during testing were probably small enough so as not to exceed the elastic range of road materials. Thus, one can estimate the rate of decay of amplitude in a particular material at any level of acceleration within the linear range of elasticity which in fact is rarely exceeded for road pavements under normal vehicular loads.

The effect of different pavement structures on decay in the level of acceleration with distance is shown in Figure (3). The results shown are for 5 cm thickness of

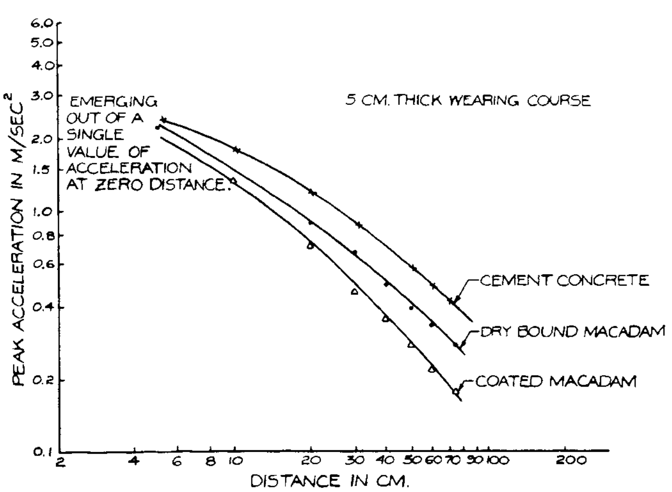


Fig. 3 Attenuation of Peak Acceleration

wearing course. Coated macadam shows the best attenuation characteristics while cement concrete transmits large amount of vibration. The curves are drawn for one particular value of source acceleration, which is liable to vary with the type and surfacing of the pavement structure for the same vehicle. For the observation reported in figure (3), the coefficient of attenuation has been calculated on the basis of measurements taken at 5 cm and 70 cm distances from the vibrator using equation (1). The various values of coeff. of attenuation for different roadbases with 5 cm wearing course are as follows: concrete 0.56/m; dry bound macadam 1.01/m; coated macadam 1.50/m. Higher value of α shows larger attenuation property of the material. The coeff. of attenuation thus calculated depends on the point selected on the curve. An equation of the form $Y = B_0 X^{B_1}$ best fits the curve; X is the distance from vibrator in cm and Y is the acceleration in m/sec. B_0 and B_1 are constants for a particular curve. The values of these constants are reported in Table I. The value of attenuation increases, as B_1 decreases.

TABLE I. Acceleration attenuation

Base	Wearing course thickness 2.5 cm		5.0 cm	
	B_0	B_1	B_0	B_1
Coated macadam	9.39	-.828	10	-.915
dry bound macadam	7.75	-.691	8.83	-.786
cement concrete	6.85	-.584	7.60	-.647

The damping characteristics of various pavement structures as presented in Figures (3) and (4) can be related to the physical phenomenon which takes place in the material of construction during transmission of waves as previously

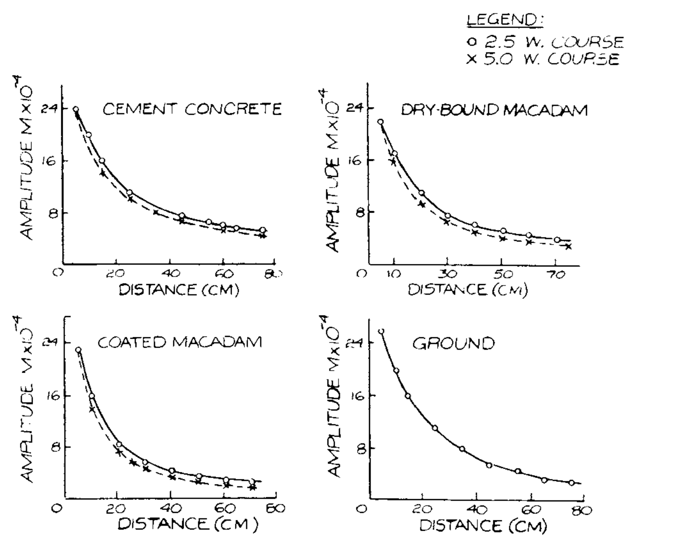


Fig. 4 Amplitude Attenuation with Distance

discussed under damping mechanism. The changes in the value of coeff. of attenuation, α, at different points of the curves in Figure (3) ascertain to a varying pattern of damping mechanism. It may be said that the damping is related to the energy dissipated by external and internal friction and the degree of shear deformation caused in the pavement material during the process of transmission of vibrational energy. Density may also influence the damping. Higher density means closely packed particles which in turn will transmit more energy as if they were bound together. On the other hand, if the particles are free to move, higher energy is absorbed at the points of contact.

However, for the densely packed particles, the normal presure at points of contact is greater, which implies more frictional force. This results in greater energy absorption. Specifically in coated macadam, the shear deformation probably occurs due to the plastic behavior of asphaltic materials present in the voids of the aggregate, which in turn absorbs some part of vibrational energy on its deformation. This tendency of absorption of vibrational energy is not present to this extent in any other case uder consideration. In addition to viscous damping, the material and frictional damping effect also absorbs the vibrational energy in coated macadam roadbase. In dry bound macadam the damping is predominantly due to frictional behavior of crushed stone aggregate particles. Also the cracks present in the mass affect the attenuation properties. The energy is dissipated in such cases at junctions of particles in widening the cracks and in overcoming the friction amongst them at their surfaces of contact. In dry bound macadam roadbase the density was greater (1860 kg/m3) as compared to coated macadam (1830 kg/m3). This may also account for smaller attenuation of dry bound macadam. This may not always occur if the cracks and air voids are present to a greater extent and may play a major role in reducing the vibrational energy by a larger degree. In the case of cement concrete roadbase, perhaps no free movement of particles is possible nor the plastic deformation takes place. This leaves it only with material damping and elastic deformation which results in lower damping property of concrete base.

TRANSMISSIBILITY

The vertical components of peak accelerations are measured for the different roadbases in the experimental pits and the adjoining ground as shown in Figure (5). Transmission of vibration is reported as the inverse ratio of

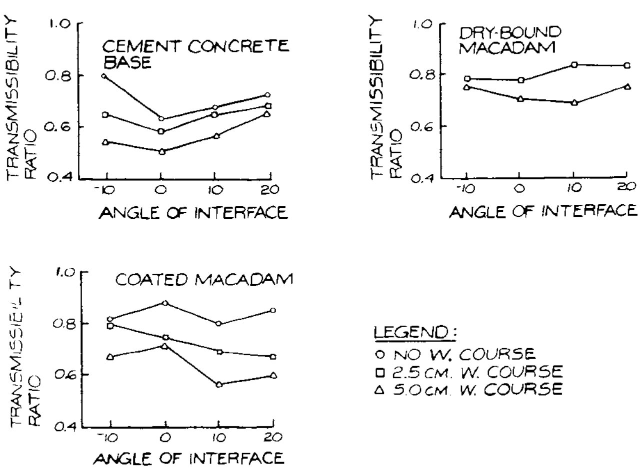


Fig. 5 Transmissibility Ratio of Acceleration (in Adjacent Ground to Edge of Pavement)

acceleration on the edge of pavement to the acceleration transmitted to adjoining ground. Measurements were taken on all four sides of the pit to establish the effect of interfacial angles between the base material and the confining soil. The effect of the acceleration on transmissibility ratio was found to be negligible. Figure (5) shows that as the thickness of the wearing course increases, the acceleration transmitted to adjacent ground decreases to a varying degree in different materials. This may be on account of an overall increase in the thickness of the pavement. However, the change in transmissibility ratio is not uniform for all interfacial angles with the same increase in the thickness. Nor does transmissibility ratio change uniformly with the increase in thickness for a particular interfacial angle. Cement concrete shows minimum transmissibility at zero degree of angle of interface for all thickness of wearing course. The minimum transmissibility for coated macadam is at 10° angle of interface. In general, for 2.5 cm and 5 cm thick wearing courses, the transmissibility ratios are minimum or near minimum at 10° angle of interface. There is some likelihood that given small dimensions of the experimental pits, the effect of the reflection of different waves from other three faces may interfere with the observed vibration at the test face. The range of dynamic force applied during the investigation varied from 5 kg to 100 kg at various frequencies between 8 to 40 cycles per second. The amplitude of vibration continuously increases with the increase of frequency within the range of operation.

CONCLUSIONS

An increase in thickness of the wearing course helps reduce the transmission of vibration in a road pavement. Attenuation property of a pavement structure is a function of the damping mechanism of the material. Coated macadam appears to have the maximum value of attenuation. It also transmits minimum vibration to adjacent ground. An interface angle of +10° of road edge appears to minimize transmission of vibration to adjacent ground except for cement concrete where the vertical edge gives best results.

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Acknowledgement: This paper is dedicated to the memory of Mr. Rajendra Puri who was greatly instrumental in its initiation. This is a small effort in continuation of the work started by him before his untimely demise.