Optimising low acoustic impedance back-fill material wave barrier dimensions to shield structures from ground borne high speed rail vibrations

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Abstract

Ground borne vibrations generated due to high speed train passage can cause undesirable effects on the nearby environment. One approach to mitigate vibration levels is to use "wave barriers", however their installation cost may be very high. In an attempt to minimize construction costs, numerical modelling and physical experiments are performed to determine guidelines for the optimisation of trench dimensions. Substantial savings are found to be achievable through carefully chosen barrier dimensions.

Firstly, for the purposes of testing a numerical model that can be used by railway wave barrier designers, a geophysical investigation is undertaken on a high speed railway line outside Edinburgh, Scotland. The testing schedule consists of vibration measurements adjacent to the line and a multi-channel analysis of surface waves technique to determine the underlying soil properties.

An outline is then presented describing a newly developed three dimensional finite element railway model using commercially available software. The resulting model is modified to replicate the track and soil properties at the test site and then it is shown that the model results exhibit a strong correlation in comparison to those collected during the experimental stage.

The numerical model is then used to assess the ability of a range of wave barrier configurations to protect nearby sites from railway vibration. It is found that depth and length have a strong influence on the mitigation of vibration levels but the effect of trench width is negligible. Lastly, for a specific example it is shown that cost savings of 95% are achievable if trench dimensions are carefully planned. All of the analyses require that the ratio of the acoustic impedance of soil compared to wave barrier backfill material must be greater than eight.

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Research highlights
(a) Ground borne vibrations measured on the London to Edinburgh railway line, UK
(b) Experimental vibration data used to validate a 3D ground vibration prediction model
(c) Performance of trenches with low acoustic impedance backfill modelled using FEM
(d) An acoustic impedance ratio greater than eight modelled via an open trench condition
(e) Trench depth found to strongly affect performance but width does not

INTRODUCTION

High speed rail infrastructure is experiencing rapid growth in America, Europe and Asia. Projects such as the Californian high speed line in America and HS2 in the UK will inevitably require sections of track to traverse relatively urban environments [1], [2]. It is possible that these sections may result in the transmission of high amplitude ground borne vibration from the track into neighbouring structures, thus causing stress to residents, and possibly structural damage. These effects may reduce real estate values, require public relocation exercises [3] and/or require mitigation measures.

Rail construction projects typically result in a cost escalation of 44.7% when compared to initial estimates, with high speed rail projects contributing significantly to this figure [4]. These cost overruns are caused in-part by such vibration concerns. Therefore to prevent overruns and reduce project costs it is important that vibration levels can be both predicted [5] and mitigated.

Techniques to mitigate vibration propagation can be divided into two categories: active and passive isolation. Active isolation refers to the isolation of vibration within locations either close to or inside the track structure such as floating slab track [6], rail pads [7] or resilient wheels [8]. Passive isolation refers to screening vibration through measures placed at locations in close proximity to vibration sensitive sites rather than in close proximity to the track.

Wave barriers or trenches are a form of passive vibration isolation and are the focus of this research. They offer an attractive option because they offer high isolation performance and do not require direct access to the railway line. To maximize performance, trench properties such as size, shape and infill material must be selected relative to the excitation frequency(s). Despite this, few researches have investigated the effect of trench properties and their ability to mitigate moving excitations, which emit a broad band of frequencies, as is the case of a high speed train.

Early research by (Woods, 1968) [9] illustrated that open trenches were capable of reducing vibration amplitudes for a stationary excitation. It was shown that trench depth and its distance from the source have a significant influence on isolation. More recently a 2D frequency domain Boundary Element Method (BEM) was used to investigate the performance of open and in-filled trenches for the purpose of vibration isolation [10]. The advantage of using BEM rather than FEM meant that no absorbing boundary condition was required. For a harmonic excitation it was found that both trench depth and breadth play an important role in vibration isolation.

(Yang & Hung, 1997) [11] presented an alternative approach through the use of a frequency domain finite/infinite element method (FEM). All trenches were modelled with respect to the soil Rayleigh wavelength from a 31Hz pulse source. It was found that an acoustic impedance ratio of at least 8 between soil material and trench infill material was optimal.

Due to the wide range of parameters that affect trenches screening ability, (Di Mino et al. 2009) [12], and (Alzawi et al. 2011) [13] used 2D models similar to (Yang & Hung, 1997) [11] to develop an artificial neural network to investigate each individual parameter. It was found that trench efficiency is improved by placing the trench at greater distances from the track.

Although such an approach allows for a rapid analysis of optimal trench properties, the underlying method is based on approximating a physical 3D space

using a 2D numerical model. A disadvantage of 2D modelling is that the trench must be assumed to be infinite in length and the multi-path 3D wave-field is reduced to 2D. Thus the effect of trench length cannot be investigated and only two out of three velocity components can be modelled (x and y directions).

A 3D analytical solution based upon the Green's solution of Lamb's problem was developed to approximate the ability of in-filled trenches to reduce vibration [14]. It was found that stiff backfill materials perform better than soft backfill materials. A limitation of this analytical approach is that it is only valid for a narrow range of assumptions.

(Shrivastava & Kameswara Rao, 2002) [15] proposed a more versatile, implicit 3D FEM model to test the ability of open and in-filled trenches to screen vibration. A fixed boundary condition was used rather than an absorbing boundary, thus possibly allowing reflections to contaminate the solution; and a stationary excitation with narrow frequency content was utilized. Therefore the results only have limited relevance to the railway industry, as a moving train acts as a series of moving point sources of different amplitude and frequency rather than a single point/line load. The variation of source location and frequency content can have a significant effect on trench performance as this body of research will show. In addition, trench length cannot be properly investigated because the source location is fixed.

(Karlstrom & Bostrom, 2007) [16] overcame the challenges associated with a stationary excitation and investigated trench performance for a constant point load moving at different speeds. It was found that low frequency vibration (typically caused by a low velocity source) was effectively screened but high frequency vibration (high velocity source) levels were amplified by trench presence.

In practice, early forms of the gas cushion trench wave barrier were utilized at several locations in Sweden such as Gnarp, Stockholm, Uppsala and Saffle in the 1980's [17]. In Gnarp a 50m long trench with a depth of 6.5m was used to reduce the transmission of railway vibration into a residential building by 70%. Similarly, in Stockholm a 95m long trench with a depth of 6.5m was used to reduce the transmission of railway vibration into a temple by 65%. More recently, advanced gas cushion wave barriers have been developed capable of being installed under a wider range of soil conditions and to greater depths. Such barriers have been installed to protect a two storey residential building in Dusseldorf. In this case the gas cushion was 75m long, extended to a depth of 12m and provided a significant reduction in vibration levels [17]. Using a similar technique, a polystyrene wave barrier with concrete side panels was also used to effectively reduce vibration levels at a test track in Brussels [18].

This paper first outlines a 3D FEM railway capable of simulating high speed train passage. It is capable of simulating quasi-static and dynamic excitation mechanisms, thus providing a more realistic approximation of the physical problem than a moving point load. Then, using a similar methodology to (Ahmad & Al-Hussaini, 1991) [19] the model is used to investigate the effect trench depth, width, length and distance from the track have on the ability of screen vibration. The relationships found between these parameters are used to show that substantial savings can be made by optimizing wave barrier geometry based upon geotechnical conditions and excitation frequency.

EXPERIMENTAL INVESTIGATIONS

The chosen site was located in Edinburgh, on a mixed passenger and freight line, connecting Edinburgh, Scotland and London, England. The route consisted of two parallel tracks with trains travelling South to London on the near track and North to Edinburgh on the far track.

24 low frequency (4.5Hz) vertical component geophones were placed in a straight line at distances between 11-50m lateral from the centre of the track. The passage of various passenger trains was recorded using a 24 channel GEODE seismograph. A sampling interval of 1ms was used in conjunction with a negative 2s manual trigger to maximize the recording window.

Figure 1. MASW testing on the London-Edinburgh line

Multi-channel analysis of surface wave tests (MASW) were also undertaken to determine the material properties of the underlying soil (Figure 1) [20]. This was an important step because high speed rail vibrations are significantly affected by soil characteristics [21], [22], [23].

MASW techniques rely on the principle that when a ground surface is excited, the seismic waves that propagate do so at a range of frequencies, and each frequency has its own wavelength. The lower frequency components will have longer wavelengths and be less attenuated than high frequency signals – thus giving them greater penetration depth. The signals with greater penetration depths will have different velocities in different soil layers. Analysis of the dispersion curve thus allows for determination of layer thicknesses and wave speeds of the supporting ground.

24 low frequency (4.5Hz) vertical component geophones were spread at 1 metre intervals over a distance of 23m on the soil surface. Coupling with the ground was achieved through 150mm steel spikes. Geophone placement was chosen at a distance close enough to the track to ensure that the soil properties would be similar to those of the supporting track material, yet far enough away to prevent the presence of nearby structures from contaminating the signal.

Excitation was performed by striking a steel impact plate, resting on the soil surface using a sledge hammer with in-built automatic triggering mechanism. Excitation was performed at seven locations (Figure 2) and despite relatively calm conditions, 3 vertical stacks at each location were also undertaken.
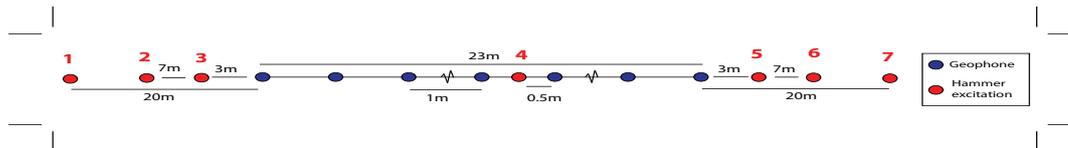
Figure 2. MASW testing - geophone and source arrangement

The resulting velocity time histories were inverted to obtain a dispersion curve, which was then used to approximate the properties of the underlying soil layers. The analysis was undertaken using a neighbourhood algorithm [24] in the frequency-wavenumber domain, using geophysical software Geopsy [25]. Results showed that the upper soil stratum of interest was composed of 3 distinct layers (Table 1). Physically the results indicated the presence of a weaker soil layer resting on 2 layers of higher quality soil. This was consistent with existing borehole information which showed the existence of sandy clay overlying a layer of mudstone which was in turn supported by a layer of sandstone. The theoretical and experimental dispersion curves were strongly correlated meaning the theoretical properties were a reasonable approximation of the test site.

	Young's modulus (Mpa)	Poisson's ratio	Density (kg/m3)	Layer thickness (m)
Soil layer 1	104	0.25	2,000	6.2
Soil layer 2	750	0.27	2,000	7.7
Soil layer 3	776	0.31	2,000	inf
Homogenous soil	60	0.3	2,000	15
Ballast	200	0.35	1,800	0.3
Subballast	140	0.35	2,200	0.2
Subgrade	110	0.35	2,100	0.5

TABLE 1. TRACK MATERIAL AND SOIL PROPERTIES
(Note: Track material data is from published literature; soil layers 1-4 are field experimental data from the authors (MASW).)

COMPUTER MODELLING

A dynamic, explicit time domain, finite element model was developed using the commercial software package ABAQUS [26]. The modelling procedure can be broken down into its primary three components, the track, the train and the soil.

Track modelling
The rail and ties were modelled explicitly [27] and were supported by ballast, subballast and subgrade layers respectively (Table 1), in accordance with (International union of Railways, 1994) [28]. Track component dimensions and material properties are shown in Table 1. Only half of each track component (except the rail) was modelled due to symmetry and the extremities of each were bounded using an absorbing boundary condition to simulate infinity. Track components were

defined using full integrateable, 8 noded solid elements, except for the rail which was modelled using 1D Timoshenko beam elements.

Train modelling

Vehicle modelling was based upon a Thalys high speed train, as found operating in continental Europe. The vehicle was assumed to be symmetrical in the same axis as the track model and thus only half of it was modelled. Its motion was simulated using a rigid multi-body dynamics approach [29], the equations of motion, for which, were solved using an explicit central differencing procedure [30]. This allowed for the simulation of interconnected movement between components (wheels, bogies and cars) and a higher accuracy approximation of the wheel/rail input force.

A non-linear Hertzian contact spring was used to couple the train wheel and the aforementioned track model. This meant that the wheel/rail input force was a function of the wheel position relative to the rail. This relationship was described using Equation 1:

$$F_{wr} = k_H \left(u_w - u_r \right)^{1.5}, \quad u_w - u_r < 0$$
$$F_{wr} = 0 \qquad\qquad u_w - u_r > 0$$

Equation 1

Where u_w is the wheel displacement, u_r is the rail displacement, k_H is the Hertzian constant and F_{wr} is the rail/wheel contact force. Note that track irregularity was assumed to be negligible.

Soil modelling

The soil was modelled as a linear elastic soil with the material properties as found from the MASW tests (Table 1). In contrast to the model outlined in (Connolly et al.) [26], the domain was modelled using the shape of a cuboid, rather than a sphere. This allowed for a more straightforward implementation of the various trench geometries under investigation due to the regular arrangement of finite element bricks.

To prevent spurious reflections from the truncated boundaries of the soil, an absorbing boundary condition was used [31], [32] . This acted as an infinity condition and was implemented using Equations 2, as developed by (Lysmer & Kuhlemeyer) [31]:

$$\sigma = a\rho c_p \dot{\omega}$$
$$\tau = b\rho c_s \dot{\upsilon} \qquad \text{Equation 2}$$

Where σ and τ are the normal stresses and shear stresses respectively. *a* and *b* are dimensionless absorption parameters which were set to 1 to achieve maximum absorption. Lastly, ω and υ are the normal velocities and tangential velocities respectively at the boundary.
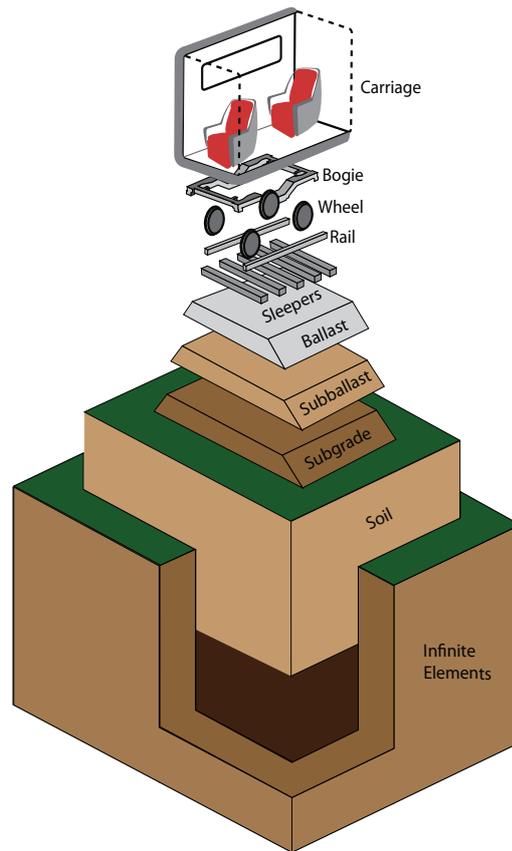
Figure 3. Numerical model visualization

Model Validation

Model validation was undertaken by comparing numerical and experimental results. Figure 4 compares velocity traces on the ground surface at a distance of 18m from the track for a 5 carriage, class 220 Super Voyager passenger train travelling at 30m/s (67mph).
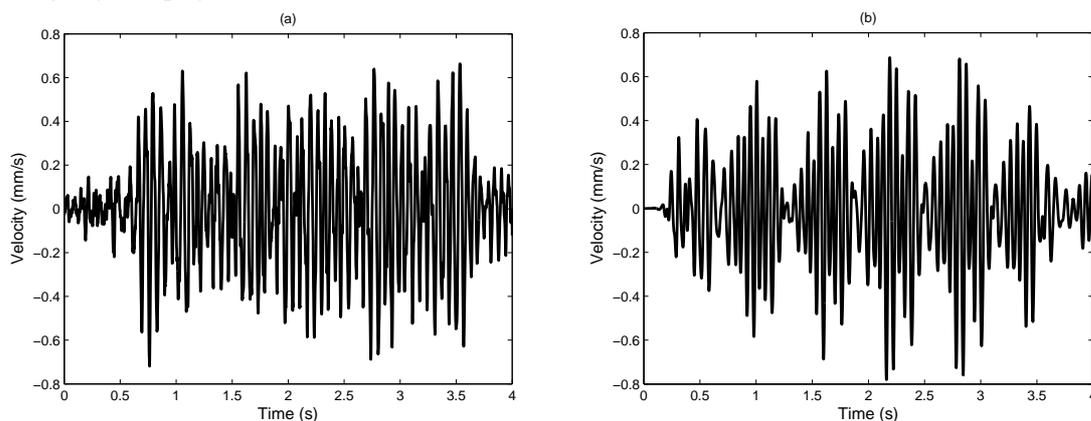
Figure 4. Velocity trace histories, (a) field experiment, (b) numerical result

The two traces have similarities in timing and magnitude although the individual axle passages are more clearly defined for the numerical model. This was possibly caused by surface wave scattering due to the presence of a fence and shrubs

located between the track and the velocity transducers. Another possible source of discrepancy was due to the presence of greater wheel/track irregularities on the "real track" than those modelled. Wheel/track irregularities produce predominantly high frequency vibration that is rapidly damped with increasing distance from the track. It is of less of a concern for nearby structures and is unlikely to affect the performance of a trench. Thus the numerical model can be considered to provide a satisfactory replication of the physical problem for this particular application.

Trench Modelling
The efficiency of a trench to isolate vibration is a function of its geometrical dimensions in relation to the dominant frequency(s) of the propagating wave(s). Approximately 2/3 of total wave energy is transmitted via surface waves (e.g. Rayleigh) meaning it is common to define trench dimensions in terms of Rayleigh wavelength. To avoid the ratio of trench geometry to excitation frequency skewing results, previous researchers such as (Yang & Hung, 1997) [11] have focused on utilizing stationary point excitations of single frequency, thus making it trivial to define trench dimension based upon this single frequency.

A single frequency source defined in this manner is an unrealistic approximation of typical high speed train passage. To achieve a more realistic approximation of the physical problem, a single Thalys high speed train passenger car was used as the excitation mechanism and modelled using the multi-body excitation model described earlier. The frequency content of this excitation source at a point 18m (observation point) from the track is presented in Figure 5. Although the frequency content was spread over a range predominately below 50Hz, and varied with distance from the track [33], the dominant frequency was 12 Hz - which was used to calculate the Rayleigh wavelength and subsequent trench dimensions.
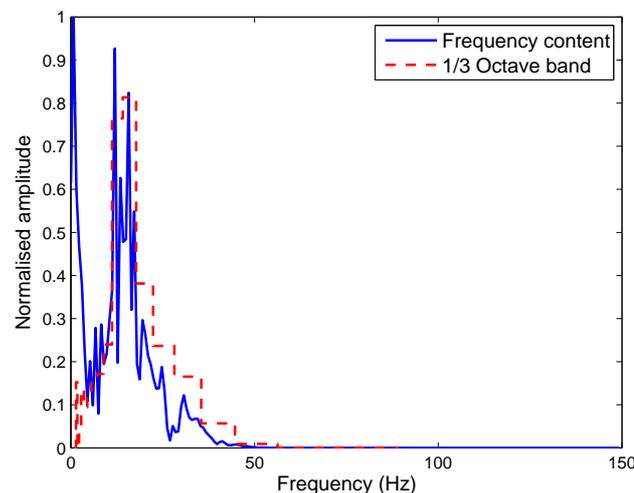
Figure 5. Soil frequency spectrum due to a single passenger car axle (18m from track)

Based on this frequency value, the Rayleigh wavelength for the homogenous soil model was 7.7m. If a different soil was investigated the Rayleigh wavelength value would change because a change in soil material properties would generate different Rayleigh wave speeds and corresponding Rayleigh wavelengths.

Trench geometry was defined using the notation:

$$d = D / \lambda_R,$$
$$w = W / \lambda_R, \quad \text{Equation 3}$$
$$l = L / \lambda_R,$$
$$s = S / \lambda_R,$$

where 'D' is trench depth, 'W' is trench width, 'L' is trench length and 'S' is the distance between track and trench as shown in Figure 6.

Unless otherwise stated the trench dimensionless quantities were: d=1, w=1/3, l=6 and s=1.5. Physically this translates to a trench with dimensions, D = 7.7m, W = 2.54m, L = 46.2m (nearly the full width of track) and S = 11.55m.

All trenches were treated as open trenches. This is physically impractical as trenches require in-fill material for safety and stability criteria. A common engineering solution is to fill trenches with low density gas cushions [34] or polyurethane [13]. Rather than introduce additional approximations for in-fill material properties it was found that open trenches provided an effective condition under which to analyze trench geometry. This assumption has been shown to be valid, as low density materials offer screening performance similar to open trenches [17] – provided that the acoustic impedance ratio between soil and trench in-fill is at least 8.

To assess the ability of each geometric trench permutation to isolate vibration, velocity levels were monitored and averaged over a 1m^2 surface area located approximately 18m from the track. Trench performance was then evaluated using a reduction ratio approach similar to that used in (Yang & Hung, 1997) [11], and (Hung & S. Ni) [35]:

$$Ar = RMS_{trench} / RMS_{default} \quad \text{Equation 4}$$

Where RMS_{trench} is the root mean squared amplitude of the vibration level recorded in the presence of a wave barrier, and $RMS_{default}$ is the root mean squared amplitude of the vibration level recorded when no wave barrier is present. The root mean squared amplitude for each was calculated as outlined in (U.S. Department of Transportation - Federal Railroad Administration, 2005) [36], using a reference velocity amplitude of 2.5x10^{-8} m/s. Physically this implies that if a trench does not exist then Ar = 1, and in contrast, if the trench isolates 100% of the vibration, then Ar = 0.

Before any simulations were undertaken, the trench model was validated by comparing results to those outlined in (Beskos et al., 1986) [10]. The results exhibited a strong correlation with those published but are excluded for brevity.

After validation an initial simulation without any trench presence was conducted. The RMS values were 0.068, 0.14 and 0.072 mm/s in the x, y and z directions respectively. Therefore for this case the vertical vibration was approximately twice that of the horizontal vibration. The vertical vibration was thus the critical condition and was more likely to cause structural damage than the horizontal components.
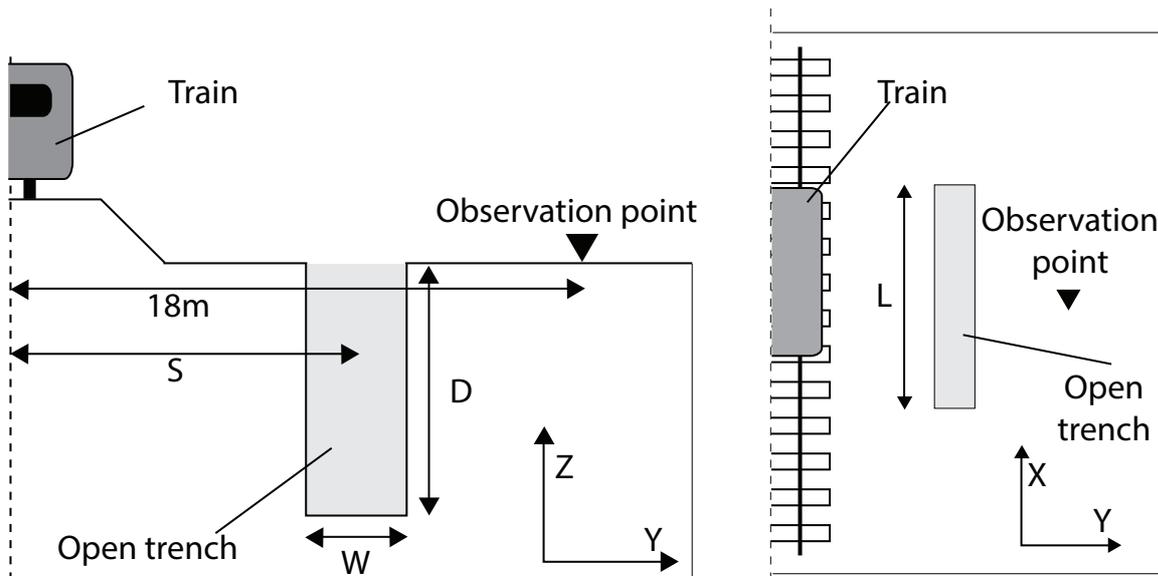
Figure 6. Trench geometry schematic, (a) side-on view, (b) Birdseye view

NUMERICAL RESULTS

The Effect of Trench Width
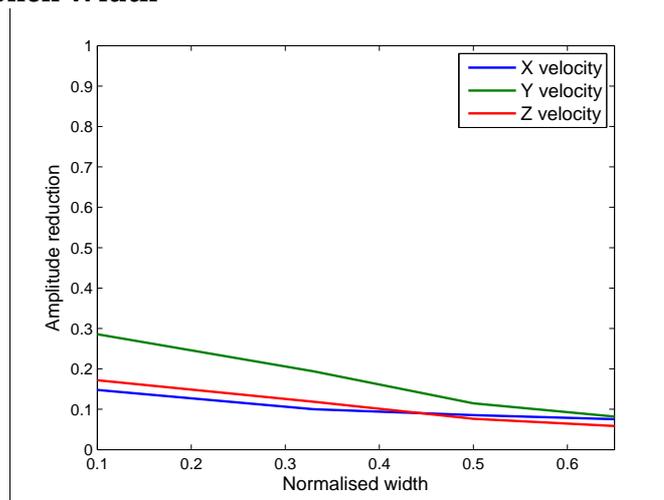
Figure 7. The affect of trench width on amplitude reduction ratio (regarding amplitude reduction, 0.0 = 100% isolation, 1.0 = 0% isolation)

Figure 7 shows the effect of trench width on vibration reduction ratio for the vertical velocity component (red) and both horizontal components (blue and green). A range of width parameters varying between w=0.1 and w=0.65 were tested and all were found to offer high levels of screening. Despite this, for all three vibration components there is only minimal reduction when the trench width parameter is increased from w=0.1 to w=0.65. Therefore it can be concluded that trench width has little effect on the overall ability of a trench to screen vibration.

The Effect of Trench Depth
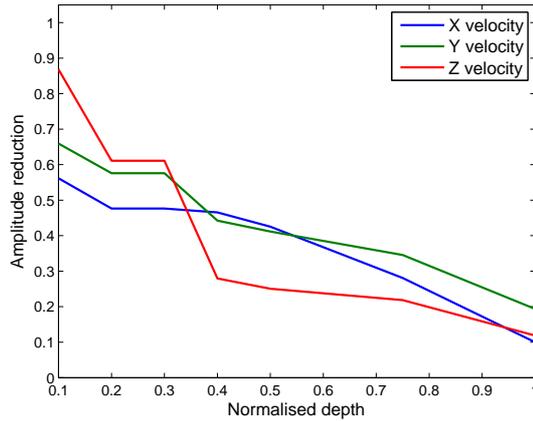
Figure 8. The affect of trench depth on amplitude reduction ratio

Trench depth can be seen to have a greater impact on amplitude reduction ratio in comparison to trench width. Figure 8 shows that amplitude reduction performance increases rapidly with depth for a series of seven depth parameters varying between d=0.1-1.0.

Regarding vertical vibration, depth parameters greater than 0.4 offer large reductions which is important because vertical vibration is typically more dominant than horizontal vibrations for the case of railway traffic. When the trench normalized depth is increased from 0.1 to 1, the amplitude reduction capability increases by 83%. This is consistent with results presented by (Jesmani et al. 2008) [37].

Horizontal vibrations also reduce as normalized depth is increased, albeit more steadily. For both cases, an increase in normalized depth from 0.1 to 1, results in approximately a 0.45 increase in amplitude reduction performance.

Depth has a significant influence on vibration screening because Rayleigh waves carry 67% of total wave energy and decay exponentially with depth. Therefore as trench depth increases less Rayleigh wave energy passes under the trench thus increasing the trench vibration reduction ability.

The Effect of Trench Distance from Railway Line
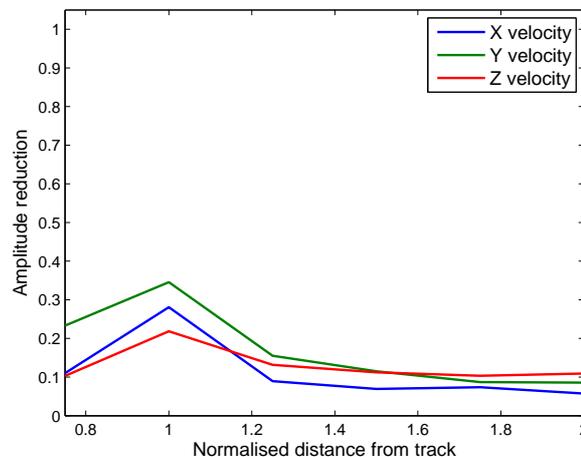
Figure 9. The affect of trench distance from track on amplitude reduction ratio

Figure 9 shows the relationship between amplitude reduction ratio and the distance between trench and track. The minimum trench distance parameter tested was s=0.75 and the maximum was s=2.0. Distance parameters below s=0.7 were not considered because such trenches would be located too close to the line and possibly interfere with the supporting track material.

Trench performance is effected by distance from the track if the distance is less than or equal to one Rayleigh wavelength. For horizontal vibration, if a normalized distance is chosen greater than 1.25 then vibration levels will be much reduced in comparison to a normalized distance of 1. For vertical vibration, reduction is also observed but to a lesser extent. Therefore distance parameters above s=1.25 are desirable due to their higher reduction ratios.

Greater distances are more effective due to the dominance of body waves in regions very close to the track. In such regions body waves carry a high percentage of the total wave energy and decay slowly with depth. Therefore the body waves readily pass under the trench and are thus unaffected by its presence. As the trench moves further from the track the influence of body waves decreases and Rayleigh waves are predominant.

The Effect of Trench Length
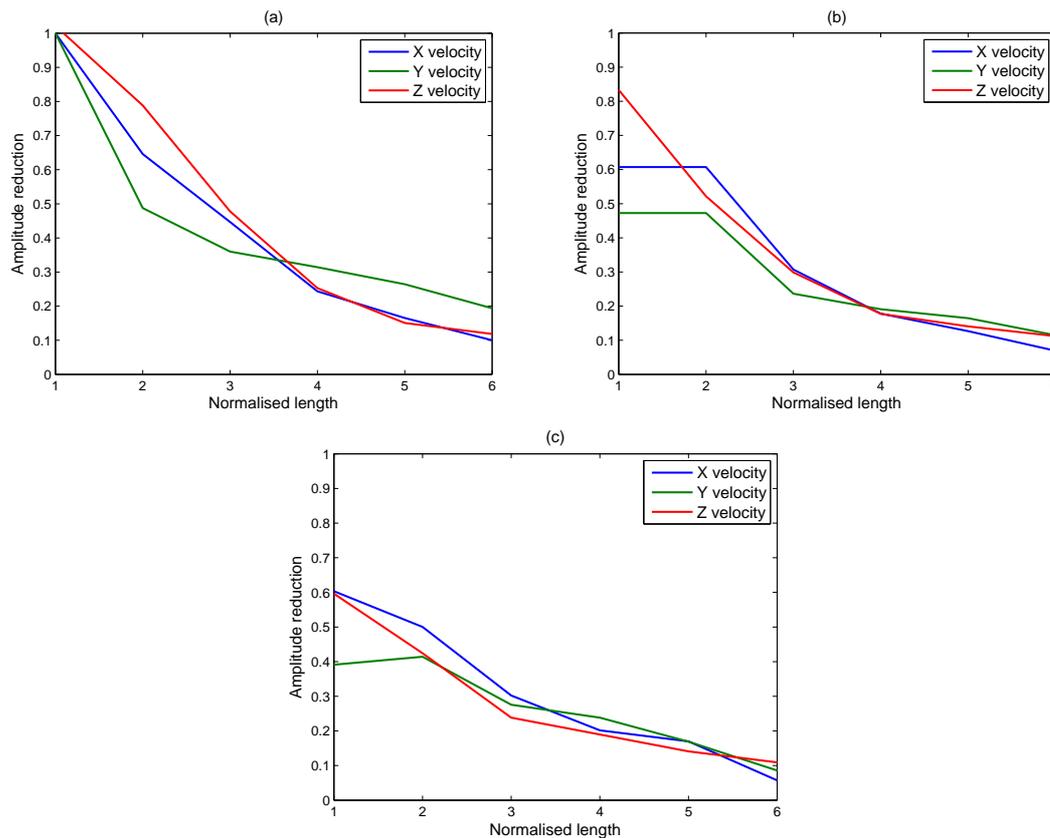
Figure 10. The affect of trench length parameters on amplitude reduction ratio, for (a) s=1, (b) s=1.5 and (c) s=2

Figure 10 shows that trench length plays an important role in vibration isolation. When the normalized trench length is 1 the reduction ratio in all three component

directions is also 1 meaning that the trench is having no effect. As the trench length is increased, greater reduction is observed and when l=6, (nearly the full length of the track) a reduction in vibrations of about 85% is found. This is caused because there is no longer a direct path between the railway line and receiver - meaning that the only wave travel path is under the trench. This is important because Rayleigh waves decay exponentially with depth meaning that only a small percentage can pass under the excavation. Therefore the unimpeded response at the receiver location is likely to be a combination of compression, shear and Rayleigh waves that passed under the trench, all carrying low levels of energy.

When the trench distance from the track is increased to s=1.5, (Figure 10b) vibration levels are reduced for short trench lengths but are similar to the s=1 case for greater trench lengths. Similarly, when s=2 (Figure 10c), vibration levels are reduced for short trench lengths in comparison to when s=1 and s=1.5, but are similar to s=1 and s=1.5 at greater trench lengths. This effect is true for all three vibration component directions because when the trench is located in close proximity to the track it is easier for the Rayleigh waves to travel around the excavation and reach the observation point. Therefore it can be concluded that if trenches are placed further away from the track and closer to the structure they are shielding, trench length can be reduced while maintaining performance.

PRACTICAL CONSIDERATIONS
A number of important practical aspects emerge from this research. In particular trench depth has been shown to have greater impact on vibration isolation performance than trench width. Despite this, when planning trench isolation strategies both construction feasibility and costs must also be considered.

For the case of vibration isolation trenches - the depth to width ratio is too large to utilize conventional backhoe excavation methods, so hydro vacuum excavation techniques are typically employed. Hydro vacuum excavation simultaneously uses high pressure water to break down soil deposits and a vacuum to remove it.

Excavated trenches must be in-filled to fulfil safety and stability criteria. Polyurethane foam is a suitable material because of its low density and hence low acoustic impedance, plus its ease of installation. The polyurethane resin is typically laid using gravity fed spraying and has an expansion ratio of 1000% (10x).

To determine the effect of trench geometry on project cost, overall construction costs were divided into two components: excavation costs and infill costs. Hydro vacuum excavation costs were been assumed to cost $310/m^3 for labour, plant and spoil disposal costs. Polyurethane foam was assumed as the infill material and costs were calculated to be $650/m^3 for labour, plant and materials. Therefore the total cost per cubic meter is $960.

For the default trench described in the 'trench modelling' sub-section (d=1 (7.7m), w=1/3 (2.54m), l=6 (46.2m)), the total trench size is 904m^3 resulting in an installation cost of $868,000. Despite this, as trench width has been found to be a non-critical parameter then reducing the width to w=1/30 (i.e. total width = 0.25m) results in a barrier size of 89m^3 and a total cost of $85,500. This saving of $782,500 only leads to a small drop in performance. Similarly if the depth is reduced to d=0.4 (3.08m), $518,000 is saved while maintaining a similar isolation performance for vertical vibrations.

To minimize costs even further, a trench with both optimized depth and width geometry was tested (d=0.4 and w=1/30). It was found that vibrations were reduced by 80% in the vertical direction and 30% and 57% in the x and z horizontal directions respectively. This optimized trench geometry offers similar performance to the default trench but for $34,200. As vertical vibration is dominant in the case of high speed rail, for this specific example vibration levels can be reduced by approximately 80% at a cost 96% cheaper than the original solution.

FREQUENCY CONTENT COMPARISON
Figure 11 shows the normalised frequency spectrum and 1/3 octave band for the optimized trench at 18m from the track. When compared to the case of no trench (figure 5), the frequency spectrum for both responses is relatively similar. Despite this, the trench damps out some of the frequencies located outside the range of 10-15Hz and an additional peak at 2Hz is present. This 2Hz peak is possibly due to Rayleigh waves reflecting against the trench, back to the track symmetry condition and back against the trench again.
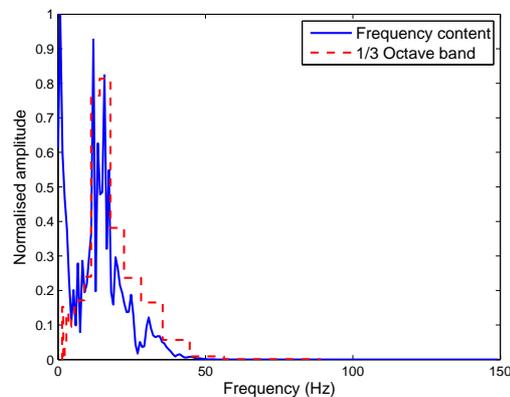
Figure 11. frequency spectrum and 1/3 octave band for the optimized trench (18m from track)

CONCLUSIONS
Trenches provide an effective method to screen railway vibrations but their installation can be cost may be very high. In an attempt to minimize construction costs, experimental and numerical investigations have been undertaken to determine the relationship between trench geometry and vibration isolation performance.

Vibration levels were recorded in the free field next to a railway line using geophones. Additionally, MASW tests were conducted at the same site to determine the underlying soil properties.

The measured/calculated soil properties were used to construct a finite element model of the railway track and underlying soil stratum. The model was used to reproduce the characteristics of the test site and the resulting simulations showed that it was capable of replicating vibration levels.

The model was then used to test the ability of various trench dimensions and geometry to isolate vibrations from railways. To facilitate the screening of Rayleigh waves an open trench condition was used to simulate a low acoustic impedance material in comparison to the parent soil. It was found that trench depth has the most significant influence on vibration reduction with isolation performance increasing rapidly with depth. In contrast trench width was found to have little

effect, with both narrow and wide trenches showing to be effective in screening vibration. Using these relationships allows wave barrier designers to develop solutions that provide high screening performance for substantially reduced investment.

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