ENGINEERING PREDICTION OF RAILWAY VIBRATION TRANSMISSION IN BUILDINGS

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1. INTRODUCTION

This paper presents measurement data collected from two buildings subject to railway vibration input at the foundations. Groundborne railway vibration propagates into nearby buildings where it may result in perceptible vibration (generally significant between about 5Hz and 50Hz) and re-radiated (structureborne) noise (generally significant in octave bands centred on 31.5Hz, 63Hz and 125Hz).

The mechanisms of propagation of railway vibration into and throughout buildings are complex (see Figure 1). The prediction process is therefore difficult and is always subject to significant uncertainty. Assessment methods range from preliminary estimates based on previous observations to comprehensive dynamic analysis and modelling (Reference 1).

In the building design process a decision about whether the substructure should incorporate vibration isolation is required early in the programme, generally in advance of the design of the superstructure. For this reason engineering predictions for a given structure must often be made on the basis of relationships developed from measurements on other structures, rather than entirely on the basis of mathematical or analytical techniques.

The two case studies presented in this paper were selected for detailed study from a wide range of current projects. The data are examined in terms of the way in which vibration levels vary with propagation throughout the structures involved and, where appropriate, throughout stages of the construction process.

2. MEASUREMENTS ON A REINFORCED CONCRETE STRUCTURE

The first case is a recent office and retail development situated on Tottenham Court Road in London. The raft foundation is 25m from the centre line of the London Underground Limited Northern Line railway tunnel which is beneath the road.

The building comprises a reinforced concrete structure with reinforced concrete shear cores (see Figure 2). Floor slabs are concrete (normal density, cast in situ), of 250mm thickness. The raft foundation of 900mm thickness forms the basement floor slab and the roof slab is 300mm thick. The building comprises seven floor levels in total (basement, ground, first to fifth) as illustrated (Figure 2).

Prior to the development, evaluation in a previous building on the site indicated that an acceptable internal environment could be achieved in the new building without the need to limit groundborne vibration transmission into the structure (eg by isolation of the superstructure on resilient bearings or by changes to the substructure design). The development was subsequently chosen as the basis of a case study on the propagation of railway vibration due the relatively simple nature of the structure.

Visits were made at the following stages of construction (outside the hours of construction activity):

1. Structure complete, no cladding or mechanical services.

2. Structure complete, cladding complete and mechanical services approximately 50% complete.

3. Structure complete, cladding complete, raised floors and ceiling grid installed, mechanical services approximately 90% complete.

On each of these visits floor slab vertical vibration velocity signals were recorded at a column and a mid-bay location at each floor level in turn. Typical measurement results are presented in Figures 3 to 6 in terms of arithmetic average L_{max} vibration levels. Data are shown for basement level and fifth floor level for each of the visits.

The results confirm that the levels of railway vibration and structureborne noise in the completed building are significantly within acceptability criteria for quality office developments (References 2 to 5). The maximum floor slab vibration velocity encountered was 0.12mm/s (rms) (approximately the threshold of human perception) while predicted re-radiated noise levels were around NR25 (below both the level of residual traffic noise break-in and the expected level of mechanical services noise).

The results have been examined in detail in terms of the variation in velocity levels:

- between column and mid-bay floor slab locations.
- between different floor levels.
- between visits at different stages in construction.

The key findings are:

- no significant difference was observed between vibration levels measured at basement level for the three visits (Figure 3).
- in the course of transmission from the basement level to the fifth floor level, vibration levels were amplified at low frequencies (4Hz, 8Hz and 16Hz octave bands) and attenuated at higher frequencies (63Hz and 125Hz octave bands).
- the amplification at low frequencies reduced with the addition of cladding and mechanical services to the basic structure. The results from the

third (final) visit show amplification (between basement level and fifth floor level) of around 5dB at low frequencies (4Hz, 8Hz, 16Hz) and attenuation of around 5dB at higher frequencies (63Hz, 125Hz); levels in the 31.5Hz octave band were similar at top and bottom of the building.

- as expected, suspended floor slabs exhibited amplification effects at mid-bay locations (with respect to column locations). Amplification effects were generally insignificant in the 4Hz and 8Hz octave bands, 10 to 20dB in the 16Hz octave band (incorporating the fundamental natural frequency) and 5 to 10dB in the 31.5Hz, 63Hz and 125Hz octave bands.
- floor slab (column to mid-bay) amplification values derived for a particular floor remained constant between the three visits. Comparison of the values for floor slabs at different levels, however, showed significant variation (eg 7dB at fourth floor level, 14dB at first floor level - visit 3). In general, amplification effects were greater at ground, first and second floor levels than at third, fourth and fifth levels.

The results for this project illustrate floor slab response effects and vibration propagation effects from lower to upper floors. Comparison with data from other buildings suggests these effects are typical. The results also highlight the variation in response which can occur in practice between essentially identical structural elements (suspended floor slabs at different levels in the building).

3. MEASUREMENTS ON A STEEL FRAMED STRUCTURE

The second case concerns the development of a 13 storey office building straddling the railway tracks and part of the platforms at the British Rail Fenchurch Street Station in London (see Figure 7).

Vibration measurements under the brick arch viaduct of the railway were undertaken prior to the development. The results confirmed that structural isolation would be necessary in order to provide acceptable conditions in the office development. The project proceeded incorporating elastomeric bearings at pile cap level with a vertical natural frequency of approximately 10Hz.

The substructure comprises piled raft foundations in clay and the superstructure is steel framed with lightweight composite floors (concrete with metal decking) of 130mm thickness. Columns are generally spaced on a 9m by 9m grid but the structure is complex because it envelops the railway (the third floor is an interstitial level housing mechanical services equipment and providing a transfer structure over the railway) and the floor layout changes with height in the building (see Figure 8).

Vibration measurements were undertaken as follows:

- borehole vibration measurements at approximately 10m depth prior to construction.

- vibration measurements at pile cap level after the construction of piles and pile caps.
- vibration measurements at pile cap level and fifth floor level after the basic structure complete (~75% of building load present).
- noise and vibration measurements at basement and fourth floor levels after the completion of the building.

The borehole measurements were undertaken to establish the amplitude of vibration at the effective foundation level. The vertical velocity data for one of the boreholes are shown in Figure 9 along with those for the pile cap subsequently constructed in the same location.

As expected, there is both a reduction in vibration levels at the pile cap level with the imposition of building load and a reduction in pile cap vibration amplitudes at high frequencies (250Hz octave band) with respect to those measured at borehole level. Comparison of the data for the borehole measurements with those for the pile cap (in loaded condition) shows that, in the frequency range covering the 4Hz to 125Hz octave bands, vibration levels are not significantly different. This result provides insight into the coupling loss effect (reduction in foundation vibration level with respect to the surrounding ground) for a piled raft foundation in clay and supplements information reported elsewhere, such as in the Transportation Noise Reference Book (Reference 6).

The basement floor slab is below the isolation line and is cast at grade. Vibration levels measured within 15m (on plan) of the railway structure were similar to the levels measured on the pile cap. The vibration levels were within acceptable limits in relation to human perception but, as expected, estimated re-radiated noise levels were in excess of appropriate limits. This confirms that, taking into account the effects of propagation up the building structure and the resonant response of suspended floor slabs, vibration isolation had been necessary in order to provide acceptable conditions on upper floors.

Vibration levels were subsequently measured at fifth floor level at column and mid-bay locations. The data are shown in Figure 10 along with the BS 6472:1984 (Reference 5) curve 4 criterion for vertical velocity. Although these measurements were undertaken at a stage in construction when the isolation bearings were suspected to be partially bridged by construction debris, the vibration levels were within the design target (curve 4) and estimated re-radiated noise levels were within acceptable excursions above the NR35 services noise (Reference 4). This is a preliminary indication of successful isolation.

The floor slab shows a resonant response with amplification of around 25dB in the 8Hz third octave band (corresponding to the fundamental natural frequency) and 5 to 10dB at higher frequencies (see Figure 10).

Subsequent noise and vibration measurements at basement and fourth floor levels confirmed the following:

- structureborne train noise levels in the basement area (not isolated) justified the vibration isolation of upper floors

- train noise and vibration levels at fourth floor level were within the target criteria set for quality office space

In summary, the results for this project show the following:

- no reduction in foundation vibration levels with respect to the ground
- successful use of isolation to limit railway vibration transmission into a building
- typical response effects of lightweight concrete floor slabs

4. CONCLUSIONS

The propagation of railway vibration in building structures is complex. Dynamic analysis and modelling techniques are under development but preliminary assessments are likely to continue to be made on the basis of observations from previous projects.

Results are presented in this paper relating to vibration propagation in two previous building projects - an isolated steel frame structure and an unisolated concrete frame structure. The key findings are:

- low frequency (4Hz to 16Hz octave bands) vibration may be amplified in transmission from lower to upper floors in buildings

- the addition of cladding and building services to a structure reduces the extent of this low frequency amplification

- considerable variation can occur in practice between responses of floor slabs of essentially the same construction

- in practice coupling loss may not be significant for piled foundations in London clay

REFERENCES

1 D Newland (1992)
Isolating buildings from vibration Proc second international congression recent developments in air and structureborne sound and vibration

2 J G Walker and S A Ridler (1991)
Prediction and Assessment of Groundborne Noise from Underground Railways Proc IOA 13(5)

3 C J Manning (1991)
Noise and Vibration from the Ludgate Railway Works
Proc IOA 13(5)

4 S A Ridler (1991)
Structureborne Noise Design Aims in Mixed Developments - a summary
Proc IOA 13(2)

5 BS 6472:1984
Guide to the evaluation of human exposure to vibration in buildings (1Hz to 80Hz)
British Standards Institution

6 P Nelson (Ed) (1987)
Transportation Noise Reference Book
Pub. Butterworths

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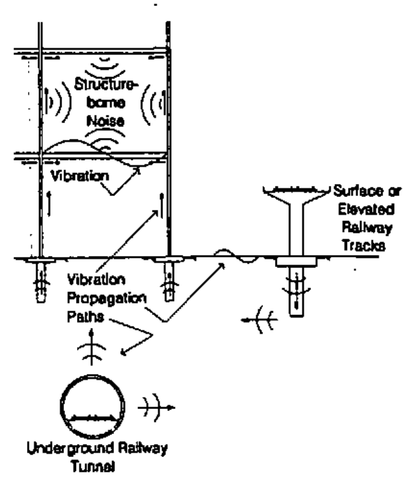

FIGURE 1: SKETCH ILLUSTRATING THE PROPAGATION OF VIBRATION INTO STRUCTURES

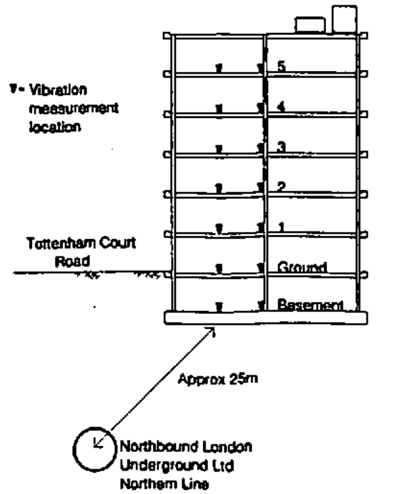

FIGURE 2: SKETCH SHOWING STRUCTURE OF DEVELOPMENT ON TOTTENHAM COURT ROAD AND RELATIONSHIP WITH UNDERGROUND TUNNEL

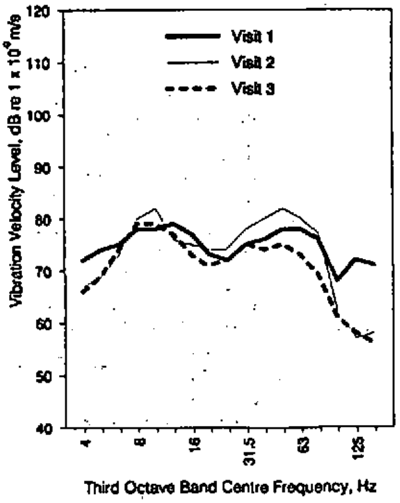

FIGURE 3: AVERAGE VIBRATION LEVELS ON THE BASEMENT FLOOR SLAB FOR EACH VISIT

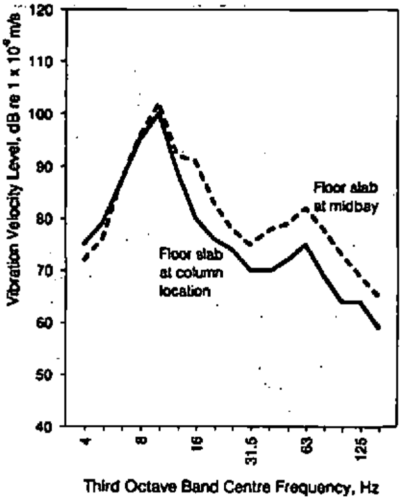

FIGURE 4: AVERAGE VIBRATION LEVELS ON THE FIFTH FLOOR SLAB FOR VISIT 1

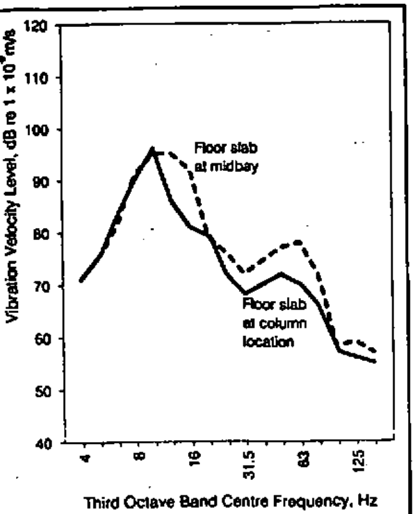

FIGURE 5: AVERAGE VIBRATION LEVELS ON THE FIFTH FLOOR SLAB FOR VISIT 2

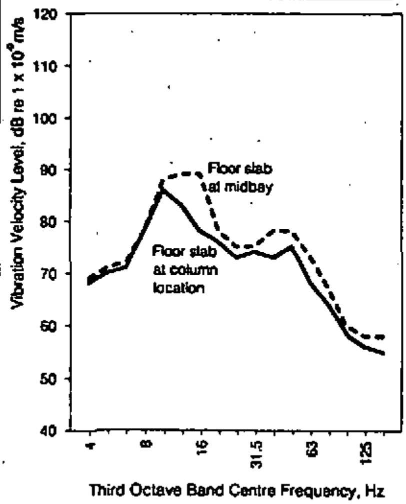

FIGURE 6: AVERAGE VIBRATION LEVELS ON THE FIFTH FLOOR SLAB FOR VISIT 3

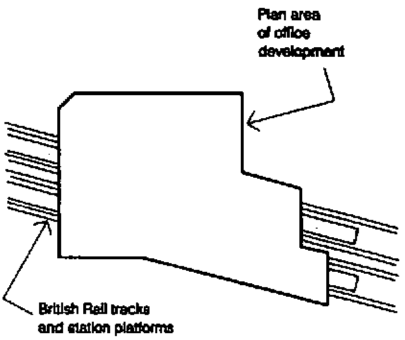

FIGURE 7: SKETCH ILLUSTRATING ON PLAN THE DEVELOPMENT AT FENCHURCH STREET STATION

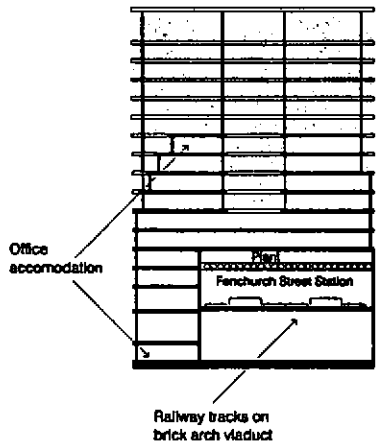

FIGURE 8: SKETCH ILLUSTRATING IN SECTION THE DEVELOPMENT AT FENCHURCH STREET STATION

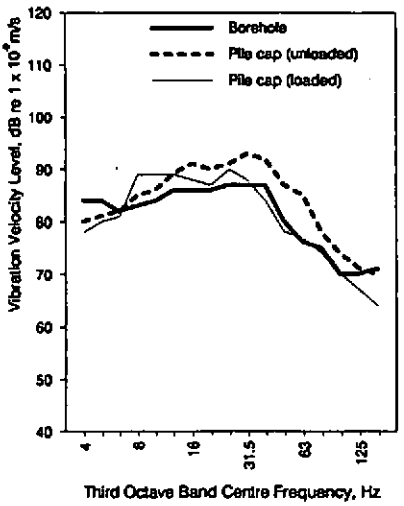

FIGURE 9: AVERAGE VIBRATION LEVELS AT BOREHOLE AND PILE CAP LEVEL

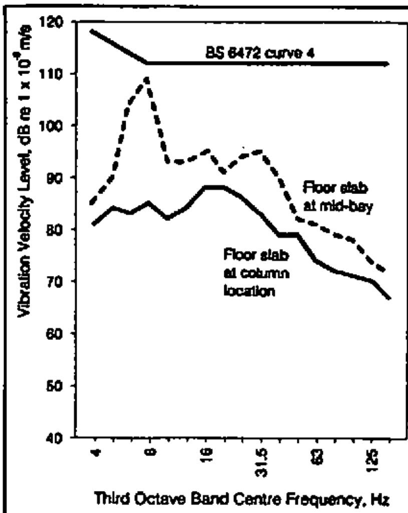

FIGURE 10: AVERAGE FLOOR SLAB VIBRATION LEVELS ON THE FIFTH FLOOR