Proceedings of The Institute of Acoustics

# MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHODS

R A Hood and C Marshall

Travers Morgan Planning, East Grinstead, West Sussex

## INTRODUCTION

An experiment which was carried out under contract to the Transport and Road Research Laboratory was designed to investigate the effects of road traffic vibrations on house structures. An empty property was acquired and subjected to simulated groundborne and airborne traffic vibration. Adjacent to the vibration source, six test foundation strips were constructed and subjected to varying dead loads. Dynamic behaviour, movement and damage, in both the main structure and the foundation strips, were closely monitored throughout the experiment. This paper describes the simulation and monitoring techniques employed. Further details are given in Ref.1. The reasons for carrying out the experiment are given in Ref.2.

## EXPERIMENTAL ARRANGEMENT

The general layout of the site is shown in Fig. 1. The test structure comprises a pair of semi-detached houses, approximately 90 years old, constructed of brickwork in lime mortar. The test foundation strips each consisted of an 'H' shaped area of mass concrete surmounted by brickwork. They were arranged in two rows, approximately three and six metres from the vibration source respectively. Loading was arranged to provide ground bearing pressures of half, one and two times that under the main structure in each set of three strips.

Trial pits were dug on the site before and after the simulation, to assess ground conditions and to evaluate soil densities. This work was conducted in order to assist in interpreting any settlement of the structure which occurred. The investigation showed the soil to be a loose to medium dense uniform sand, with a lightly cemented layer at a depth of approximately two metres. It was calculated that if the soil above the cemented layer were to densify during the experiment to optimum density a settlement of between 10mm and 20mm would result.

## COMPUTER SYSTEM

This experiment called for a considerable amount of generation, collection and analysis of electrical signals. For these purposes, a CED Laboratory Interface linked to a BBC microcomputer was employed. This system is capable of fast analogue to digital and digital to analogue conversion of signals on up to 16 channels.

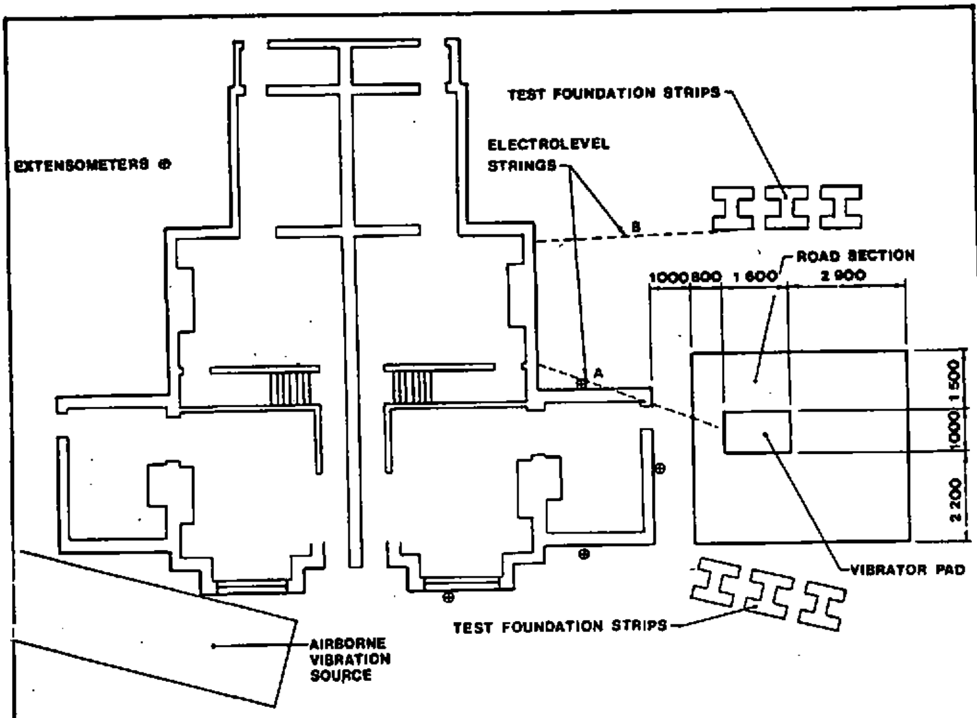



FIG 1 SITE LAYOUT

For the simulation of airborne vibration, the system was operated using an inverse Fourier transform technique to generate a waveform of any chosen frequency content.

For vibration monitoring, data was captured on 12 channels from 4 geophone arrays. Analysis software was developed during the experiment. Facilities developed included: production of waveform amplitude envelopes, fourier analysis of waveforms and cross correlation of waveforms, permitting accurate assessment of wave speed.

## SIMULATION

Building vibrations are generated by road traffic by two separate mechanisms. In simple terms, tyre contact with irregularities in the road surface leads to groundborne vibrations; engine and exhaust noise produces airborne vibrations. For this study, these two vibration sources were simulated independently of each other.

MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHODS

Groundborne Vibrations

Monitoring of building foundations close to main roads has indicated that the groundborne component of traffic-generated vibration typically has the following characteristics:

| | |
|---|---|
| Frequency - | in the range 5 to 30 Hz. The predominant frequency in any particular case depends upon the nature of the vehicle suspension and its loading. |
| Pulse duration - | up to a few tenths of a second, depending upon vehicle speed and number of axles. |
| Maximum amplitude - | the vertical component of vibration in building foundations adjacent to uneven road surfaces frequently exceeds 1 mm/s. Figures of 2-3 mm/s have been recorded in a few instances. |

Simulation was achieved using a geophysical surface vibrator This equipment is capable of vibrating the ground surface with vertical impulses of a selected duration and frequency. A suitable interface was required between the vibrator plate and the soil, both to prevent local soil failure, and to ensure that the passage of vibrations into the ground realistically modelled the effect of a lorry on a road pavement.

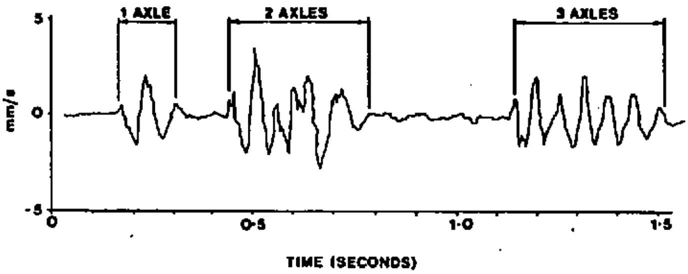
It was decided that this would be best achieved by the construction of a small area (5m x 5m) of flexible road pavement close to the structure under test, on which the vibrator would be mounted. The road pavement was built to withstand 7 million axles in accordance with the DTp Specification for Road & Bridge Works.

The waveform generated by the vibrator had the following characteristics (measured on the adjacent house foundations):

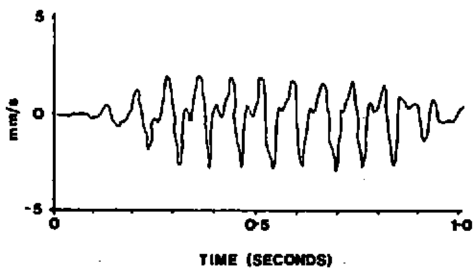
| | |
|---|---|
| Fundamental Frequency | - 12 - 13 Hz |
| Pulse duration | - approximately 1 second, including rise and fall. The waveform typically included 8 reversals at peak amplitude which is broadly equivalent to 4 heavy goods vehicle axles. |
| Maximum amplitude | - 2.5 mm/s (vertical component) |

Figure 2 compares the waveform produced by the vibrator with a typical roadside measurement of a heavy goods vehicle.

MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC
VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHODS




VERTICAL COMPONENT OF VIBRATION MEASURED ON A WALL 1m FROM KERB IN RESPONSE TO FULLY LADEN 6 AXLE VEHICLE TRAVELLING OVER 20mm DEEP IRREGULARITY IN SURFACE




VERTICAL COMPONENT OF VIBRATION MEASURED ON HOUSE FOUNDATION IN RESPONSE TO VIBRATOR

FIG 2 COMPARISON OF VIBRATIONS PRODUCED BY HEAVY LORRY AND VIBRATOR

In addition to the generation of pulses as described above, the vibrator was used on a number of occasions to generate a waveform of continuously varying frequency, such that the dependence of response on frequency could be determined. These "frequency sweeps" ranged from 80Hz to 10Hz in a period of about 15 seconds.

Airborne Vibrations

Noise is generated by traffic over a wide frequency range. However, significant structural excitation only results from low frequency noise (up to about 200 Hz). Noise throughout this range is generated by vehicle engines and exhausts. For the large diesel engines fitted to heavy commercial vehicles vibration levels often peak in the 50-80 Hz region.

Simulation of airborne vibration was achieved by mounting four 18" Celestion loudspeakers in the wall of a high sided refrigeration lorry, parked adjacent to the house facade. These were powered by a 500 watt amplifier. The signal to the amplifier was provided by the CED 1401 Laboratory Interface.

Initially the system was used to generate a broad band signal, ranging in frequency from 0 to 200 Hz, and peaking in the 50-80Hz range characteristic of heavy goods vehicles. Signal amplitude was monitored in the space between the vehicle housing the loudspeakers and the house facade. The signal was pulsed such as to produce a noise level of 110dB during pulses and 100dB between pulses.

The resulting vibration levels were lower than had been expected even in the window adjacent to the loudspeaker system. The broad band signal was replaced with a single frequency source at the resonant frequency of the window (27 Hz). In this way an "upper bound" experiment was carried out. The window vibration levels achieved were the highest possible for the particular noise level (110dB). Therefore it could reasonably be assumed that they would equal or exceed any produced by traffic.

The pulse length used for the majority of the experiment was 2 seconds and the passage of approximately 500,000 vehicles was simulated.

## VIBRATION AND NOISE MONITORING

Vibrations were monitored using four 3-dimensional arrays of geophones. Signals were recorded and analysed using the CED Laboratory Interface. The availability of fast data capture and extensive analysis made it possible to gain considerable understanding of how the structure was responding to the vibration stimulation. In all, vibration response was measured at 82 locations on the structure, 7 on the test foundation strips, and 10 elsewhere.

MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHODS

Noise was monitored using three systems: a B & K Sound Level Metre Type 2209; a CEL Environmental Noise Analyser Type 162 and CEL Level and Waveform Recorder Type 160. Noise levels were analysed using third octave band filters, and a Fourier analysis undertaken using the CED 1401.

Measurements were undertaken of noise level and character within the structure due to groundborne and airborne vibration sources, and an assessment was made of fenestration attenuation. The main measurements are described below:

i. Response of structure to vibration simulation

With the vibrator operating normally, measurements were taken at 20 locations on the outside of the structure, and 9 locations internally. The purpose of this experiment was to assess the dynamic response of the main structural elements to the vibration. By assessing how the groundborne pulse moved through the structure, likely areas of stress concentration were identified. The excitation of floors and walls by the groundborne vibrations resulted in low-frequency noise within the houses. Noise levels were measured in all the front rooms with the vibrator alone operating, and a fine frequency analysis was performed. Noise and vibration levels in response to the airborne vibration source were similarly monitored.

ii. Response of floor joists to groundborne vibrations

Subjective response of house occupants to vibration is often associated with the fact that suspended floors can amplify vibrations. Measurements were carried out to assess the dependence of floor response on the frequency and amplitude of vibration to which it was subjected.

iii. Vibrations due to normal use

The response of different parts of the structure to such activities as slamming doors and running down stairs was measured in order to put the traffic-generated vibrations into context. The levels of noise and vibration in the structure due to external sources (primarily traffic) prior to the start of the experiment were also measured.

MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHODS

## MONITORING OF MOVEMENT

As well as monitoring dynamic behaviour, a number of techniques were employed to monitor changes in the condition of the structure during the course of the experiment. Methods were used to assess movements of the structure, movements within the soil underlying the structure and changes in the pattern of cracking. Details of individual techniques are given below.

All measurements of movement were carried out simultaneously on a series of selected dates. The following table lists the amount of vibration exposure which had occurred at each measurement stage:

| Measurement Stage | Number of vibrator pulses completed | Percentage of total |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 20,000 | 2 |
| 3. | 42,000 | 5 |
| 4. | 85,000 | 10 |
| 5. | 164,000 | 19 |
| 6. | 317,000 | 36 |
| 7. | 558,000 | 63 |
| 8. | 888,000 | 100 |

### Level Survey

In order to assess whether any heave or settlement was occurring, levelling stations were installed at 36 locations on the structure. These were levelled using at Wild N3 level and an Invar staff, with which it was possible to resolve movements in the foundations of $\pm$0.3mm.

### Moire Photography

To determine whether or not any differential movement was occurring within the structure, the N.P.L system of high resolution Moire photography was employed(3). Specially prepared paper printed with a fine grid of lines was attached to the front facade of the house and photographed with a modified 35mm camera. When two negatives produced on different dates were overlaid, interference fringes were produced which related to movements of the structure. By this technique, differential movements in the plane of the facade were resolved to 0.2mm.

MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHODS

Crack Survey

During the preparation of the houses for the experiment, all wallpaper and ceiling finishes were removed. This revealed very extensive existing cracking in the plaster. Due to the extent of the cracking, it was not possible to accurately measure and monitor every crack. Instead, 40 existing cracks in various locations were selected and monitored for movement with a Demec gauge. In addition, the location of every significant crack was recorded on a plan or elevation of the relevant facade. On each measurement day, an inspection was carried out, and any further cracking recorded.

Soil Movements

The level survey was intended to measure settlement of the structure. Such settlement could develop by three mechanisms:

(i) Settlement directly under the vibrator pad extending to the soil beneath the structure.

(ii) Soil densification below the house footings.

(iii) Soil particle movements, perhaps without change in density, within a "log-spiral" zone under each footing. A log spiral is the curve along which a failure surface would typically develop within the soil. Slight shearing along such a surface could lead to settlement.

In order to assess which mechanism was responsible for any observed settlement and to corroborate the results of the level survey, two techniques were employed for monitoring movements within the soil.

(i) Electrolytic levels

Electrolytic levels measure change in inclination. For this study, six such levels were positioned at intervals along each of two horizontal boreholes. The boreholes were about one metre below ground level. Borehole locations are shown on Fig.1. Soil movements were calculated by integrating the measured inclination changes. This technique was developed at the Building Research Establishment(4) but has never previously been used in a sand deposit. We assessed the accuracy of the system to be better than $\pm$ 0.1mm.

MONITORING THE EFFECTS OF SIMULATED ROAD TRAFFIC VIBRATIONS ON A TEST HOUSE - EXPERIMENTAL METHOD

(ii) Magnetic Extensometers

Magnetic Extensometers consist of a series of magnets embedded in the soil, a plastic guide tube, and a probe. The probe is passed up and down the guide tube in the soil and detects null points in the magnetic fields. This enables relative vertical movements within the soil to be deduced. For this study, systems were installed and operated by Soil Instruments Limited, Uckfield, Sussex. The accuracy claimed for the system was $\pm$ 0.1mm. Four extensometers were installed, each to a depth of 4m (see Fig.1).

By using the above techniques the degredation of a building due to the effects of road traffic noise have been studied. The results of this work are given by C Marshall in a subsequent Paper(5).

## REFERENCES


1. R A Hood and C P Marshall, 'The Effects of Simulated Traffic Vibration on a Dwelling House', TRRL Contractor's Report CR44 (to be published).

2. P M Nelson and G R Watts, 'Traffic Vibration and Building Damage' - paper presented at 'Acoustics '87' (1987)

3. J M Birch and C Forno, Optical Engineering Vol. 21, No. 4, 602-614 (1982).

4. R W Cooke and G Price, 'Horizontal Inclinometers for the measurement of vertical displacement in soil around experimental foundations', Field Instrumentation in Geotechnical Engineering pp 112-125. Butterworths.

5. C P Marshall and R A Hood, 'Monitoring the effects of simulated road traffic vibrations on a test house - results' - paper presented at 'Acoustics '87', (1987).


The authors of this report are employed by Travers Morgan Planning. Work reported herein was carried out under a contract placed on them by the Transport and Road Research Laboratory. The views expressed are not necessarily those of the Department of Transport.