THE EFFECTS OF GROUND VIBRATION DURING BENTONITE SHIELD TUNNELLING AT WARRINGTON

by

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THE EFFECTS OF GROUND VIBRATION DURING BENTONITE SHIELD TUNNELLING AT WARRINGTON

ABSTRACT

The research was carried out during the bentonite shield tunnel drive for the Acton Grange trunk outfall sewer at Warrington, Cheshire. This tunnel was driven through cohesionless Drift deposits beneath a built-up urban environment, with a cover of less than 6 m. The environmental effects of the ground vibration caused by the excavation process were investigated with particular regard to ground settlement by compaction.

Vibration data were recorded from transducers located in boreholes, on the surface, on the tunnelling machine and on the concrete tunnel lining. These records were processed to characterise the vibrations in terms of peak particle velocities, frequency spectra and spatial attenuation.

The maximum measured ground vibration (expressed in terms of resultant peak particle velocity) was 3.9 mm/s. The vibration was characterised by random high velocity particle motions resulting from impacts between the machine's disc cutters and glacial boulders in the tunnel face.

Surface and subsurface settlement measurements were made along the tunnel line. Laboratory tests and other field data showed that the ground in this area was likely to settle at levels of vibration lower than those measured from the tunnelling machine.

Vibration from the excavation process probably caused ground compaction which contributed significantly to ground settlement and its effects. The vibration was not likely to have caused any direct damage by dynamic stressing but the associated low level noise did cause concern among local residents.

1. INTRODUCTION

The viability of civil engineering construction techniques will often depend upon their effects on existing structures, and recently increasing importance has been given to the preservation of 'environmental amenity' during construction works. Vibrational energy transmitted either through the ground or, in the form of sound, through the air can be a major contributor to structural and environmental damage; Steffens\(^1\), Whiffin and Leonard\(^2\), and Roberts\(^3\) have reviewed vibration and its effects.

Vibration and noise from 'construction' sources will generally be temporary. The disturbance caused, however, may result in permanent damage to property, and substantial nuisance to the surrounding population\(^4,5\). Both these factors may prevent the works from continuing efficiently, so resulting in additional costs or even curtailment of activity.
Explosive blasting\textsuperscript{6,7,8}, and piling operations\textsuperscript{9,10,11} have in the past been the cause of greatest concern, but in recent years mechanisation of tunnelling methods has resulted in the use of plant which can put large amounts of energy into the ground. Pakes\textsuperscript{12} reports restrictions imposed on the construction of a tunnel due to disturbance of the local population.

Many methods of tunnel construction will dissipate energy into the surrounding ground in the form of vibration and cause disturbance at the surface either directly by shaking the overlying property, or indirectly by causing settlement which may distort and undermine it. If the tunnel has little cover then the noise created may disturb the local population, particularly at night.

Little, if any, work has been undertaken to investigate the effects of vibration from the tunnelling process, although information is available on vibrations produced when tunnels are in operation\textsuperscript{13,14}. Many studies have reported the settlements\textsuperscript{15} caused by tunnel and mining excavations but no reference is made to any possible effects from vibration. Boden and McCall\textsuperscript{16} noted that disturbances produced by tunnelling operations may result in compaction of a loose granular soil with consequent substantial ground settlement. Information on earthquake induced settlements and damage\textsuperscript{17,18} is widely reported but is not easily related to tunnelling as the amplitude, frequency and duration of energy from such tremors is not similar to that produced by tunnelling machines.

The construction of a 1350 m length of 2.44 m diameter trunk outfall sewer at Warrington\textsuperscript{19} using the bentonite tunnelling process\textsuperscript{20} provided an excellent opportunity to study vibration caused by tunnelling. The tunnel was constructed by Edmund Nuttall Ltd for the Warrington New Town Development Corporation. An aim of the bentonite process is to reduce settlements, caused by deformation of the ground towards and into the tunnel, to a minimum. Thus settlements caused by compaction of the ground could well assume a dominant role; the coupling effect of the bentonite slurry is likely to enhance the transmission of energy to the ground. Plate 1 shows the completed tunnel lined with bolted concrete segments with dry weather flow channel installed subsequently.

2. THE SITE AT WARRINGTON

2.1 The geology

Warrington is in North East Cheshire and the tunnel, approximately 2 km south of the town centre, runs for 1.4 km parallel to and about 20 m south of the Manchester Ship Canal.

The tunnel was driven through the Upper Mottled Sandstone of the Bunter Sandstone series and the windblown sands and fluvo-glacial gravels overlying it. The Downall Green fault passes close to the tunnel portal and the Upper Mottled Sandstone east of the fault dips at about 5° to the SSE practically normal to the tunnel line. Undifferentiated marine alluvium is also present in this area of the Mersey valley. The area geology is fully described in the British Regional Geology series\textsuperscript{21}.

2.2 The site investigation

The initial site investigations depended almost entirely on information derived from boreholes along the proposed line of the tunnel. These boreholes confirmed broadly the lithologies shown by the Geological Survey data but did not reveal the loose ground and boulders mentioned below which led to serious tunnelling problems. It was on the basis of this geological data that the contractor decided to use the bentonite tunnelling system.
Vibration and settlement studies were carried out at the two sections designated A and B shown on the site map, Figure 1. Transducers were installed in boreholes at each section and, during the sinking of these, stratigraphical logs were taken (Figure 2). The first 1 m of the ground was excavated as a pit to reveal any services, and each borehole log was overlain by about ½m of fill material in the form of tarmacadam, sand and sandstone boulders.

The effective size of the soil obtained from these boreholes was typically 0.2 mm with a coefficient of uniformity of 2.5. This indicates a uniformly graded ‘fine’ to ‘medium’ grained sand. During tunnelling the material was found to be extremely varied with bands of silty clay and gravel.

Tunnelling operations also revealed the presence of mainly granite and dolerite boulders up to 500 mm in size. These glacial erratics were derived from the Southern Uplands of Scotland and the Lake District and, together with the sandstone often found in the tunnel invert, were to have a critical effect on the level and type of ground vibrations caused by the excavation process. The level of the water table was derived from borehole logs and piezometer readings and was at approximately tunnel axis level at both Sections A and B.

2.3 The penetration resistance and density of the soil

Standard penetration tests (SPT) carried out during construction in the vicinity of the tunnel at Sections A and B often gave values of below 10 and values of 1 to 5 were common; this indicates areas of very loose ground\(^{22,23}\) with considerable potential for settlement due to compaction.

During the excavation of a trench for a feeder sewer to the main tunnel the opportunity arose to measure the \textit{in situ} density of the soil on the proposed tunnel line at a depth of 4.5 metres. Twenty-two \textit{in situ} density determinations were made using a sand replacement method (7 tests) and modified core cutter method (15 tests). No significant difference was found between the results given by the two methods. Table 1 gives the summarised results, and the high standard deviations show the extremely varied nature of the soil. The dry density, moisture content and air content varied considerably, even over distances of less than 1 metre, and reflected not only changes in the packing of the particles but also variations in the material itself, eg bands of silty clay were clearly visible in the trench floor.

\begin{table}[h]
\centering
\caption{Results of \textit{in situ} density measurements}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Type of test & No. of tests & Dry density Mg/m\(^3\) & Moisture content per cent & Air content per cent \\
\hline
& & Mean & Standard deviation & Mean & Standard deviation & Mean & Standard deviation \\
\hline
Sand replacement & 7 & 1.59 & 0.08 & 17.7 & 2.4 & 11.3 & 3.4 \\
Core cutter & 15 & 1.55 & 0.09 & 10.9 & 6.4 & 24.3 & 8.9 \\
Both* & 22 & 1.57 & 0.09 & 13.1 & 6.3 & 19.9 & 9.7 \\
\hline
\end{tabular}
\end{table}

* Mean Void Ratio 0.68 \hspace{1cm} Mean Porosity 0.40
The maximum dry density of the soil was found (Test 13, BS 1377:1975, 4.5 kg rammer) to be 1.80 Mg/m$^3$ at a moisture content of 11 per cent. The 'relative compaction' of the soil, i.e., the ratio of the field dry density to the maximum dry density found in the BS compaction test (4.5 kg rammer) was 87 per cent. This is subjectively described as loose/medium and corresponds to the SPT values of 10 and under$^{22,23}$, which were found at similar levels in the vicinity of Sections A and B.

These density measurements confirmed that there was scope for an increase in the in situ density of the soil at Warrington and, consequently, settlements at the ground surface. The wide variation of density values indicated the inhomogeneous nature of the lensed Drift deposits.

3. THE MEASUREMENT, RECORDING AND PROCESSING OF THE VIBRATION DATA

3.1 Transducer type and location

It was decided at an early stage that the vibrations to be measured would be expressed in terms of their peak particle velocity and frequency. A review of current literature revealed that this is the most usual approach, although acceleration-frequency and displacement-frequency descriptions are also found. In the context of structural damage vibrations are generally expressed in terms of particle velocity although the relevant factor to human perception is related to the frequency range involved. At frequencies below 10 Hz acceleration seems to be the dominant consideration, whilst at frequencies between 10 and 50 Hz velocity criteria are appropriate. At frequencies above 50 Hz displacement is the more important factor. Studies on the effect of vibration on settlements of sands are usually at the low frequencies which are associated with earthquakes and commonly used acceleration as a criterion.

Most measurements were made with arrays of three mutually perpendicular transducers to enable maximum particle velocities to be calculated if required by vector summation as follows:

\[ V_{\text{res}} = \left( V_{\text{vert}}^2 + V_{n-s}^2 + V_{e-w}^2 \right)^{\frac{1}{2}} \]

where

- \( V_{\text{res}} \) = Maximum resultant velocity
- \( V_{\text{vert}} \) = Maximum vertical velocity
- \( V_{n-s} \) = Maximum velocity in a north-south direction
- \( V_{e-w} \) = Maximum velocity in an east-west direction.

Calculation of resultant velocity in this way provides an inherent factor of safety as it is unlikely that maximum velocities recorded individually from the three transducers will occur simultaneously.

Velocity type geophones were used for all surface and borehole measurements. The 'horizontal' and 'vertical' type geophones were of type Z–2CA manufactured by Walker-Hall-Sears and had an effective field sensitivity of 15 mV/mm/sec. The sensitivity of these geophones falls rapidly at frequencies below 10 Hz. The low frequency ground motion at the site was monitored by accelerometers (bandwidth DC to 2 kHz) and found to be negligible.
Arrays of three mutually perpendicular geophones were placed at approximately 0.2 m, 1.0 m, 2.25 m and 3.7 m below the pavement surface in boreholes above the tunnel crown at Sections A and B. The boreholes were backfilled with the excavated material and tamped to restore the ground to as near its original condition as possible.

Supplementary measurements were carried out on the pavement surface using geophone and accelerometer arrays as required.

A model 2100 portable vibration analyser produced by Environmental Equipments Ltd of Wokingham, Berkshire, was used to make the vibration measurements in the tunnel. This fully portable equipment employs a piezoelectric accelerometer with magnetic mounting and provides meter read-out in terms of acceleration, velocity or displacement. It also incorporates a narrow-band tuneable filter, which allows measurement of each variable at any particular frequency.

3.2 Conditioning and monitoring

The conditioning and monitoring equipment was housed in a mobile laboratory parked close to the borehole (Plate 2). The arrangement of the equipment is shown fully in Figure 3.

A headset for listening to the seismic noise proved a valuable asset. With experience it was possible to recognise, by ear, almost all forms of seismic noise from the tunnel and environmental sources. Viewing the signal on the oscilloscope was not so useful for this purpose.

3.3 Recording

The twelve amplifier outputs were fed to an ultra-violet chart recorder which provided hard copy in real time of all the geophone outputs from any one borehole. This facility was particularly useful when deciding which were the most appropriate channels to record on magnetic tape for subsequent spectral analysis. In order to resolve frequencies of up to 500 Hz it was necessary to run the paper at fairly high speeds and this meant that only relatively short bursts of data could sensibly be recorded.

A four-channel instrumentation cassette recorder was used to record data from selected geophone channels. This form of data storage allowed a tape library containing many complete ‘mucks’ (the excavation for one lining ring, 0.615 m long) to be recorded in a form suitable for direct input to a spectrum analyser or ultra-violet chart recorder. It was usual to record either all three geophone outputs at one level or one geophone output from each level (all four having a common direction of sensitivity).

3.4 Processing

The principal objectives of the processing were:

(a) to determine the maximum soil particle velocities; and
(b) to characterise the seismic energy in terms of its frequency spectrum.

Objective (a) was achieved by replaying the data held on cassette and recording on the UV recorder the period of maximum observed particle velocities.
Spectrum analysis was carried out using a Honeywell-Saicor analyser model SAI-52B \(^{24}\) (see Plate 3). This analyser is essentially a hard wired computer using a swept filter combined with a time compression system to provide the frequency domain characteristic of the applied signals. The relative phase of the individual Fourier components is lost, and as the maximum value of the signal (in this case velocity) may be of interest, this information must be obtained from time domain processing.

The information derived from the spectrum analysis allows the principal frequencies to be identified and possibly attributed to the source and the nature of the propagating medium. It also indicates the deployment of the seismic energy over the frequency range.

A spectrum which is characteristic of a long record length is produced through the digital integrator section of the analyser. Another useful feature is the 'peak hold' facility which, during the processing of data, captures and holds the peak value occurring in each bin. This is particularly useful when the signal comprises a low background noise with high amplitude oscillations occurring with frequent but random periodicity.

3.5 The spectrum analysis of field data

It was decided to simplify the comparison of the frequency spectra by standardising on a single bandwidth for all the processed data. This bandwidth was determined by analysing data when the source, the tunnelling machine, was at its closest to a geophone array. Since high frequencies are selectively attenuated to a greater degree than low frequencies these conditions indicated that the maximum bandwidth required was 500 Hz. The input/output gain factors in the processor were also fixed and the relative amplitude of each spectrum obtained from the original amplification applied to the geophone signal at the time of recording.

The vertical scale of the spectra was output from the analyser in volts/bin and was proportional to the voltage output from the geophone which, in turn, was proportional to velocity. Owing to the non-stationary nature of the spectra, the unrelated phase distribution of Fourier components, and the finite window size of the processed data, it was not permissible to scale the spectra in terms of particle velocity. The relative amplitudes of the spectra were scaled in terms of a common and arbitrary unit, and when required, the particle velocity was derived directly from the time domain records as previously stated. As all the records were from a common source, and were processed in the same manner, each spectrum is directly correlated by its common scale with any other, so allowing conclusions to be drawn based on comparative measurements. Owing to the non-linear response of the geophones and the effect of low frequency speed variation of the recorder, the part of the spectrum below 10 Hz should be disregarded. A few records were obtained giving high amplitudes at frequencies below 10 Hz; these were invariably found to be the result of over-modulation of the magnetic tape and were discarded as unreliable. It has been noted earlier that independent measurements using piezoelectric accelerometers indicated no significant signal below about 10 Hz.

The raw data were fed directly in analogue form from the tape recorder to the analyser input. The continuous and averaged spectra were displayed throughout the processing period. Headset monitoring was also found to be most useful at this time for identifying particular events noted in the cassette log book, and to ensure that spurious events, such as a tape stop-start, did not influence the processed data. Having identified the period of seismic noise to be processed, an average and peak hold spectrum was produced together with a UV recording of the period of maximum velocities. The records were catalogued and stored for future manual analysis.
4. VIBRATION CAUSED BY THE TUNNELLING PROCESS

4.1 Introduction

The bulk of the data at Section A was collected between 15 September 1976 and 23 September 1976, and at Section B between 5 October 1976 and 8 October 1976. Many supplementary data were also collected between May 1975 and May 1977.

The data were reduced to a format suitable for analysis and each magnetic tape was replayed with significant events reproduced on UV charts and a full spectrum analysis performed. In all, well over two hundred peak hold and mean spectra were produced. To quantify and tabulate the amplitudes the 500 Hz bandwidth was divided into ten equal parts and an average value was measured for each 50 Hz bandwidth. The relative amplitude and frequency of the principal peaks were also noted. The peak particle velocity was measured from the UV charts and wherever possible the dominant frequency was also noted.

Figure 4 shows a typical peak hold and mean spectrum, and illustrates the method of processing the data into tabular form. A data sheet similar to that shown in Figure 5, was attached to each spectrum. Figure 6 shows a short extract from the UV chart recorder associated with the spectrum shown in Figure 4.

Figure 7 is a typical direct record UV chart taken during the muck for ring 1063 (1 E-W geophone is not working). A large quantity of data of this type was recorded and was useful in assessing patterns in the data. However, the maximum values which are of particular interest were always to be found and processed from the complete magnetic tape records.

Pilot laboratory experiments, briefly described in the next section, had confirmed the findings of other workers that it was the peak levels of vibration rather than their duration which were of most importance when considering compaction.

The emphasis of the experimental effort was, therefore, placed on the determination of peak particle velocity and the majority of the data were recorded in the immediate vicinity of the machine.

4.2 Measurements of excavation induced vibration

4.2.1 The type of vibration and peak particle velocities. During the excavation process the vibrations were characterised by periods of low particle velocities with random periods of relatively high velocities. This is shown in Figure 8 during 1.8 seconds of a recording typical of the data collected. The periods of high velocities (in Figure 8 between 1.3 and 1.6 secs) were rarely more than 0.5 seconds in duration whereas 'quiet' periods (between 0.42 and 0.88 secs in Figure 8) were often as long as 1 or 2 seconds. This cutting action is explained by considering the sandy ground with randomly distributed boulders. The periods of high particle velocities occur when a boulder is being smashed by a disc cutter or by a milling action against other boulders in the face. When standing on the pavement above the tunnel face, the vibrations could be felt and heard quite distinctly, and 'clearly perceptible' was considered an appropriate subjective description by site personnel.

Figure 7 shows a typical record of a disc-boulder or boulder-boulder impact during the excavation for ring 1063, with the machine some 5 metres from the instrumented borehole. Note the increase of particle velocity with depth. Consequently, the tape records that were made concentrate on the bottom...
geophone array where maximum ground particle velocities occur.

Tables 2 and 3 give the peak velocities recorded in the N-S, E-W and vertical directions respectively, and demonstrate the increase in particle velocity with tunnel face proximity. Negative tunnel face-borehole distances indicate that the tunnel face has passed beneath the borehole.

**TABLE 2**
Peak particle velocities at Section A

<table>
<thead>
<tr>
<th>Tunnel face - borehole distance (m)</th>
<th>4 N-S (mm/s)</th>
<th>4 E-W (mm/s)</th>
<th>4 V (mm/s)</th>
<th>Resultant (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.4</td>
<td>0.09</td>
<td>0.06</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>7.4</td>
<td>0.46</td>
<td>0.50</td>
<td>0.29</td>
<td>0.74</td>
</tr>
<tr>
<td>4.3</td>
<td>2.07</td>
<td>2.07</td>
<td>0.83</td>
<td>3.04</td>
</tr>
<tr>
<td>-0.6</td>
<td>2.48</td>
<td>2.74</td>
<td>1.34</td>
<td>3.93</td>
</tr>
<tr>
<td>-1.2</td>
<td>2.69</td>
<td>1.19</td>
<td>1.67</td>
<td>3.38</td>
</tr>
<tr>
<td>-2.5</td>
<td>1.11</td>
<td>0.78</td>
<td>0.44</td>
<td>1.43</td>
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<tr>
<td>-8.0</td>
<td>0.55</td>
<td>0.49</td>
<td>0.49</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**TABLE 3**
Peak particle velocities at Section B

<table>
<thead>
<tr>
<th>Tunnel face - borehole distance (m)</th>
<th>4 N-S (mm/s)</th>
<th>4 E-W (mm/s)</th>
<th>4 V (mm/s)</th>
<th>Resultant (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>0.32</td>
<td>0.55</td>
<td>0.54</td>
<td>0.83</td>
</tr>
<tr>
<td>0.6</td>
<td>1.13</td>
<td>1.09</td>
<td>1.16</td>
<td>1.95</td>
</tr>
<tr>
<td>0</td>
<td>1.85</td>
<td>2.48</td>
<td>1.85</td>
<td>3.60</td>
</tr>
<tr>
<td>(3 N-S)</td>
<td>(3 E-W)</td>
<td>(3 V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-5.5</td>
<td>0.34</td>
<td>0.45</td>
<td>0.53</td>
<td>0.77</td>
</tr>
<tr>
<td>-6.1</td>
<td>0.31</td>
<td>0.48</td>
<td>0.54</td>
<td>0.79</td>
</tr>
<tr>
<td>-10.5</td>
<td>0.12</td>
<td>0.15</td>
<td>0.10</td>
<td>0.22</td>
</tr>
<tr>
<td>-11.1</td>
<td>0.17</td>
<td>0.24</td>
<td>0.17</td>
<td>0.34</td>
</tr>
</tbody>
</table>

**4.2.2 The spectral distribution of particle velocity.** Over 200 detailed spectra similar to that shown in Figure 4 were produced, and analysis of these processed records yields much information not directly relevant to this Report. The simplified presentation which follows here will serve to indicate general trends observed.

Figures 9 and 10 show the spectral distribution of particle velocities and are representative of the trends shown by the majority of data. These figures were plotted as described in Section 3.5 with the average relative amplitude for each 50 Hz bandwidth plotted at the midpoint of the bandwidth. As expected, the distribution of energy varies with distance from the source; the closer to the source the greater the proportion of energy at higher frequencies. The figures indicate the smoothed trends in the vibrational energy distribution resulting from the excavation process. Investigation of the detailed spectra (see Figure 4) showed that the shape of the spectra changed from one second to another and although the
smoothed envelopes shown in Figures 9 and 10 indicate a similar general shape (for a given distance from the source) there was little evidence of spectral stationarity. That is, there were no significant spectral peaks at frequencies associated either with vibrations from oscillating machinery below ground or the excavation process itself.

Some records were taken while the main motors of the machine were running but the cutting head was not being driven. The vibration levels were very low but the spectra produced showed some signs of stationarity at about 12 Hz. The energy at this frequency may have originated directly from the main motors which run at 720 rpm (12 Hz).

Sample records were processed to confirm that the relative amplitude of the spectra beyond 500 Hz was not significant. Spectra were obtained of ambient noise while the machine was idle and there were no other obvious sources (road traffic etc) present. The relative amplitude of these spectra never exceeded 0.01, showing that ambient noise levels were not significant with respect to machine vibration levels.

4.2.3 Other borehole measurements. The process of tunnel construction produced little significant ground vibration other than that directly associated with excavation. The only exception to this was the ‘dropping’ of the tunnel lining segments into the invert during the building of a ring. Figure 11 shows a segment-invert impact when the tunnel face was approximately 2 m past the borehole. As the lowest geophone array is just above the crown of the tunnel, the source to geophone distance was approximately 3 metres. The maximum particle velocity produced by this impact was about 0.33 mm/sec but velocities of up to 0.6 mm/sec were occasionally observed during ring construction.

Handsley\textsuperscript{26} found that the vibrations produced by heavy lorries at this site were largest at the shallowest geophone array and were predominantly vertical in direction; maximum resultant particle velocity recorded was 0.25 mm/sec. Numerous recordings of road traffic were collected between periods of tunnel excavation and the results were similar to those of Handsley quoted above. A maximum resultant velocity of 0.18 mm/sec was recorded from a heavily laden articulated lorry. The frequency of this velocity maximum was approximately 20 Hz and the vibrations from the lorry were measurable for a period of about 5 seconds. Passing cars produced resultant velocities well below 0.1 mm/sec. Most of the large motions from passing traffic occurred close to the surface and showed the general characteristics of a retrograde ellipse with a principal axis close to vertical. This indicates the predominance of surface waves over body waves from surface sources between approximately 10 and 50 metres distant.

4.2.4 Measurements at number 54 Ellesmere Road. At the invitation of the householder, vibration measurements were made on the cellar floor at 54 Ellesmere Road during the excavation for the build of ring 1039. At this point the tunnel face is directly beneath the front garden wall and at its closest to this property. A geophone array was placed on the cellar floor about 150 mm from the front wall at some 2 metres below pavement level. Figure 1 gives a plan of this site and the line x-x shows the position of the tunnel face during the acquisition of this data. Table 4 gives the peak particle velocities caused by the two largest impacts during the excavation for ring 1039. These vibrations were similar in character (as shown by their frequency spectra) to those recorded by the borehole geophone arrays and had a maximum peak particle velocity of 0.5 mm/s.
TABLE 4
Peak particle velocities in cellar of
No 54 Ellesmere Road

<table>
<thead>
<tr>
<th>Peak particle velocities mm/s</th>
<th>N-S</th>
<th>E-W</th>
<th>V</th>
<th>Resultant</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.17</td>
<td>0.37</td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>0.24</td>
<td>0.24</td>
<td>0.37</td>
<td></td>
<td>0.50</td>
</tr>
</tbody>
</table>

4.3 Disturbance by noise

Vibration from the tunnelling machine was transmitted through the ground and resulted in noise in the houses along Ellesmere Road. The sound was similar to distant thunder and appeared to result from resonances of floors and ceilings within the houses. The direction of the source was not at all apparent. Occasionally, windows, doors and household items were caused to rattle. The sound was clearly audible in houses for some 20 m behind and in front of the tunnel face and was at its loudest when the face was at its closest to the property. Few, if any, complaints were made during the day shift working; however, many complaints were made between 22.00 and 24.00 hours. Due to the reduced level of ambient noise, and the fact that they were trying to sleep, the noise seemed to the residents, to be more severe at night. The vibration from the tunnelling machine was more noticeable indoors than it was standing on the pavement above the machine.

4.4 In-tunnel vibration

The portable vibration analyser described in Section 3.1 was used to determine the level of vibration on the tunnelling shield, on various parts of the machine, and on the tunnel lining during the excavation process. Table 5 gives the values found and the locations of the points of measurement.

The level of vibration on the tunnelling shield and the lining rings was lower than expected, although certain parts of the machine resonated at high peak particle velocities. There were few vibrations of the shield or the lining that were directly attributable to any individual source, although there was considerable evidence that the area of the machine around each main motor was excited at about 12–13 Hz. No energy was found, at this frequency, in the tunnel lining adjacent to the main motors.

5. GROUND SETTLEMENT

5.1 Laboratory tests of vibration induced settlement

To obtain an estimate of the level of vibration at which settlement may begin to occur, a brief series of experiments was carried out on a shake table in the laboratory (see Plate 4). Samples of the soil from the Warrington site were prepared at dry densities and moisture contents similar to those found on the tunnel line. These samples, contained in a steel mould 150 mm in diameter and 125 mm high, were clamped to a vibrating table which had a fixed frequency of 100 Hz and controllable amplitude. The motion of the mould was measured by an accelerometer. A plaster disc placed on top of the sample provided a small surcharge and prevented loosening of the surface sand.
<table>
<thead>
<tr>
<th>Probable source of vibration energy</th>
<th>Location of measurement</th>
<th>Peak particle velocity mm/s</th>
<th>Dominant frequency Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation</td>
<td>Shield tailskin (parallel to tunnel line)</td>
<td>0.1</td>
<td>15–50 (with other peaks between 150–900)</td>
</tr>
<tr>
<td>Excavation</td>
<td>Shield tailskin (normal to tunnel line)</td>
<td>0.08</td>
<td>20–40 (with other peaks between 200–800)</td>
</tr>
<tr>
<td>Excavation</td>
<td>Rear bulkhead of shield</td>
<td>0.12</td>
<td>15–100</td>
</tr>
<tr>
<td>Excavation</td>
<td>Last lining ring erected</td>
<td>0.08</td>
<td>10.35</td>
</tr>
<tr>
<td>No 2 main motor</td>
<td>On motor</td>
<td>27</td>
<td>12.3</td>
</tr>
<tr>
<td>No 2 main motor</td>
<td>Rail adjacent to motor</td>
<td>4.0</td>
<td>12.4</td>
</tr>
<tr>
<td>Erector pump</td>
<td>Rail adjacent to pump</td>
<td>0.25</td>
<td>24.5</td>
</tr>
<tr>
<td>Excavation?</td>
<td>Erector (parallel to tunnel line)</td>
<td>2.7</td>
<td>15</td>
</tr>
<tr>
<td>Excavation?</td>
<td>Erector (normal to tunnel line)</td>
<td>0.7</td>
<td>15–50</td>
</tr>
<tr>
<td>Main motors</td>
<td>Lining ring by main motors (parallel to tunnel line)</td>
<td>Below 0.05</td>
<td>—</td>
</tr>
<tr>
<td>Main motors</td>
<td>Lining ring by main motors (normal to tunnel line)</td>
<td>Below 0.05</td>
<td>—</td>
</tr>
<tr>
<td>Grout mixer</td>
<td>Rail by grout mixer</td>
<td>Below 0.05</td>
<td>—</td>
</tr>
</tbody>
</table>
The sample was subjected to increasing levels of vibration until the first sign of settlement was observed. The vibrations were held at this level for two minutes and the total settlement was then measured. The level of vibration was then raised in stages to a peak level of 2 g to 3 g and settlements again recorded after periods of two minutes at each level (Table 6). The tests suffixed 'a' give the threshold levels at which the first settlements were observed and those suffixed 'b' indicate the settlements after the maximum accelerations had been applied.

### TABLE 6
Laboratory vibration induced settlements

<table>
<thead>
<tr>
<th>Test number</th>
<th>Initial dry density Mg/m$^3$</th>
<th>Moisture content %</th>
<th>Direction of vibration</th>
<th>Peak acceleration g</th>
<th>Peak particle velocity mm/s</th>
<th>Settlement %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>1.52</td>
<td>12.0</td>
<td>Vert</td>
<td>1.4</td>
<td>22</td>
<td>0.20</td>
</tr>
<tr>
<td>1b</td>
<td>1.52</td>
<td>12.0</td>
<td>Vert</td>
<td>2.8</td>
<td>44</td>
<td>3.84</td>
</tr>
<tr>
<td>2a</td>
<td>1.79</td>
<td>6.7</td>
<td>Horiz</td>
<td>0.1</td>
<td>1.6</td>
<td>0.04</td>
</tr>
<tr>
<td>2b</td>
<td>1.79</td>
<td>6.7</td>
<td>Horiz</td>
<td>3.0</td>
<td>47</td>
<td>4.26</td>
</tr>
<tr>
<td>3a</td>
<td>1.59</td>
<td>9.6</td>
<td>Horiz</td>
<td>0.2</td>
<td>3.1</td>
<td>0.22</td>
</tr>
<tr>
<td>3b</td>
<td>1.59</td>
<td>9.6</td>
<td>Horiz</td>
<td>2.0</td>
<td>31</td>
<td>7.50</td>
</tr>
<tr>
<td>4a</td>
<td>1.50</td>
<td>11.7</td>
<td>Horiz</td>
<td>0.2</td>
<td>3.1</td>
<td>0.22</td>
</tr>
<tr>
<td>4b</td>
<td>1.50</td>
<td>11.7</td>
<td>Horiz</td>
<td>2.0</td>
<td>31</td>
<td>5.45</td>
</tr>
<tr>
<td>5a</td>
<td>1.37</td>
<td>9.2</td>
<td>Horiz</td>
<td>0.05</td>
<td>0.8</td>
<td>0.44</td>
</tr>
<tr>
<td>5b</td>
<td>1.37</td>
<td>9.2</td>
<td>Horiz</td>
<td>2.0</td>
<td>31</td>
<td>23.24</td>
</tr>
</tbody>
</table>

It was not possible to apply a substantial surcharge stress to the sample to simulate true field conditions. The following observations can be made:

(i) Samples 3 and 4 had very similar dry densities and moisture contents to the soil at Warrington and under horizontal unidirectional shaking at 100 Hz began to compact at a peak particle velocity of 3.1 mm/s.

(ii) Samples 2 and 4, which are similar to the extremes of dry density found on the site, began to settle at 1.6 and 0.8 mm/s respectively.

(iii) The higher the initial dry density of the sample, the lower was the final settlement.

(iv) The samples were far less affected by unidirectional vertical shaking than by horizontal shaking.

(v) The majority of the settlement due to a given level of vibration occurred within a few seconds of the start of shaking and no significant settlements occurred thereafter until the vibration level was increased.

Observations (iii), (iv) and (v) confirmed that the results were consistent with those obtained by other workers$^{25,27-31}$ for different frequencies.
In the field two factors not simulated in the laboratory will have an important influence on the vibration induced settlements.

(a) The effective stress in the soil due to the overburden will increase the strength of the soil and increase the energy levels required to re-order the particle structure. This effect may be mitigated to an extent by the stress relief in the soil close to the excavation.

(b) The multi-directional shaking present in the field will tend to reduce the vibration threshold levels observed for unidirectional motions.

These effects are opposite in character and will be, to some extent, self-cancelling.

5.2 Ground settlements at Sections A and B

An important part of the TRRL research programme at Warrington was the measurement of surface and subsurface ground movements due to tunnel construction\textsuperscript{32,33}.

The surface and subsurface ground settlements at Sections A and B were similar and as follows:

(a) At both sections over 95 per cent of the total settlement occurred during the period when a given reference settlement point was between 5 m before to 15 m behind the advancing tunnel face.

(b) The maximum surface settlement at Section A was 18.7 mm and at Section B 25.3 mm; these maxima occurred directly above the tunnel crown.

(c) The settlement profiles at A and B were distinctly asymmetrical. Settlements 2 m north of the tunnel centre line were appreciably lower than those 2 m to the south. This effect may be due to the greater degree of initial compaction of the ground beneath the main road (Ellesmere Road) or some other difference in ground conditions. Preferential ‘take’ of material related to the direction of rotation of the cutting head offers another possible explanation.

(d) At Sections A and B the volume of the settlement trough expressed as a percentage of the volume of ground excavated was typically between 1 and 2 per cent.

(e) These settlements resulted in maximum ground surface slopes of between 1:90 and 1:250 along lines displaced some 2 m either side of the tunnel centre line.

(f) Settlements at tunnel invert level, about 2 m south of the tunnel centre line were 7 mm at Section A and 10 mm at Section B.

5.3 Settlement due to ground treatment

Owing to tunnelling difficulties encountered in the very loose ground conditions immediately beyond Section B, it was decided to treat the ground with cementitious and chemical grouts. These works are beyond the scope of this Report but it is relevant to mention the ground settlement caused by the drilling of the 4-in (100 mm) diameter holes necessary for the injection of the grouts. Groups of five holes up to 9 m deep, were drilled beneath the pavement at 4 ft (1.22 m) centres along the tunnel line. The 75 hp (56 kW)
air flushed drill rig advanced a steel casing with the drill bit. Unfortunately measurements of ground vibration caused by the drilling were not obtained as the drill rig had left site before the author learned that this process was causing substantial settlements.

At various stages during the treatment process the contractor measured the settlement at each end of the garden parting wall between houses. Settlements of 10 mm to 20 mm were common with several instances of 20 mm and above. These settlements can only be explained by compaction as excessive take of material did not occur.

6. DISCUSSION AND CONCLUSIONS

6.1 Vibration induced ground settlement

The tunnel excavation process resulted in maximum ground vibrations (expressed in terms of resultant peak particle velocity) of 3.93 mm/s and 3.60 mm/s in boreholes at Sections A and B respectively. Close to the tunnel face the majority of the vibrational energy lay in the bandwidth 50 Hz–350 Hz. The vibration was characterised by random heavy 'impacts' separated by short periods of low amplitude vibration. The large amplitude motions showed no preferred direction of particle motion and were due to a combination of:

(a) the impacts between the cutting discs and the boulders;
(b) the impacts between boulders in the face; and possibly
(c) the impacts between the cutting discs and the weak sandstone or dense sand present in the tunnel invert, at Sections A and B.

It was the interaction between the cutting head and the ground which was the major source of vibration, and other sources of periodic type, generated for example by the main motors, were small by comparison. It follows that the spectra produced were predominantly of a non-stationary nature with a complex and varied frequency and amplitude content. These ground vibrations were quickly attenuated with spatial progress and were reduced to less than 1 mm/s (resultant peak particle velocity) when the tunnel face was more than 5 metres distant from the recording point.

Because of the complex nature of the site geology and geometry, and the likely deployment of body wave energy into surface waves, no directly useful conclusions can be drawn regarding the attenuation of the vibration energy over distances in excess of 20 metres. However, the results given do indicate that high frequencies are attenuated more than low frequencies and may be used empirically to predict maximum peak particle velocities at distances up to 20 m from the tunnel face.

The results indicate that only the ground close to the tunnel face was subjected to vibration levels likely to produce compaction, and it is therefore difficult to assess the relative contributions of compaction and excess material take to the total ground settlement. Settlement caused damage to the bay window of a house at Section B, and evidence of minor damage (cracking of garden walls, paths and road surface) was present at Section A. The surface settlement above the tunnel crown was 18 mm and 25 mm at Sections A and B respectively. Also, sub-surface ground settlements of between 7 and 10 mm occurred at tunnel invert level some 2 m from the tunnel centre line when normally there is no movement or heave at this level. The pressure in the plenum chamber of the tunnelling machine was capable of supporting the cover and the immediate grouting of the lining to the rear of the shield should have ensured complete ground support. From this it seems reasonable to infer that compaction of the ground, caused by vibration from the excavation process, was the cause of a considerable element, perhaps even the greater part, of these ground settlements.
Further weight is added to these arguments by:

(a) the drilling of holes for ground treatment ahead of tunnelling caused settlements similar to those induced by tunnelling although excessive ground take could not have occurred in these small holes;

(b) the potential for settlement of the ground as evidenced by the low values of relative compaction and penetration resistance; and

(c) the laboratory vibration tests on samples of the Warrington sand at similar dry density and moisture content to that in situ which showed that settlement could occur at vibration levels less than the peak values measured in the field.

On the basis of these studies it is recommended that when tunnelling in non-cohesive ground:

(i) Densification through vibration must be considered as an important potential source of ground settlement.

(ii) Some reliable measure of the initial density (relative compaction or SPT value) of the ground in the vicinity of any proposed tunnel should be obtained during the site investigation in order to assess the degree of possible settlement.

(iii) Laboratory studies should be carried out to investigate the effect of vibrations, similar in magnitude and frequency to those produced by excavation processes, on the densification and settlement of sands.

6.2 The direct effects of the vibrations

Measurements of vibration in the cellar of a house when the tunnel face was only some 4 m away revealed a maximum resultant peak particle velocity of 0.5 mm/s. The results from the borehole measurements indicate that the peak particle velocity of the ground at foundation level for houses 5 m or more from the tunnel was not likely to exceed 1 mm/s. These levels are well below the established thresholds for either architectural or structural damage.

The vibration from the tunnelling machine caused low level noise and minor vibrations within the houses situated close to the tunnel. The noise was less than that caused by some passing road traffic, but was of an unusual nature and was often present for periods throughout the night. The nuisance, or intrusion, was at its worst when the tunnel face was at its closest and gave rise to little complaint when more than 20 m from the houses. Most of the noise complaints that were received were related to the disturbance at night.

7. ACKNOWLEDGEMENTS

The work described in this Report was carried out in the Tunnels Division of the Structures Department of TRRL. The project was carried out jointly with Durham University and was supervised by Dr P B Attewell (Reader in Engineering Geology, Durham University) and Mr M P O'Reilly (Head of Tunnels Division, TRRL).

The research was carried out by permission and with the active co-operation of the Warrington New Town Development Corporation and their main contractor for the works, Edmund Nuttall Ltd. In particular the author would like to thank Mr P Wild (of WNTDC), Mr C Bishop, Mr A Finch, Mr D Thornton and
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The author expresses his gratitude to Mr G West and Mr A S Nagarkatti for their assistance with this research and to Mr D A Barratt and the other members of Tunnels Division who provided the ground settlement data.

8. REFERENCES


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18. HOLMES, A. Principles of physical geology. Ch. 25. 1965 (Thomas Nelson and Sons Ltd).


33. BARRATT, D A. (personal communications).
DESCRIPTION OF STRATA
The strata shown in these sections show Pleistocene and Recent blown sands and fluviolacustrine gravels resting unconformably on Triassic Sandstone of Burnet age.

DESCRIPTION OF LITHOLOGIES
1. Brown medium to fine SAND with occasional fine to medium gravel and cinder fragments
2. Brown medium to coarse SAND and fine to coarse GRAVEL.
3. Brown medium to coarse SAND with much fine to medium gravel
4. Red-brown slightly silty fine to coarse SAND with much fine to coarse gravel and red sandstone chippings
5. Highly weathered red-brown fine to medium grained SANDSTONE
6. Brown fine to coarse SAND with occasional fine gravel and ash fragments and a layer of medium to coarse gravel at the base
7. Brown medium to coarse SAND with much medium to coarse gravel and a layer of black ash material interstratified with reddish-brown clay layers
8. Red-brown silty fine SAND
9. Red-brown completely weathered SANDSTONE
10. Fine to coarse SAND
11. Brown fine to coarse SAND and some fine to medium gravel with occasional ash fragments, increasing gravel content towards base becoming slightly silty with occasional red-brown clay balls
12. Red-brown completely weathered slightly silty SANDSTONE
13. Fine SAND
14. Grey-brown slightly silty fine to coarse SAND with occasional gravel and red-brown clay balls increasing fine to medium gravel content towards the base
15. Red-brown completely weathered SANDSTONE

Fig. 2 WARRINGTON TUNNEL; STRATIGRAPHY OF ROCKS IN ELLESMERE RD. BOREHOLES
Fig. 4 TYPICAL SPECTRA WITH TABULATED VALUES
### ANALYSER

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<thead>
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<tr>
<td>GEOPHONE REFERENCE</td>
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</tr>
<tr>
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<td>M/c cut ring 1167</td>
</tr>
<tr>
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<td>4.92 m</td>
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<tr>
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<th>100–150</th>
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<th>200–250</th>
<th>250–300</th>
<th>300–350</th>
<th>350–400</th>
<th>400–450</th>
<th>450–500</th>
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<tbody>
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<td>9.5</td>
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<td>1.9</td>
<td>1.3</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>MEAN AVE</td>
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<td>3.0</td>
<td>2.4</td>
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<td>1.1</td>
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<table>
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<tr>
<th>PRINCIPAL PEAK</th>
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<td>a)</td>
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<td>b)</td>
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<td>103</td>
</tr>
<tr>
<td>c)</td>
<td>12.5</td>
<td>168</td>
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</table>

<table>
<thead>
<tr>
<th>PEAK PARTICLE VELOCITY mm/s</th>
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</tr>
</thead>
<tbody>
<tr>
<td>at Hz</td>
<td>P to P</td>
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</table>

**UV**

**Fig. 5 TYPICAL DATA SHEET**
Fig. 6 TYPICAL UV CHART RECORD DERIVED FROM CASSETTE TAPE
Fig. 7 TYPICAL UV CHART RECORD
Fig. 8 UV CHART RECORD SHOWING TYPICAL VIBRATIONS INDUCED BY THE EXCAVATION PROCESS
Fig. 9 AVERAGE (N–S) AMPLITUDE SPECTRA FOR VARIOUS TUNNEL FACE–BOREHOLE A DISTANCES
Fig. 10 AVERAGE (E–W) AMPLITUDE SPECTRA FOR VARIOUS TUNNEL FACE–BOREHOLE B DISTANCES
Fig. 11 LINING SEGMENT DROPPING INTO INVERT DURING CONSTRUCTION OF RING 1075 (BOREHOLE A)
Plate 1 VIEW OF TUNNEL SHOWING PLACEMENT OF DRY WEATHER FLOW CHANNEL
ABSTRACT

The effects of ground vibration during bentonite shield tunnelling at Warrington: B M NEW: Department of the Environment Department of Transport, TRRL Laboratory Report 860: Crowthorne, 1978 (Transport and Road Research Laboratory). The research was carried out during the bentonite shield tunnel drive for the Acton Grange trunk outfall sewer at Warrington, Cheshire. This tunnel was driven through cohesionless Drift deposits beneath a built-up urban environment, with a cover of less than 6 m. The environmental effects of the ground vibration caused by the excavation process were investigated with particular regard to ground settlement by compaction.

Vibration data were recorded from transducers located in boreholes, on the surface, on the tunnelling machine and on the concrete tunnel lining. These records were processed to characterise the vibrations in terms of peak particle velocities, frequency spectra and spatial attenuation.

The maximum measured ground vibration (expressed in terms of resultant peak particle velocity) was 3.9 mm/s. The vibration was characterised by random high velocity particle motions resulting from impacts between the machine’s disc cutters and glacial boulders in the tunnel face.

Surface and subsurface settlement measurements were made along the tunnel line. Laboratory tests and other field data showed that the ground in this area was likely to settle at levels of vibration lower than those measured from the tunnelling machine.

Vibration from the excavation process probably caused ground compaction which contributed significantly to ground settlement and its effects. The vibration was not likely to have caused any direct damage by dynamic stressing but the associated low level noise did cause concern among local residents.

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