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ASSESSMENT OF LOCATIONS ALONG THE PROPOSED HS2 ROUTES THAT ARE LIKELY TO EXPERIENCE GROUND VIBRATION BOOM FROM HIGH-SPEED TRAINS

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1 INTRODUCTION

The demand for high speed rail transportation has significantly increased over the last decade. This way of transportation is convenient and environmentally friendly. However, high train speeds bring into consideration some new environmental problems that were unknown for conventional trains. One of the most important is a dramatic increase in the level of railway-generated ground vibrations that can occur when the train speed exceeds the velocity of Rayleigh surface waves in the supporting ground. This phenomenon is known as 'ground vibration boom' (GVB), and it was first predicted theoretically in the papers[1-3]. Soon after that, it was observed experimentally on the new high-speed railway line in Sweden[4]. Further theoretical investigations of GVB have been carried out in the papers[5-8]. Note that the phenomenon of ground vibration boom from high-speed trains is similar to the well-known phenomenon of 'sonic boom' from supersonic aircraft that occurs when the speed of aircraft exceeds the velocity of sound in air. The essential difference though is in the fact that, whereas sound velocity in air is roughly the same in all locations above earth surface, the Rayleigh wave velocity is different in different locations, depending on geological properties of the ground. In some locations, where the ground is soft and marshy, the Rayleigh wave velocity can be very low. Such 'sensitive' locations are most likely to experience ground vibration boom from operating high-speed trains.

In the majority of geographical areas ground vibration boom is not a problem within high speed rail networks as, although the technological development of high speed trains now has them reaching service speeds surpassing 320km/h, Rayleigh waves usually travel at much higher velocities than this. However, in softer ground the propagation velocity of Rayleigh waves can be severely reduced, resulting in a higher number of occurrences of ground vibration boom along the route.

The present paper describes the results of the preliminary assessment of the proposed HS2 route from the point of view of possible occurrence of the phenomenon of ground vibration boom. The analysis is based on the available geological information about the soil composition along the proposed HS2 route and on the available information about the expected train speeds along the route, including areas of train acceleration and deceleration after departure from or before approach to railway terminals. Rayleigh wave velocities have been calculated for all distinctive sites along the route using the geological data and compared with the expected train speeds at the relevant locations. Using this method, several sensitive locations have been identified where ground vibration boom is likely to occure if no mitigation is applied. The expected levels of ground vibration boom have been estimated using the earlier developed theory[6, 7]. Some vibration reduction techniques are suggested to reduce effects of ground vibration boom on local residents and busineses.

2 INFLUENCE OF GEOPHYSICAL PROPERTIESS OF SOILS

As was mentioned above, ground vibration boom occurs when the speed of a train exceeds the velocity of Rayleigh waves. Therefore, it is necessary to study the effects of geophysical properties of soils and rocks on Rayleigh wave velocities. Soils can experience a wide spectrum of conditions and undergo massive geological changes resulting in huge variation in the physical properties of the soils. In what follows we merely concentrate on the immediate fundamental parameters that govern Rayleigh wave velocity. The value of Rayleigh wave velocity c_R in the ideal homogeneous elastic half space can be calculated using the well known approximate formula[9]:

$$c_R = c_t\left(\frac{0.87 + 1.12\nu}{1+\nu}\right). \tag{1}$$

Here ν is Poisson's ratio of the ground, and $c_t = (\mu/\rho)^{1/2}$ is its shear wave velocity, where μ is shear modulus of the ground and ρ is its mass density. Note that shear wave velocities of soils depend on the type of soil in question and on the saturation of the soil. The saturation of the soil affects the density of the soil, changing the velocity of shear wave propagation along it. For this investigation, saturation level of the soils will be considered as typical for the UK. Figure 1 shows typical shear wave velocities (m/s) and mass densities (kg/m^3) for selected types of UK soils.

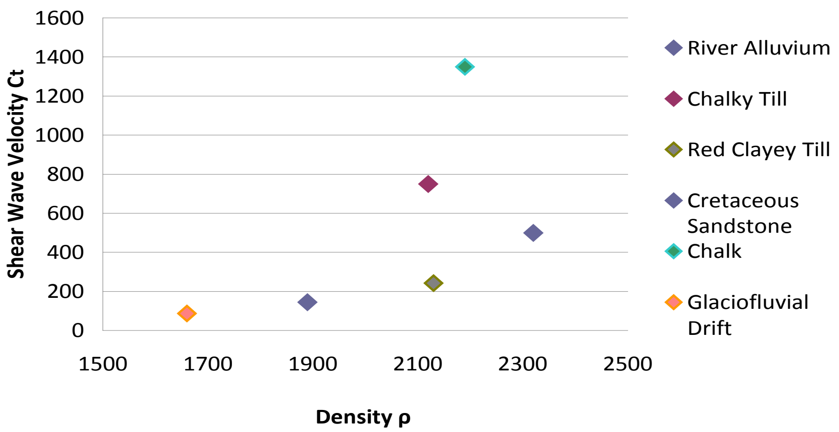

Figure 1. Typical shear wave velocities (m/s) and mass densities (kg/m^3) for selected types of UK soils.

3 ASSESSMENT OF THE SOILS SURROUNDING HS2 ROUTES

3.1 General Comments

The distinct effect that the soil type has on ground vibration boom makes it necessary to thoroughly investigate the soils along the proposed HS2 routes. The present investigation provides some initial database for types of soils and their characteristics, which allows theoretical evaluation of the magnitudes of ground vibration boom along the HS2 routes to be conducted. Several different sources were considered to provide soil characterisation data along the routes.

Very few organisations have the expertise and finance to be able to conduct widespread extensive soil surveys across the UK. The British Geological Society and Cranfield University are two of the organisations that conduct multiple geological surveys throughout the UK and have an extensive database. Rayleigh waves generated by railway trains can be assumed to transmit the most of their energy within the upper few metres of the soil, dependent on the wavelength. Thus, for this study it was only necessary to access data for the upper layer of the soil. The above-mentioned two organisations rely upon licensing out their geotechnical information about the top soil layer. Without special funding for this preliminary investigation, it was not possible to proceed using these databases. Therefore, the Soil Map of England and Wales was used instead[10].

The Soil Map of England and Wales is the result of a soil survey conducted by Lawes Agricultural Trust in 1983, and it was funded by the British government. In what follows, we will describe the routes of the HS2 and provide the soil classifications along the routes from this survey. Typical geophysical data for each soil classification along the route will then be used to calculate Rayleigh wave velocities along the route and finally ground vibration levels for a typical location where the Rayleigh wave velocity is lower than speed of a train.

3.2 Geophysical Data for Sites of Specific Interest: Wetlands

In addition to the information obtained from the above-mentioned soil survey, it was necessary to investigate certain areas separately to the database from the soil survey. These areas are not accounted for within the survey and must be considered as sites of specific interest (SSI's). A type of land which is of particular interest to this study is extremely soft soils, such as those found along the high-speed rail route in Sweden. These areas, that are called 'wetlands', can have especially low Rayleigh wave velocities.

Wetlands are areas which are saturated with water, the extent of saturation can be dependent on season. Well known types of wetlands include: swamps, marshes, bogs and fens. These wetlands are sparse throughout England, but this investigation attempts to locate all of such areas on the HS2 lines. In this investigation, the typical value of Rayleigh wave velocity of 45 m/s will be assumed for all wetland areas. Typical values of Poisson's ratio and mass density for wetlands are 0.30 and 1620 kg/m^3 respectively.

3.3 Train Speeds Along the HS2 Routes

The HS2 railway network will consist of three sections, the first one linking London with Birmingham and then two sections providing extensions from Birmingham to Leeds and from Birmingham to Manchester[11]. There will be one sub-station stop along the route to Manchester - at Manchester Airport, and two sub-stations along the route to Leeds - at Toton and at Sheffield. There will be further junctions linking existing lines to the new high speed lines, connecting Wigan and York to the HS2 system. Figure 2 shows the current proposed planned routes for the HS2. It should also be noted that the HS2 line will be directly linked to the HS1 Eurostar line.

To assess the possibility of ground vibration boom it is necessary to specify train speeds along the HS2 routes. The maximum train speed of a HS2 carriage is designed to be 400 km/h, and this speed will be achieved for the majority of the journey distance[11]. However, whilst departing from or arriving to terminals, there will be zones of acceleration or deceleration before the train reaches its top speed or arrives to a terminal. The large mass of high speed rail carriages results in a relatively low acceleration rate, making it necessary to calculate train speeds at set distances from the terminals.

The assumptions used for calculations were as follows: Maximum train speed was taken as 400 km/h. The train was expected to accelerate at constant acceleration of 0.255 m/s^2 (based upon French TGV acceleration rates). The train's deceleration rate was assumed to be the same as the acceleration rate.

Figure 2. Satellite image highlighting HS2 phase one and phase two routes.

The acceleration distance to achieve the given velocity from zero can be calculated using the well known cinematic formula. For convenience, the distances from a terminal required for an accelerating train moving with acceleration of 0.255 m/s^2 to reach certain velocities is shown in Figure 3. It is seen from Figure 3 that an accelerating train will reach its maximum speed of 400 km/h at a distance of 24.2 km from its departing terminal.

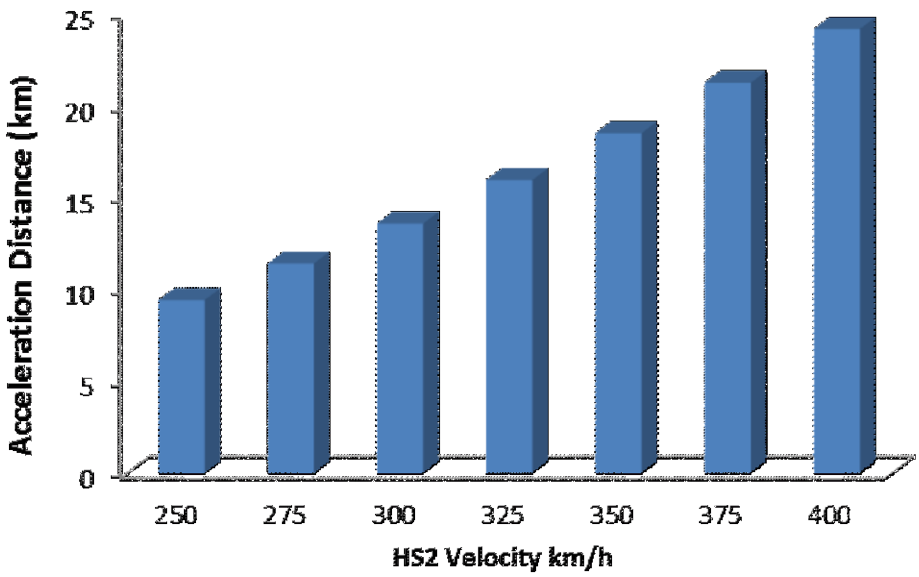

Figure 3. Acceleration distances from HS2 terminals to reach specific velocities.

Figure 4 shows the HS2 routing with the zones of acceleration indicated. In any of the cases where a very low Rayleigh wave velocity in the underlying soil is located, the approximate train speeds in these locations will be calculated considering constant acceleration.

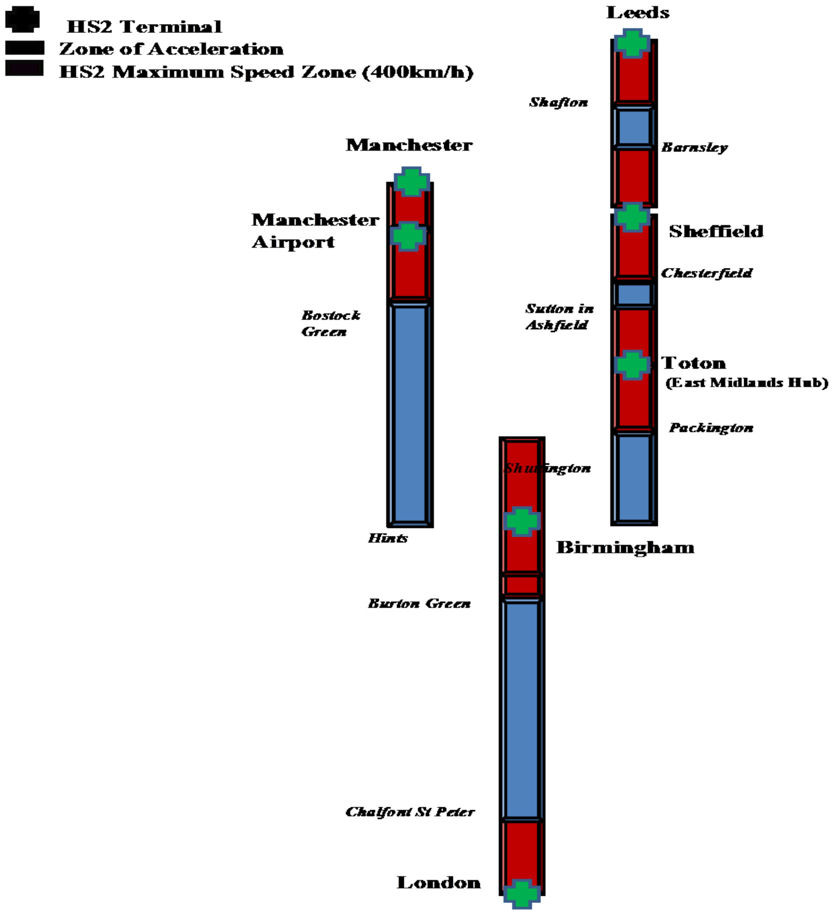

Figure 4. Schematic showing the zones of acceleration and zones of maximum velocity on HS2 route.

It can be seen from Figure 4 that there is a significant percentage of the route that is within the acceleration/deceleration zone (shown in red). These zones must be accounted for and analysed for exact train speeds at locations where the trans-Rayleigh condition is satisfied.

4 POTENTIAL AREAS OF GROUND VIBRATION BOOM

Investigating the potential locations of ground vibration boom (GVB) will be sub-categorised into two sections. The first will highlight the areas of GVB with use of the soil classifications from the soil survey maps. The second sub-category will identify the sites of specific interest described in the previous section. The potential areas of induced GVB are defined as locations where Rayleigh wave velocities are lower than HS2 train speeds. Once these areas have been located and the magnitudes of each velocity found it will be possible to calculate the ground vibration levels at each location.

4.1 Areas of Possible GVB According to the Soil Survey Map

In order to locate the areas where the trans-Rayleigh condition is likely to be satisfied it was necessary to formulate a database where all classifications of underlying soils were ascertained. To determine this, the HS2 routing was accurately corresponded to the soil ordinance survey of the UK. Figure 5 shows the designated routes imposed over the soil survey for the Northern section of the route.

The key provided within the map survey could then be used to classify soils passed over. The typical geophysical properties of the soil classifications at the surface-rail interface were collected and used for calculation of Rayleigh wave velocity. To simplify and make the data digestible this database was separated into four sections and tabulated. These sections are covered and evaluated below.

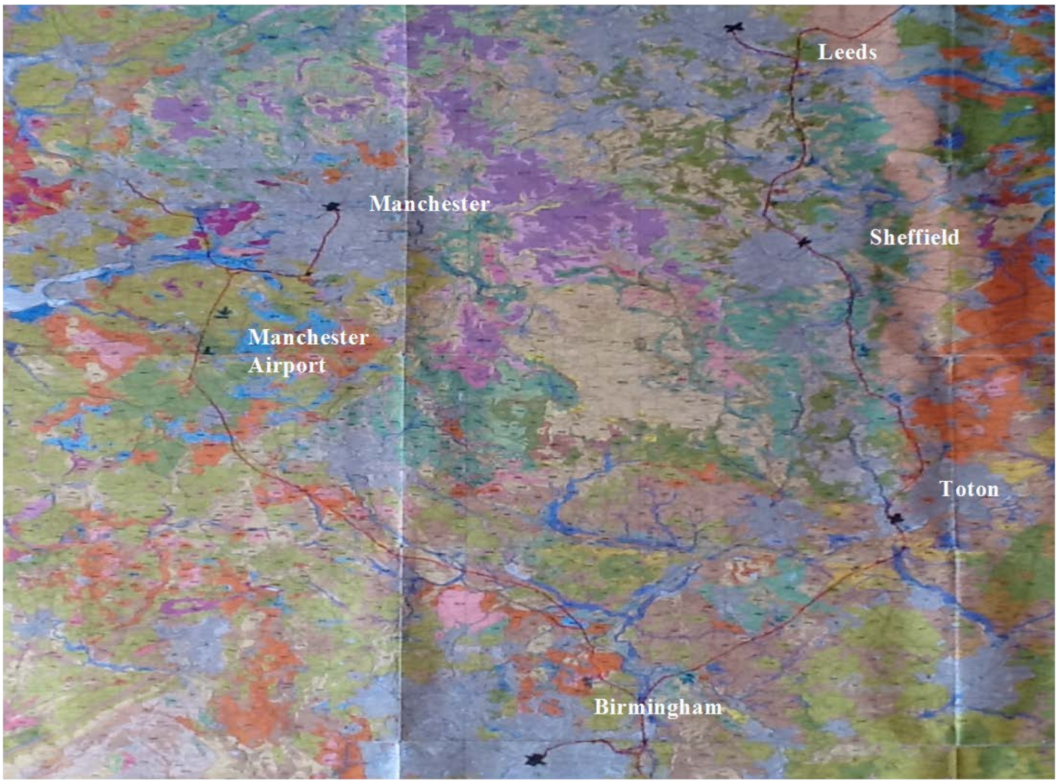

Figure 5. The soil survey data with the Northern section of the HS2 route superimposed to allow formation of the HS2 soil.

London to Birmingham

Initially the route and soil correspondence were analysed from London to Birmingham. The specific direction is of importance for the tabulated data which shows the number of occurrence. Maintaining information on the number of occurrence allows effected locations to be easier traceable once a potential GVB location is highlighted. Every time the route crosses a soil classification a new number of occurrence was awarded to that classification.

For each of the soil classifications encountered there is corresponding geophysical data which allows the calculation of Rayleigh wave velocity, which was also put within the table (not shown for this section for brevity). Technical data for the ‘urban’ category was not collected as the likelihood of GVB on solid foundations is almost zero.

The most significant result in this section is that for occurrence #5 across a soil mixture of Glaciofluvial and Aeolian Drift. The value for Rayleigh wave velocity across this soil surface is 83 m/s, and it satisfies the trans-Rayleigh train condition. The occurrence #5 is located at approximately 22.5 km from the London terminal. As highlighted previously, the HS2 will not reach its maximum velocity until a distance of 24.2 km from a terminal. The distance of 22.5km falls into the spectrum where the train velocity is 375-400 km/h. Therefore, the velocity will be rounded to the higher end of the spectrum, 400km/h or 111 m/s for this location, and this value will be used in further analysis.

It is worth noting that occurrence #47 and #49, with a Glaciofluvial Drift soils, also have particularly low Rayleigh wave propagation velocities of 82 m/s. However these occurrences are not selected because they both occur within 14 km of Birmingham’s terminal, and therefore the train speed will not be great enough to satisfy the GVB condition.

Birmingham to North Junction

As a consequence of the fact that the routes from Birmingham to both Manchester and Leeds share a short section of the route it was deemed rational to analyse this zone separately rather than twice within their respective sections. The North Junction is the name given to the place of separation of the two routes either side of Tamworth. Figure 6 shows this section of the route.

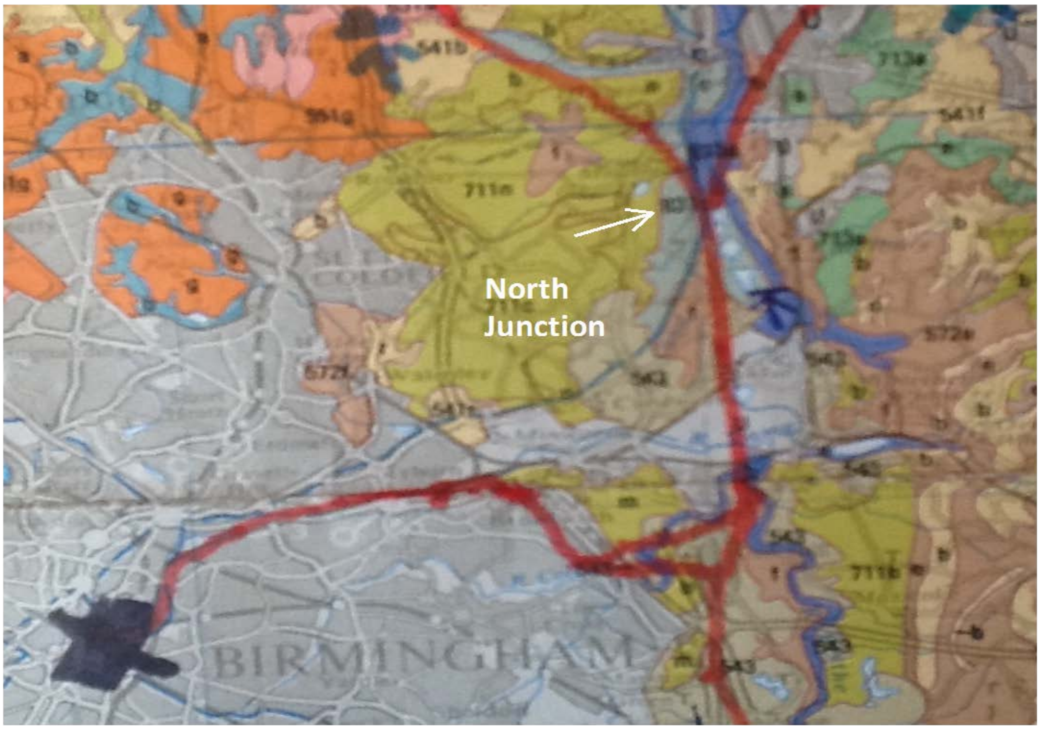

Figure 6. A photograph of the soil survey map highlighting the North Junction and the route from Birmingham.

There is little for discussion within the section from Birmingham to North Junction (again, the full table with the data for this section is not shown for brevity). There are no potential areas of induced GVB, and none of the data will be carried forward into further parts of the investigation. There is another location where Rayleigh wave velocity is low at 81.8 m/s across another area with soil classification of Glaciofluvial Drift. However, this location is at 7 km for the Birmingham terminal and therefore HS2 carriage will still be in the early phase of acceleration.

North Junction to Manchester

The North Junction to Manchester section extends up the North-west side of England bisecting small towns and villages by bypassing large urban city developments. There is a single sub-terminal at Manchester Airport which is located 10 km south of the Manchester Terminal. The speed of the train between the two terminals will be at the lower end of its performance capabilities due to acceleration time required. There is a number of potential GVB occurrences in this section of the route. Therefore, the soil classifications along the route of this section are shown in Table 1. Like in the case of London to Birmingham section, this table has occurrence numbers to provide traceability. With consideration to this, the direction of travel is Northwards from North Junction to Manchester.

Occurrence Number #	**Soil classification**	**Mass density ρ (kg/m^3)**	**Poisson's Ratio ν**	**Shear wave velocity c_t (m/s)**	**Rayleigh wave velocity c_R (m/s)**
1,7,11,24	River Terrace and Glaciofluvial drift	1770	0.35	122	114
2,8,16,28,30, 38,40	Red Clayey Till	2130	0.33	243	226
3,6,14,21,29	Glaciofluvial and Aeolian Drift	1705	0.385	88.5	**83**
4,27	Reddish Conglomerate and Sandstone	2440	0.31	750	697
5,9,12,26,31, 36	Reddish Sandstone	2320	0.295	500	463
10,31,39	Glaciofluvial Drift	1660	0.39	87	**82**
13,18,20	River Alluvium	1890	0.26	144	133
15,17,19,23, 25,27	Cretaceous Sandstone	2320	0.295	500	463
22	Reddish Mudstone	2030	0.395	380	358
32,34,37	Chalky Till	2120	0.33	750	699
35	River Alluvium	1890	0.26	144	133
33,41	Urban	-	-	-	-

Table 1. Soil types along the route from North Junction to Manchester and their corresponding Rayleigh wave velocities.

There are seven potential areas of induced GVB along this part of the route towards Manchester, each of which is highlighted in bold text in Table 1. The soil classifications over which they occur are five over a mixture between Glaciofluvial and Aeolian Drift and a further two over purely Glaciofluvial Drift. Again, the corresponding typical Rayleigh waves velocities are 83 m/s and 82 m/s respectively as these soil classifications use the same typical geophysical characteristics throughout. All of these instances are within the maximum speed train zone. Note that the occurrence #39 is located only at 2 km from Manchester Airport terminal. Therefore, for reasons of acceleration this location will not be carried forward within the investigation.

Note that the soils of River Terrace mixed with Glaciofluvial Drift (occurrences #1,7,11,24) result in c_R values of 114 m/s, which is slightly above the maximum velocity of the train at 111 m/s. Therefore, it can be stated that no GVB will be induced in these locations.

North Junction to Leeds

The North Junction to Leeds sections has a few intervals of acceleration caused by multiple terminals. This means that the average train speed in this section is lower, but the train will still reach maximum velocity at some locations. As can be concluded from the calculated Rayleigh wave velocities and given train speeds, there are no locations of potential GVB found in the section from North Junction to Leeds, according to the soil survey map.

Potential GVB Locations according to the Soil Map

Resuming the above analysis, the following locations of potential ground vibration boom according to the soil map are shown in Table 2:

HS2 Section	Soil classification	Occurence #	Rayleigh wave velocity at location, m/s	Train speed at location, m/s
London to Birmingham	Glaciofluvial and Aeolian Drift	5	83	111
North Junction to Manchester	Glaciofluvial and Aeolian Drift	3, 6, 14, 21, 29	83	111
North Junction to Manchester	Glaciofluvial Drift	10, 31	82	111

Table 2. Calculated Rayleigh wave velocities and operational train speeds for the locations of possible occurrence of GVB.

4.2 Possible Occurrence of GVB in Wetland Sites

Wetlands sites along the HS2 routes have been located using the British Geological Survey online data and also the information about areas of concern highlighted in the Independent newspaper. The process located four wetland sites which were in effective proximity of the proposed HS2 line. Within this subsection, the characteristics of each of these wetlands are summarised. We remind the reader that for all wetland sites in this investigation the typical value for Rayleigh wave velocity was chosen as 45 m/s.

Holbrook Marsh

Holbrook marsh is a marshland located tangential to the HS2 line on the route to Leeds. It is exactly 12 km south of the Sheffield terminal. The acceleration data shows that for a site at this distance the train speed will be approximately 80 m/s. The marsh is on the right hand side (<100 m) of the track when travelling north. Therefore, it does not cross the railway line and thus it will not induce the ground vibration boom.

Hints Wetlands

Hints Wetlands are marshes which lie on the outskirts of Hints village within Staffordshire. The HS2 line bisects this village on the route to Manchester. The area is located approximately 24 km away from the Birmingham HS2 terminal; this is where the train will be reaching its maximum velocity of 111 m/s. However, the marshes are on the left hand side (<90m) of the track when travelling north. Therefore, like in the previous case, they will not induce the ground vibration boom.

Kingsbury Waterpark
Kingsbury waterpark is a vast area of differing wetlands including swampland, marshland and a fen. It is of particular importance as it stretches for an extended distance alongside the proposed HS2 track to Leeds. Kingsbury is located 17 km away from the Birmingham HS2 terminal and therefore will have a train speed of approximately 93 m/s. The nearest perimeter of the waterpark is around 100 m to the right hand side of the track when travelling northwards. Thus, like in the two previous cases, this site will not induce the ground vibration boom.

Chat Moss Peat Bog
Chat Moss Peat Bog is particularly different for two reasons, it is located on the section of track linking the HS2 to Wigan and also that it is a vast area of wetland that is bisected by the HS2 routing. Thus, this area can induce the ground vibration boom. The furthest point at which the peat bog is crossed from a terminal is 16 km from the terminal situated in Wigan. This results in a potential train speed of 91 m/s. The nearest human receivers is a large residential estate located at quite a distance away, of 1.2 km.

Wetland locations that can induce the ground vibration boom

Summarising the above, Table 3 shows the data for the wetland location which can induce the ground vibration boom.

Wetland site	**Train speed at location (m/s)**	**Typical Rayleigh wave velocity for wetlands (m/s)**
Chat Moss Peat Bog	**91**	**45**

Table 3. The operational train speed and the estimated Rayleigh wave velocity for the wetland site of possible occurrence of GVB.

5 CALCULATION OF GROUND VIBRATION LEVELS

To estimate the expected levels of railway-generated ground vibrations under the condition of ground vibration boom in one of the locations specified above calculations have been carried out using the earlier developed theory[6, 7]. The equations from the works[6, 7] used for calculations are not displayed here for brevity.

Figure 7 shows the calculated spectra of ground vibrations generated by TGV trains containing 5 carriages and travelling at different speeds: v = 50 m/s, 90 m/s and 110 m/s. The value of Rayleigh wave velocity was assumed to be c_R = 83 m/s, which corresponds to soils characterised as Glaciofluvial and Aeolian Drift (see Table 2, occurrence #5 - on the HS2 section from London to Birmingham, and occurrences #3, 6, 14, 21, 29 -- on the HS2 section from North Junction to Manchester). We remind the reader that for estimation purposes all geophysical parameters, including Rayleigh wave velocity, were considered to be the same in all the above-mentioned locations. It can be seen from Figure 7 that for train speed v = 50 m/s, corresponding to a sub-Rayleigh regime, the values of generated ground vibrations are relatively low (solid curve). This is because only the quasi-static generation mechanism was taken into account in the calculations. For sub-Rayleigh speeds this can be done only for ideal tracks, without rail roughness (see publications[6, 7] for more detail).

The train speeds v = 90 m/s and 110 m/s correspond to a trans-Rayleigh regime, when ground vibration boom is generated. In this case, the quasi-static generation mechanism is dominant, and the calculated ground vibration spectra in Figure 7 (dotted and dashed curves respectively) show the expected maximum levels. Obviously, the ground vibration levels associated with ground vibration boom are very substantial (about 100-120 dB re 10^{-9} m/s at frequency of 30 Hz). Therefore, generation of ground vibration boom by high-speed trains should be either avoided, via reduction of train speed, or properly mitigated.

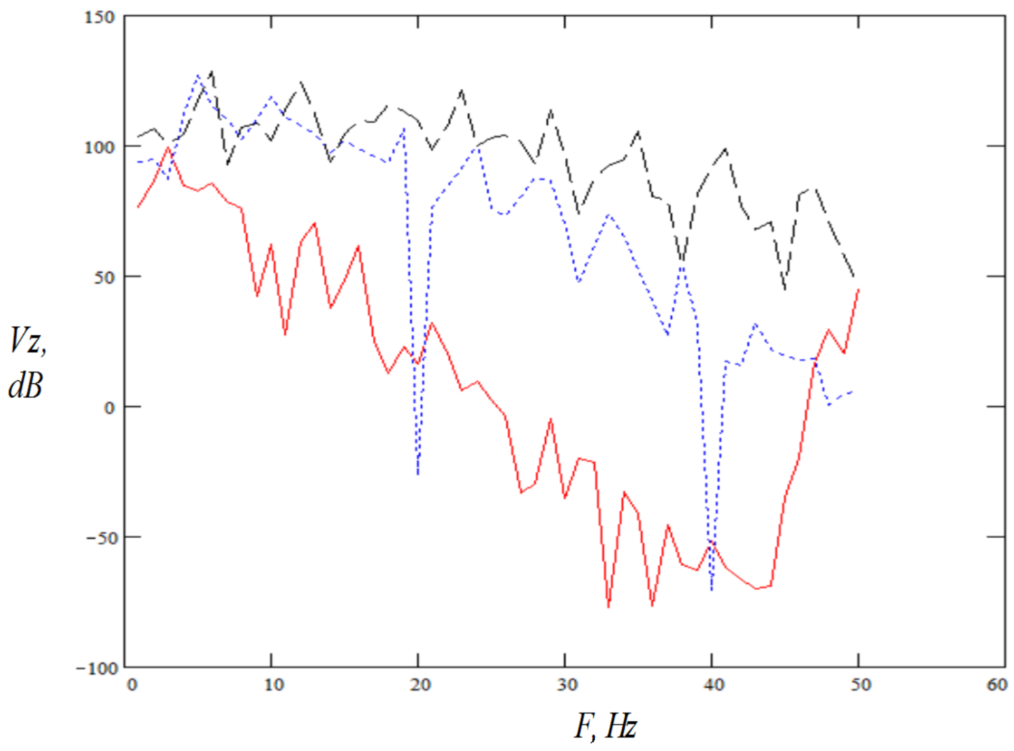

Figure 7 Ground vibration spectra for vertical component of surface vibration velocity (in dB re 10^{-9} m/s) generated by TGV trains travelling at speeds *v* = 50 m/s (solid curve), 90 m/s (dotted curve), and 110 m/s (dashed curve); the value of Rayleigh wave velocity in the ground is 83 m/s.

6 POSSIBLE MITIGATION MEASURES

The most efficient way to mitigate ground vibration boom is to avoid it at all by reducing train speeds in sensitive locations below the values of local Rayleigh wave velocity in the supporting ground. If this is not desirable, then the following mitigation measures can be applied: 1. Building a concrete-slab foundation; 2. Stiffening the soil underneath and in the vicinity of the rail tracks; 3. Using open or in-filled isolating trenches and wave barriers[12, 13].

7 CONCLUSIONS

In the present paper, the preliminary assessment of the proposed HS2 routes from the point of view of possible occurrence of the phenomenon of ground vibration boom has been carried out. The analysis was based on the available geological information about the soil composition along the proposed HS2 routes and on the available information about the expected train speeds along the routes, including areas of train acceleration and deceleration after departure from or before approach to railway terminals.

Rayleigh wave velocities have been calculated for all sites along the proposed HS2 routes using the geological data and compared with the expected train speeds at the relevant locations. Using this method, several sensitive sites, mostly on the route between Birmingham and Manchester, have been identified where ground vibration boom is likely to occure if no mitigation is applied.

The expected levels of ground vibration boom at some identified sensitive locations have been estimated using the earlier developed theory. Some vibration reduction techniques have been suggested.

It should be emphasized that the obtained results are preliminary and intended for rough estimates only. Detailed measurements of Rayleigh wave velocities in the ground along the entire HS2 network should be carried out before starting of the construction works.

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