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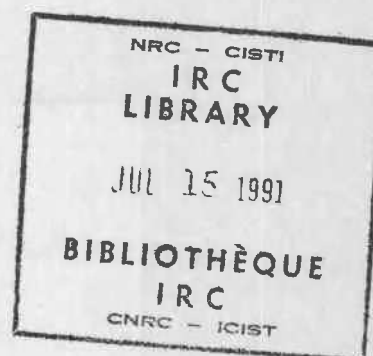
## ***Remedial Measures for Traffic-Induced Vibrations at a Residential Site. Part 2: FEM Simulations***

by M.O. Al-Hunaidi and J.H. Rainer

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## REMEDIAL MEASURES FOR TRAFFIC-INDUCED VIBRATIONS AT A RESIDENTIAL SITE. PART 2: FEM SIMULATIONS

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### Abstract

This is a companion paper to an experimental investigation, reported earlier, of traffic-induced vibrations at a site where several complaints were lodged by homeowners residing near a roadway. The objective of the previous paper was to investigate experimentally the factors influencing the level of these vibrations and their relative quantitative importance. The present paper reports on the results of the analytical part of the study in which the role of pavement/subbase characteristics, effectiveness of vibration screening by concrete walls and soil improvement were investigated using finite element simulations.

### Résumé

Ce document décrit le second volet d'une étude, signalée plus tôt, sur les vibrations produites par la circulation; cette étude avait été menée à la suite de plaintes déposées par plusieurs propriétaires de maisons situées le long d'une route. Le volet expérimental de l'étude portait sur les facteurs qui influent sur le niveau des vibrations et sur leur importance quantitative relative. Ce document fait état des résultats du volet analytique, dans lequel les auteurs ont étudié, à l'aide de simulations par éléments finis, le rôle de la chaussée-couche de fondation, l'efficacité du blocage des vibrations au moyen de murs de béton, ainsi que l'amélioration du sol.

## 1 INTRODUCTION

Information on the effectiveness of improving pavement/subbase characteristics to reduce traffic-induced vibrations is scarce. In the one study known to the authors, Tholen (1974) reports that ordinary variations in the nature and thickness of the pavement has negligible influence on the level of traffic-induced vibrations. One would tend to believe, however, that a rigid and massive road structure could be a valid remedy to reduce the level of traffic-induced vibrations.

The purpose of the present study is to investigate the influence of pavement/subbase characteristics on the level of traffic-induced vibrations. Screening of vibrations by a concrete wall and the effect of soil improvement using lime piles were also briefly investigated. The study was performed by means of computer simulations using the finite element method. Such an investigation would be theoretically very difficult and experimentally very expensive. Simulation using the finite element method provides a powerful and economical tool.

This study is the second and a companion part of an investigation of the effectiveness of various remedial measure of traffic-induced vibrations at a residential site (Al-Hunaidi and Rainer 1990). A full description of the site is presented there.

## 2 MODEL DESCRIPTION

### 2.1 Source

The source of vibrations is modelled as a steady state harmonic vertical point load applied at the center of the roadway. Although this type of load may not accurately represent the moving source of traffic vibrations (which may be said to fall somewhere between a line source and a point source), this approach is considered to provide a sufficiently accurate tool for performing a parametric study of pavement/subbase characteristics as they relate to traffic vibrations. For vibrations originating at a surface crack, the stationary point source is actually quite realistic since it is these vibration components that represent the major part of the induced signal (Al-Hunaidi and Rainer, 1990).

## 2.2 FEM Model

An axisymmetric finite element model is used to simulate the pavement/subgrade system, unless otherwise noted. Hence, it is implicitly assumed that (i) the subgrade consists of horizontal soil layers and (ii) the propagation pattern of waves generated by a vertical load on the surface of the road is axisymmetric, in spite of the fact that the system is in reality 3-dimensional. The first assumption is usually true for most sites. The second assumption was verified by a set of field experiments.

In these experiments, an electrodynamic shaker was used on a road surface to generate point load vibrations. The induced wave field was measured by a grid of vertical accelerometers placed axisymmetrically with respect to the shaker, as shown in Figure 1. Since the measured ground motion was not purely harmonic due to the presence of ambient vibration at the site, the measured signals were Fourier transformed to obtain the response that corresponds to the frequency of the excitation. For an 8 Hz excitation frequency, the accelerations at measurement stations 1, 2, 3, 4, and 5 at 10 metres from the shaker (see Figure 1) were 0.7, 1.2, 1.4, 0.9, and  $1.3 \times 10^{-3}$  (%g), respectively. While there exists some variation in acceleration amplitudes between these stations which are equidistant from the source, from a practical point of view the wave field could be considered sufficiently axisymmetric. The accelerations of measurement stations at 20 and 30 metres, and results of tests with 12 and 16 Hz excitation frequencies also show a similar trend.

The road section under consideration was simulated using the finite element model shown in Figure 2. The model consists of  $31 \times 31$  axisymmetric 4-node elements. The bottom boundary of the model, located at 13.55 m, is fixed to represent a hard (rock) layer. The lateral boundary located at horizontal distance of 13.55 m from the centre line, is a consistent silent boundary (Lysmer and Waas, 1972) which simulates the infinite dimension of the site in the horizontal direction. The maximum element size in the mesh was chosen to satisfy the condition that it is less than 1/6 the shortest wavelength of interest. The shortest wave length is based on the slowest wave velocity and the

Table 1  
Comparison between experimental and FEM results for point source test

| Frequency (Hz) | Force Amplitude (N) | Vertical Acceleration (% g) |                       |
|----------------|---------------------|-----------------------------|-----------------------|
|                |                     | Experimental                | FEM                   |
| 8              | 173.35              | $3.25 \times 10^{-3}$       | $3.73 \times 10^{-3}$ |
| 12             | 166.69              | $4.85 \times 10^{-3}$       | $5.03 \times 10^{-3}$ |
| 16             | 148.68              | $8.30 \times 10^{-3}$       | $7.75 \times 10^{-3}$ |

maximum frequency of interest which for the present analysis was taken as 28 Hz. Material behaviour was assumed to be linearly elastic and the analysis was performed in the frequency domain. Frequency response spectra were calculated for points at 0.25, 5.05 and 12.05 metres from the source by applying unit point source load starting with an excitation frequency of 4 Hz and then incrementing it by steps of 1 Hz. Calculations were performed in double precision on an IBM 3090 computer.

## 2.3 FEM Verification

The accuracy of simulations employing the finite element model shown in Figure 2 was verified by comparing numerical FEM results with those of field measurements. The test problem employed is that of a single oscillating vertical harmonic force acting at the centre of the roadway. An electrodynamic shaker was used in the field test. Vertical acceleration was recorded at a point 5.35 m from the center of the road.

The comparison between numerical and experimental acceleration amplitudes is presented in Table 1 for 8, 12 and 16 Hz excitation frequencies. Although it was not possible to reproduce exactly the conditions that prevailed in the field, numerical and experimental results show satisfactory agreement.

## 3 SOIL PROPERTIES

The subsoil investigation consisted of soil sampling, performing Dutch cone penetrometer test, and carrying out resonant column tests in the laboratory. The dynamic shear modulus profile as determined from the Dutch cone penetrometer test is shown in Figure 3 for the location under consideration (note: The dynamic shear modulus is obtained with the cone penetrometer by correlating the results with those of resonant column tests, using undisturbed high quality samples, as well as with cross-hole tests on Champlain Sea clay (Law, 1990)). The bulk soil density was  $1.7 \text{ ton/m}^3$  and damping ratio from resonant column test was found to be 1.6%. At the time of performing FEM calculations, the damping ratio was not available and it was assumed to be 0.1%. Later verification tests with 1.6% showed only negligible difference of amplitude response at the fundamental frequency of the site. Poisson's ratio was taken as 0.45.

Soil layers extended to a depth of 13.5 m, where a firm layer was encountered by the penetrometer. The soil profile from the surface down is approximately as follows: (i) 1.0 m gravel/sand fill, (ii) 4.0 m grey/brown stiff weathered clay, (iii) 8.5 m medium to stiff silty clay. The water table was at 1.0 m below the ground surface.

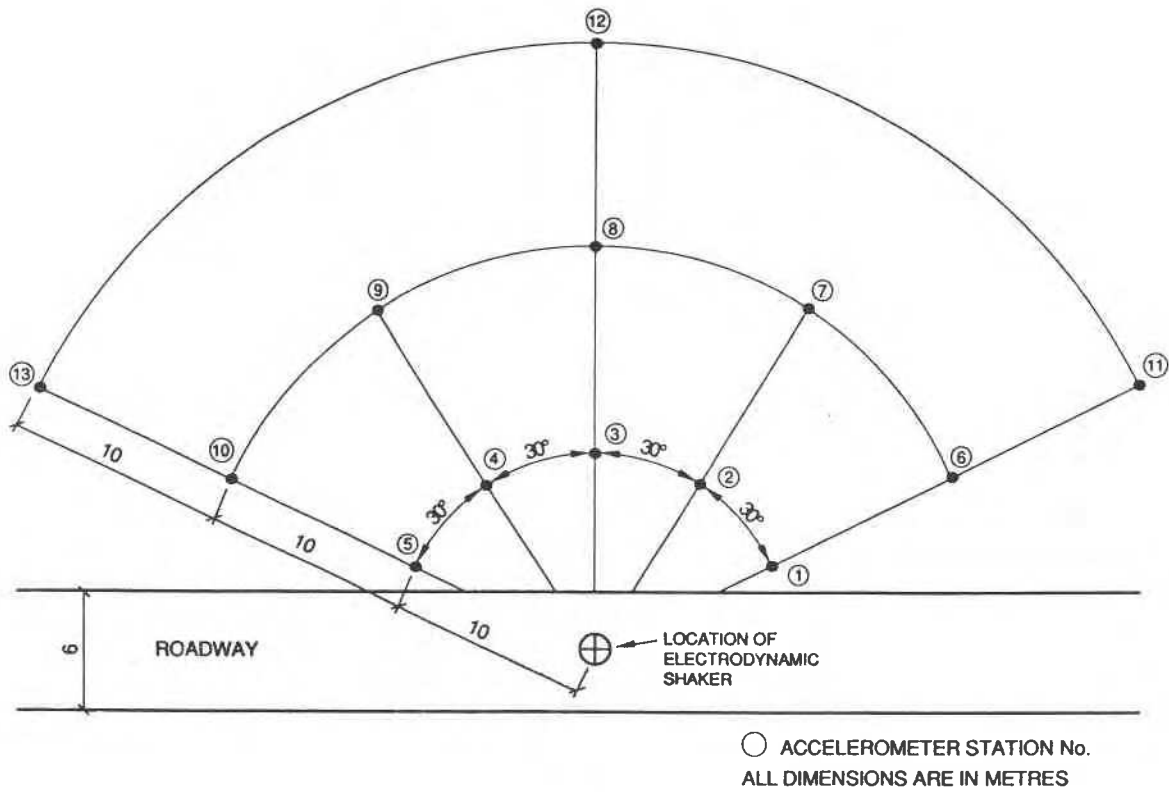


Figure 1 Axisymmetrical layout of vertical accelerometer stations.

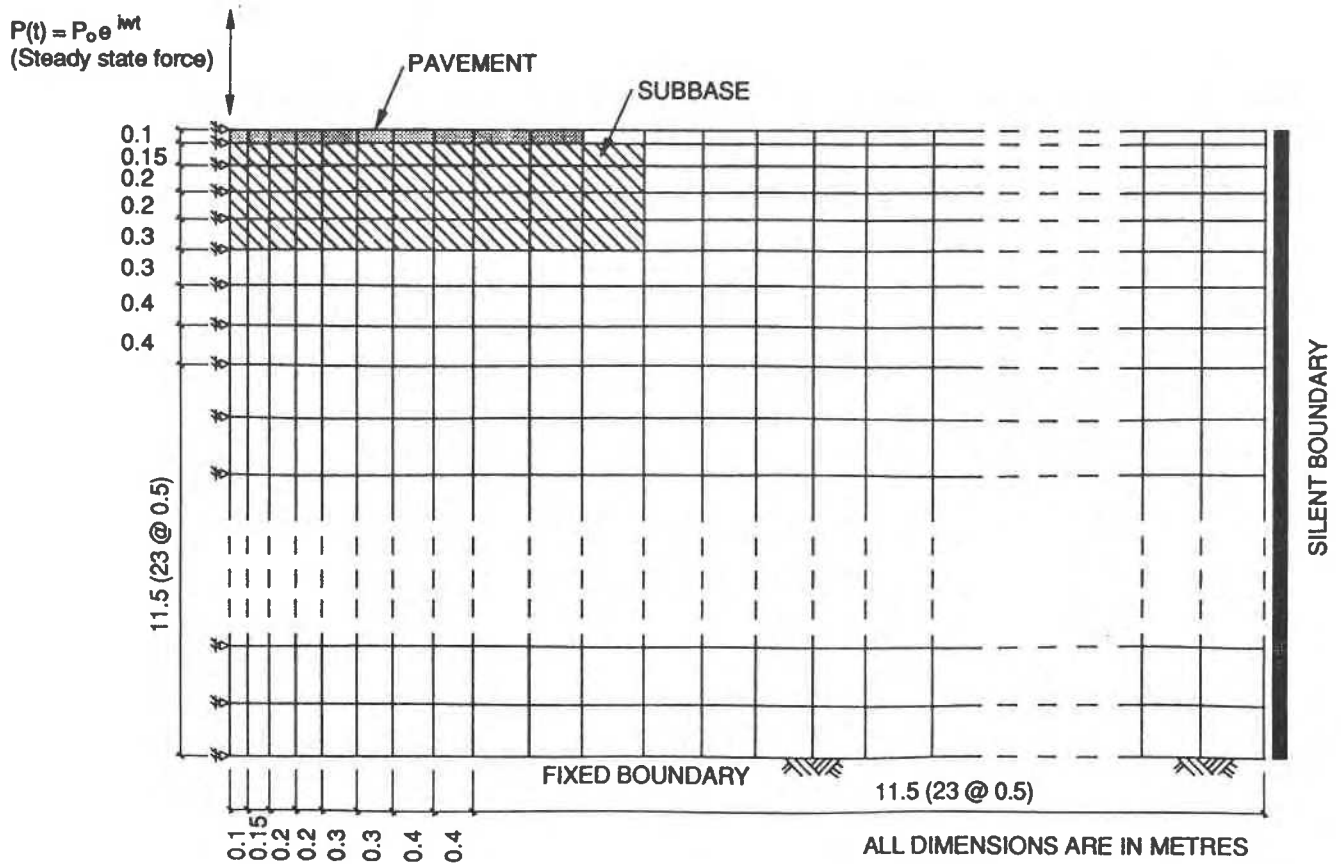


Figure 2 Finite element model of road/subgrade system

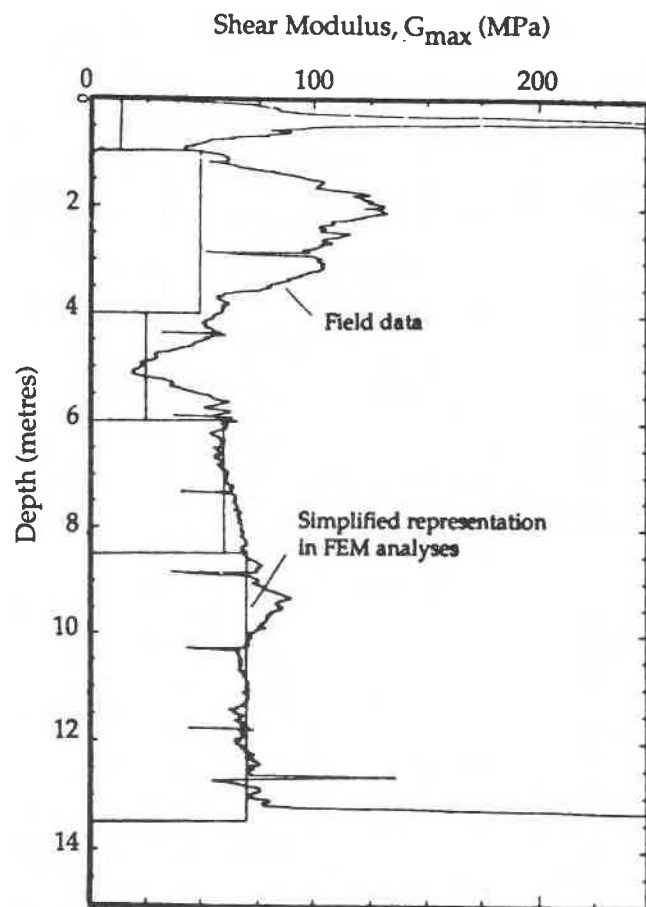


Figure 3 Shear-modulus profile at test location.

Approximate road dimensions and properties of the existing roadway and a modified design (proposed by an independent consultant) are shown in Figures 4 and 5, respectively.

## 4 DESCRIPTION OF FEM ANALYSES

The following remedial measures for reducing traffic vibrations were investigated using finite element analyses:

- Improving road structure
- Screening of waves by a concrete wall
- Soil improvement

### 4.1 Effect of road structure

Several FEM tests were performed to evaluate various road designs. Frequency response functions are generated and changes in these functions are taken as indicators of how parameter variation would affect the vibration behaviour of the site. The response spectra of the existing road design were compared with those of the modified design shown in

Figure 5. In addition, the following parametric tests were performed in conjunction with the modified design:

- Replace the 10 cm bituminous pavement with 10 cm concrete layer.
- Replace the 10 cm bituminous pavement with 25 cm concrete layer.
- Double the proposed thickness of upper and lower road base.
- Replace the bituminous pavement and upper and lower base foundations by 65 cm concrete road (admittedly an impractical extreme case).

### 4.2 Screening by a Concrete Wall

Screening of ground vibrations by placing a trench in the transmission path of surface waves is known to be an effective measure to reduce ground vibrations (Richart et al., 1970). The trench can be left open or backfilled with a material that provides a sufficient impedance mismatch with the surrounding soil. It was found that when the ratio between an open trench depth and the propagating wavelength is greater than 0.6, the vibrations amplitudes in the screened area are significantly reduced (Segol et al., 1978). A minimal value of 1/3 is usually set for the ratio between the trench depth and wavelength (Le Houdec & Picard, 1988). Contradictory results, however, are reported regarding the effectiveness of stiff obstacles (Segol et al., 1978). Therefore, finite element analyses were performed to investigate the effectiveness of a concrete wall to reduce ground vibrations for the site conditions in this study. Two wall depths were considered: 5.0 m and 10.0 m, which correspond to roughly 1/3 and 2/3 of the longest wavelengths of interest, corresponding to 8 Hz. The concrete wall is 0.5 m wide and is located at 4.05 m from the center of the roadway. For this analysis, a plane strain model was used in order to realistically simulate the wall in the horizontal direction.

### 4.3 Soil Improvement

Improvement of soil to increase its stiffness using lime piles is reported to be very effective in improving the bearing capacity of the ground (Broms, 1979) as well as reducing ground vibrations induced by dynamic loads (Taniguchi & Okada, 1981). To investigate the possible effects of this type of soil improvement on the site under consideration, several finite element analyses were performed. Only the soil under the road is assumed to be improved using 0.4 metre diameter piles at 0.9 metre spacing arranged in a rectangular grid. The improved soil's modulus is assumed to be 225% of the original modulus. Density is also assumed to increase by 18%. Calculations were performed for improvement depths of 13.55, 8.55 and 6.05 metres. An axisymmetric FEM model was used.

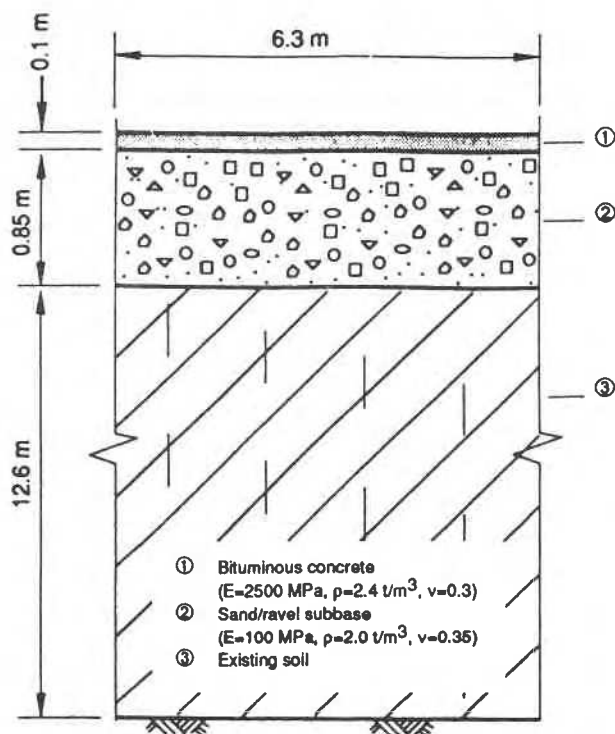


Figure 4 Existing cross-section of road.

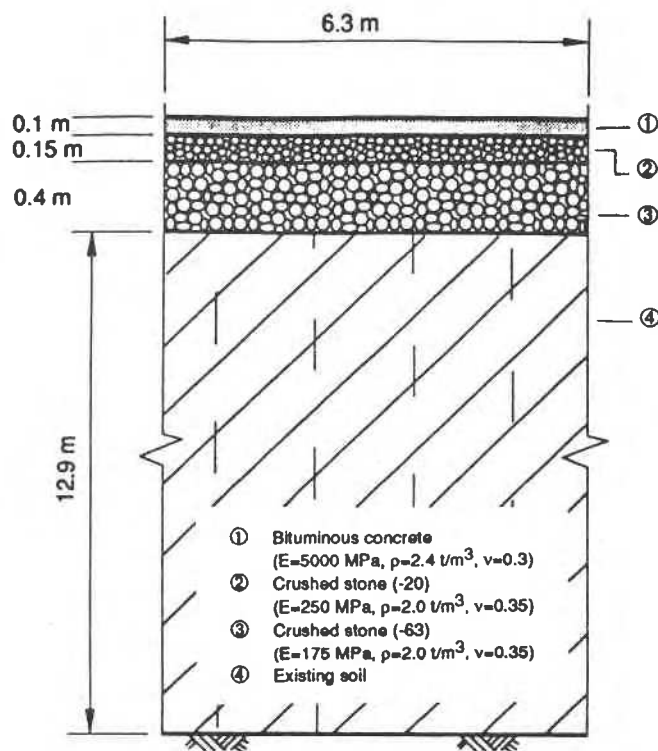


Figure 5 Modified design for road section.

## 5 NUMERICAL RESULTS

Results of finite element analysis of the road response are graphically presented as frequency response functions at surface points 0.25, 5.05, and 12.05 metres from the source. All results are compared with those of the existing road profile, shown in Figure 4.

### 5.1 Effect of Road Structure

#### Comparison between existing design and modified design

Implementing the modified road design, shown in Figure 5, introduces very little or no reduction in vibration levels at points 5.05 and 12.05 metres from the centre of the road as can be seen from the frequency response functions in Figure 6.

#### Replacing 10 cm bituminous pavement with 10 cm concrete pavement

The increased rigidity of the pavement layer in the modified design has a negligible effect on the level of vibrations at points away from the road (5.05 and 12.05 m), as can be seen from Figure 7.

#### Replacing 10 cm bituminous pavement with 25 cm concrete pavement

The 25 cm concrete pavement has a more noticeable reduction of vibration amplitudes than for the case of a 10 cm concrete pavement, especially for the horizontal component. However, close inspection of the results in Figure 8 shows that: (i) the reduction occurs generally at high frequencies, and (ii) the amplitude reduction is more pronounced for points closer to the source (compare the results at 5.05 and 12.05 m). Overall, the reduction in amplitudes is negligible.

#### Doubling the thickness of the upper and lower roadway foundations

In the modified road structure, shown in Figure 5, the thicknesses of the upper and lower foundations were increased from 0.15 and 0.4 m to 0.35 and 0.8 m, respectively. Frequency response spectra of this case (not displayed here) show that the amplitude reduction is slightly more than that gained with the original modified design. The amplitude reduction is comparable to that achieved by replacing the asphalt pavement with 25 cm concrete pavement (Figure 8).

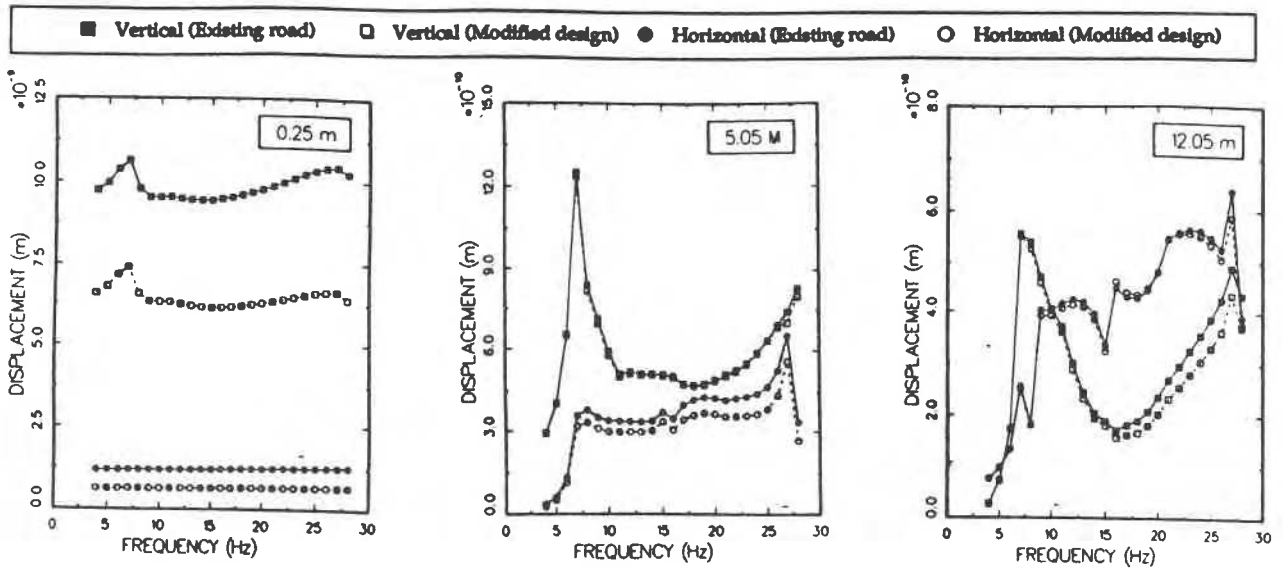


Figure 6 Frequency response functions of existing road design and modified design.

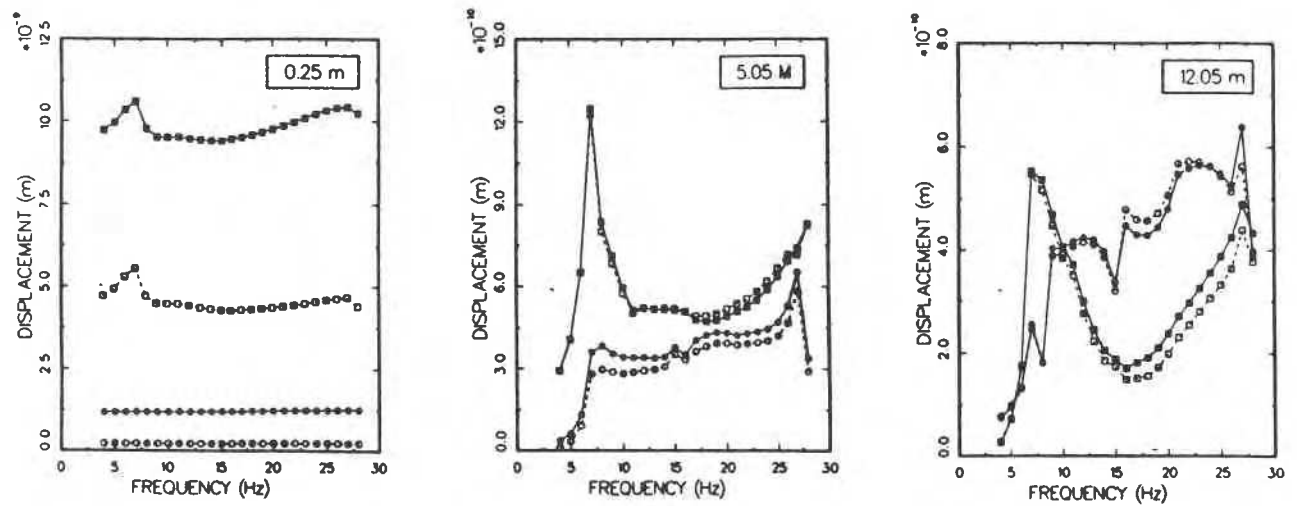


Figure 7 Effect of replacing 10 cm bituminous pavement with 10 cm concrete pavement.

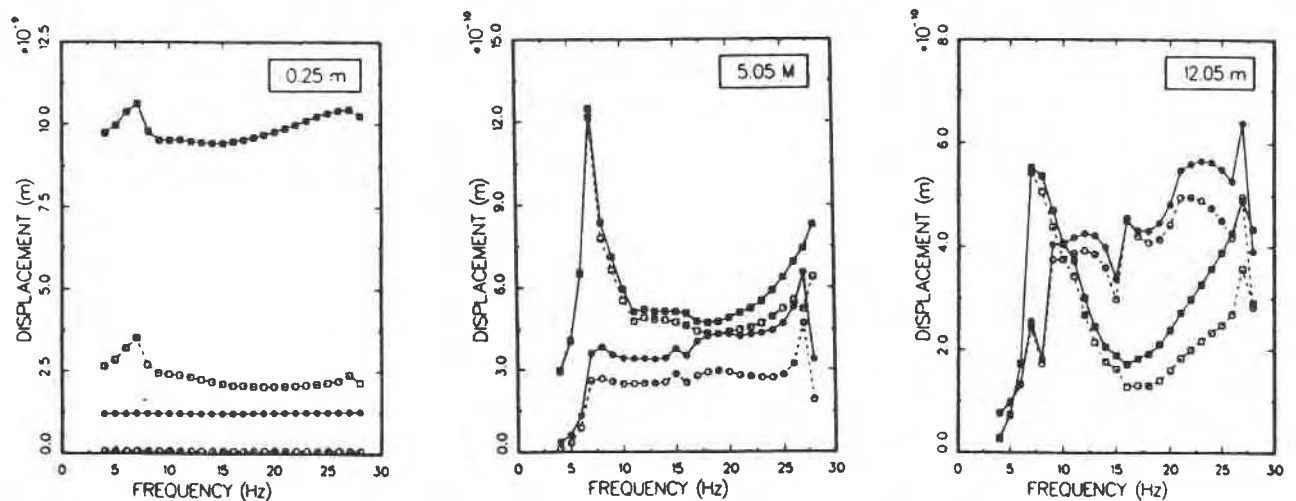


Figure 8 Effect of replacing 10 cm bituminous pavement with 25 cm concrete pavement.



## Using a 65 cm concrete pavement

The objective of such an obviously impractical design is to test a hypothetical road structure that is very stiff and massive in comparison with all previous designs so as to detect trends for extreme parameter variations. As can be seen from the response functions of this design, shown in Figure 9, there is a substantial reduction in amplitudes which has not been achieved by any of the previous road structures. The higher the frequency, the higher the reduction. However, amplitude reduction at and close to the fundamental frequency of the road/subgrade system, which is of primary interest here, is not significant.

## 5.2 Effect of Screening by Concrete Wall

Tests on the effectiveness of vibrations screening by a concrete wall were performed in connection with the existing design of the road section shown in Figure 4.

### Using a 5 metre deep concrete wall

From the frequency response functions presented in Figure 10 it seems that the reduction of vibration amplitudes varies from point to point in the screened area. While vibration amplitudes at 5.05 m are moderately reduced by the presence of the concrete wall, there is only a slight reduction at the 12.05 m location.

### Using a 10 metre deep concrete wall

As would be expected, a significant reduction of vibration amplitudes occurs in comparison with the 5 m deep wall. As can be seen from Figure 11, there is a substantial reduction especially at frequencies close to the fundamental frequency of the road/subgrade system. However, the reduction of vibration levels at 12.05 m is lower than that at 5.05 m, as was observed with the case of the 5 m wall.

## 5.3 Effect of Soil Improvement

The calculations for soil improvement were carried out in conjunction with the modified road design, shown in Figure 5. FEM calculations were performed for improvement depths of 13.55 m, 8.55 m and 6.05 m, and the resulting response functions are shown in Figures 12, 13, and 14, respectively. It can be seen that substantial reduction in vibration amplitudes can be attained for almost all frequencies. The greater the depth of the improved area, the greater the reduction in amplitudes, especially for frequencies at or near the fundamental frequency of the road/subgrade system. For frequencies higher than about 15 Hz, the vibration reduction is almost the same for the three soil improvement depths.

## 6 DISCUSSION

An explanation as to why improvement of the road structure is effective for reducing low frequency vibration levels at points on the roadway itself and not at points away from the road is due to the spreading of the applied load. The stiffer the road the less concentrated is the action of the load. Unfortunately, the effect of this action is local and only points close to the load experience the difference. For points away from the pavement, the loading action seems to be practically unchanged, i.e. the load remains as if concentrated. This can be clearly seen in Figure 15 where a comparison is shown between the wave fields at the surface for the 10 and 65 cm concrete pavements at an 8 Hz excitation frequency. Across the width of the pavement (0 to 3.0 m) the amplitude of the wave field for the case of the 65 cm pavement is much less than that of the 10 cm pavement, whereas outside the pavement width the two wave fields are almost identical.

On the other hand, the fact that improving the road structure is effective in reducing vibration levels at high frequencies may be explained as follows. As the wavelength becomes shorter it approaches the road dimensions, leading to propagation action within the pavement itself. Due to the impedance mismatch between the road materials and the surrounding soil a great proportion of the wave energy is trapped within the pavement (box effect). For long wavelengths, however, the pavement behaves more like a rigid body, i.e. there is no propagation action, and therefore most of the wave energy is transmitted to the soil. As the base of the road becomes thicker, lower frequency components start to propagate in the subbase structure. This would explain the effectiveness of soil improvement below the road since it would create a bigger box of sufficient impedance mismatch with the rest of the soil.

## 7 CONCLUSIONS

Based on the FEM simulations of the site considered in this study, the following conclusions are reached:

- Increasing the stiffness and mass of the road structure is not effective for reducing traffic-induced vibrations in the frequency range of interest. However, improvement of the road structure would slow road deterioration and hence indirectly forestall vibration problems by preventing cracking and structural damage, which are the major causes for vibration generation.
- The substantial depth necessary for concrete walls to be effective in reducing ground vibrations renders them impractical.
- Soil improvement under the road is an effective remedial measure for reducing traffic-induced

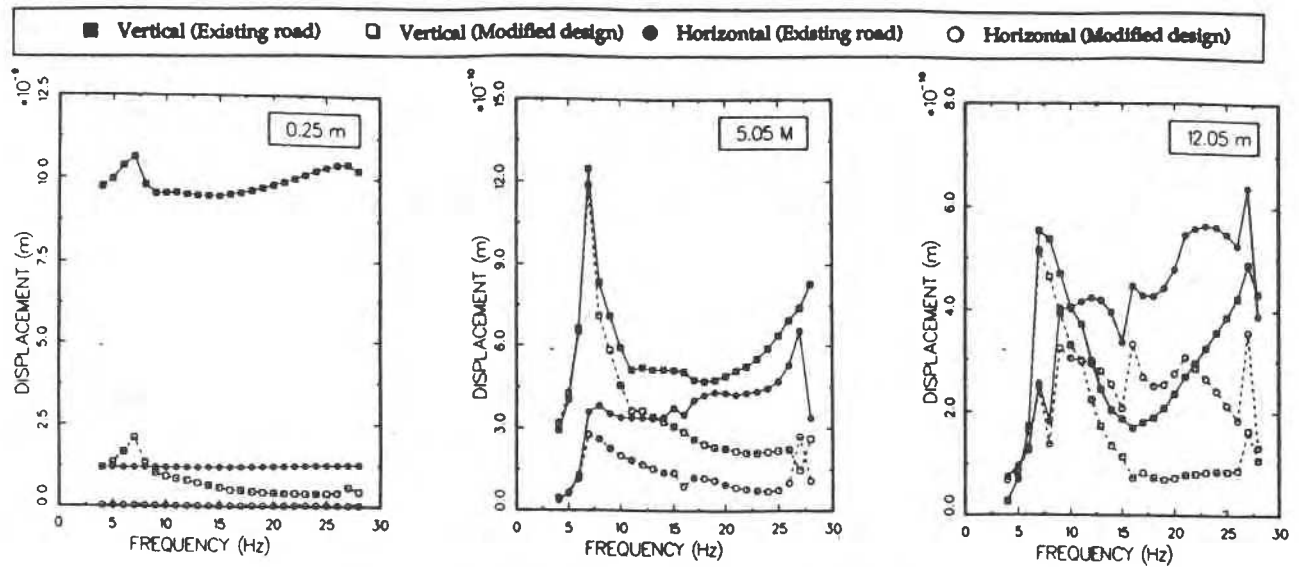


Figure 9 Effect of using a 65 cm deep concrete pavement.

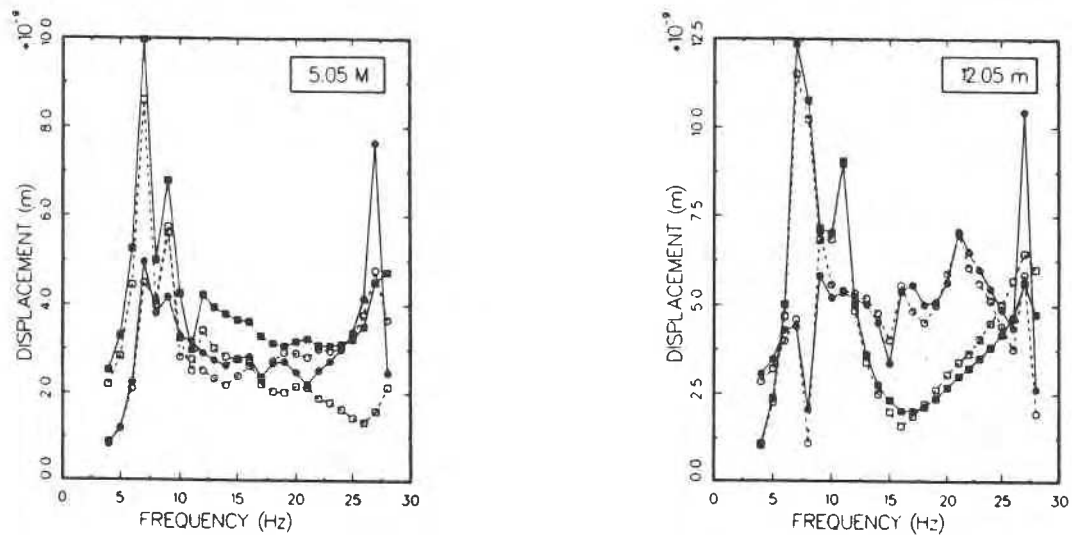


Figure 10 Effect of screening ground vibrations with 5 m deep concrete wall

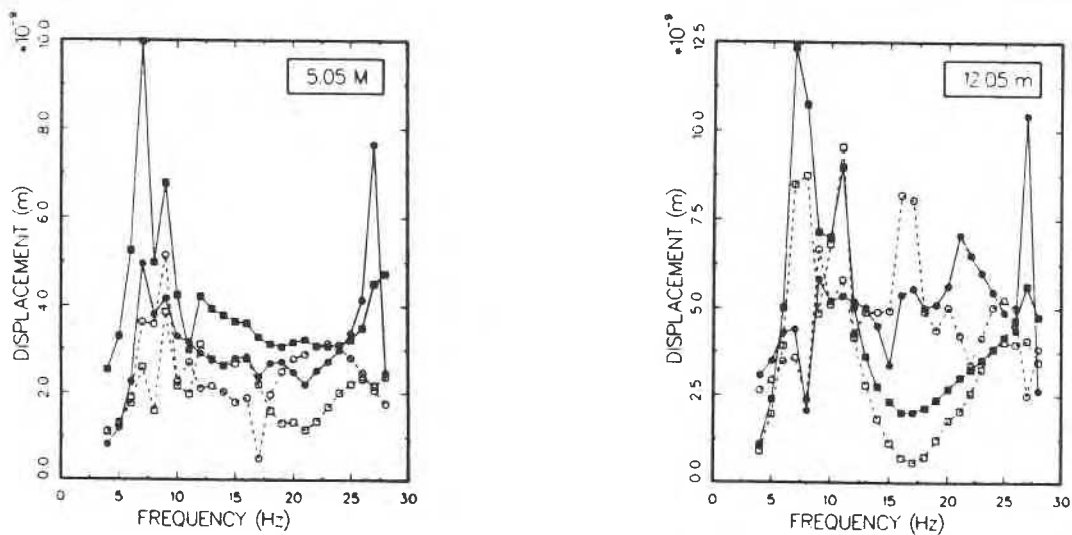


Figure 11 Effect of screening ground vibrations with 10 m deep concrete wall

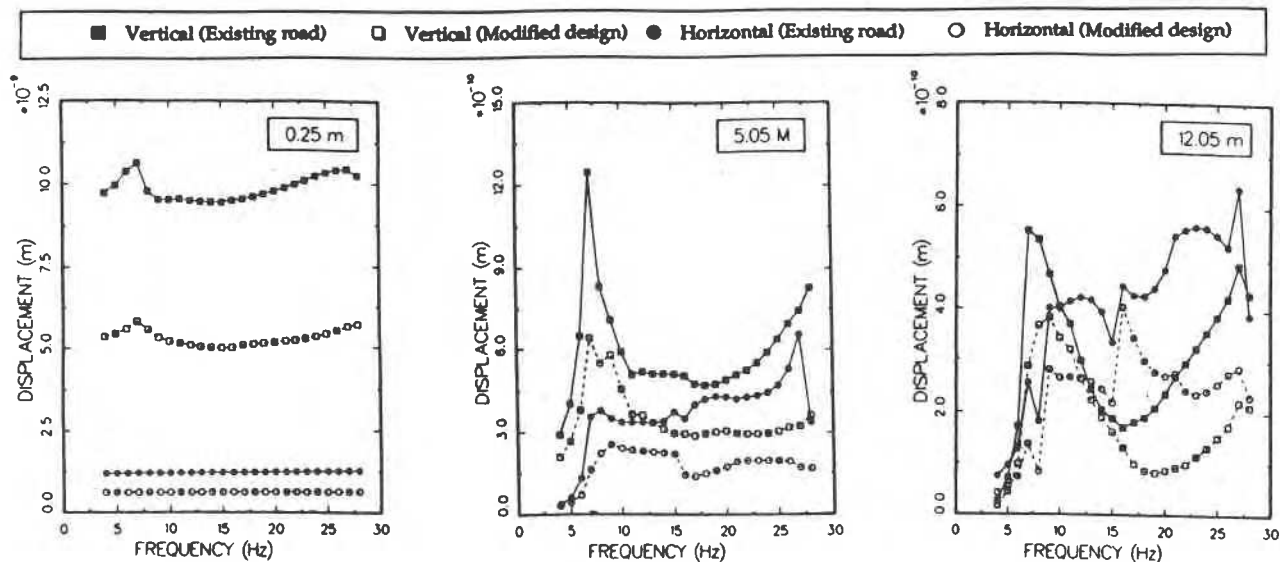


Figure 12 Effect of using 13.5 m deep soil improvement under the road.

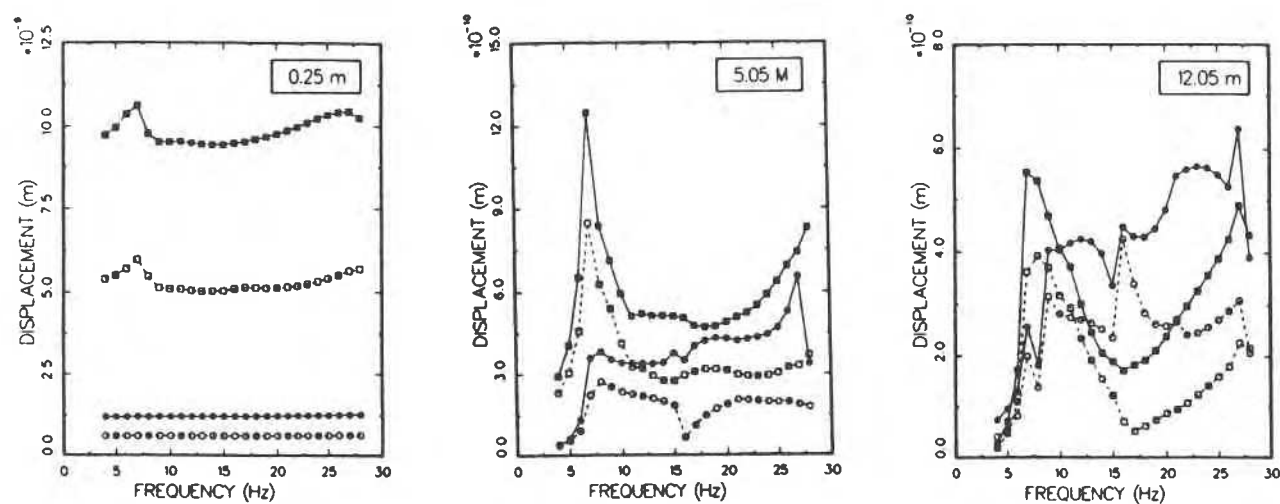


Figure 13 Effect of using 8.5 m deep soil improvement under the road.

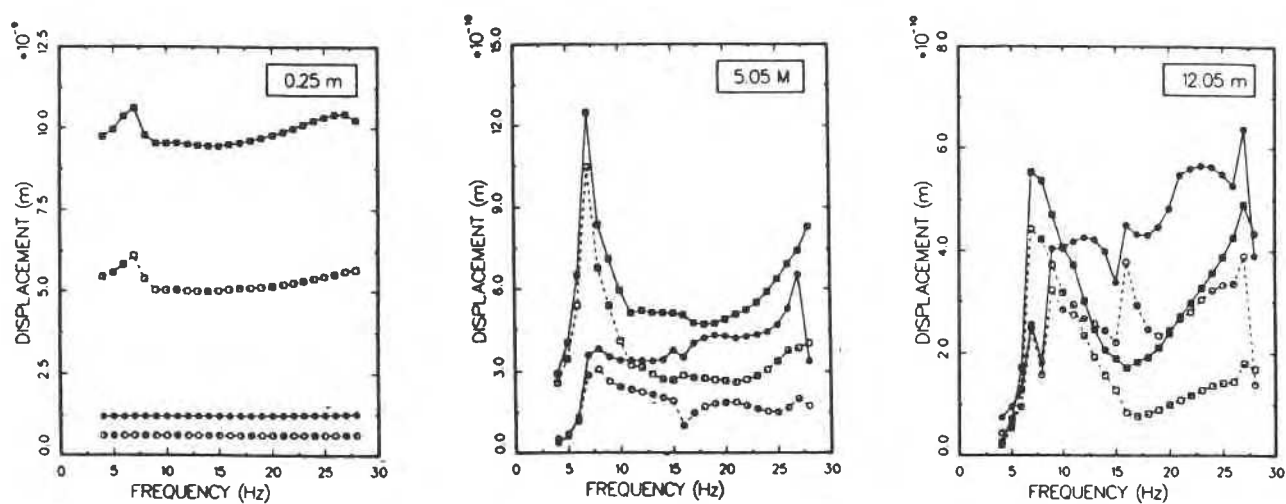


Figure 14 Effect of using 6.0 m deep soil improvement under the road.

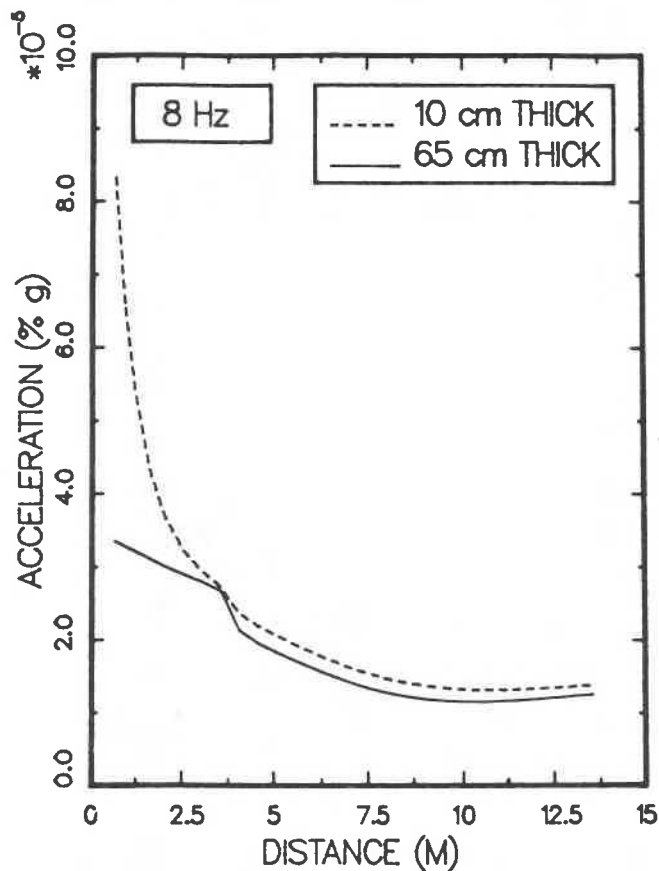


Figure 15 Vertical wave fields at the surface for 10 cm and 65 cm thick concrete pavements.

vibrations. In addition, since the bearing capacity of the soil is also improved, the structural integrity of the road will be further improved, and hence indirectly lead to less vibration generation. The degree of vibration reduction depends on the soil improvement design which is a highly specialized field and beyond the scope of this study. Increasing the soil modulus by at least a factor of 2 and an improvement depth of about 8 m resulted in satisfactory reduction of vibration levels for the site considered in this study.

- The fundamental frequency of the road/subgrade system is governed by the properties and profile of the site. None of the remedial measures that were analysed succeeded in significantly altering it.

## ACKNOWLEDGEMENTS

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