Rayleigh wave propagation assessment for transport corridors

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Abstract

Wheel loading from high speed trains generate Rayleigh waves that propagate in the near surface causing track and ground displacements. There is potential for amplification of ground displacements over low density, poorly consolidated soils with low Rayleigh wave velocities. Rayleigh wave characteristics are mapped onto soil engineering geological classifications using lithological and density parameters in effective stress-based algorithms that model shear wave velocities with depth. Use of small scale engineering geological maps and 1D modelling identified low Rayleigh wave velocity profiles associated with alluvial and terrace deposits in river catchment and floodplains along transportation routes, such as at Hampton, Aylesbury and Perivale along the proposed High Speed 2 route. Examination of the velocity-depth profiles indicated that sites are especially susceptible to dynamic displacement amplification where train-induced ground motion occurs within an interval of up to half the wavelength of the Rayleigh wave frequency induced by the train load centres. Using the algorithms to attribute density and shear wave velocities to the engineering geological section, a 2D ground model was created for an alluvial-terrace structure at Perivale. Wave propagation modelling using a finite difference code indicated amplification due to interference effects from wavefronts that propagated along different pathways of up to 2 times on vertical and 2.5 times on the horizontal displacement.

Notations:

V_S = shear wave velocity (ms^{-1} or m/s); V_R = Rayleigh wave velocity (ms^{-1} or m/s);

υ = Poisson's ratio (dimensionless); σ' = effective stress (Pa);

ρ_b = bulk density; ρ_s = solid density; ρ_d = dry density; ρ_a = air density;

ρ_w = water density, (density units:- kgm^{-3}); g = earth's gravitational acceleration (ms^{-2});

S_w = water saturation (proportion); n = porosity (dimensionless);

d = burial depth (m); V_{Train} = train speed (km/hr or ms^{-1} or m/s);

A_D = Dynamic Amplification Factor (dimensionless); D_{AD} = depth of maximum A_D (m);

F_{Train} = train load frequencies [ratio: load (bogie or axle) spacing / V_{Train} – Hz or rad/s]

Keywords: Geology; Field Testing & Monitoring; Transport Planning

Introduction:

Towards the late twentieth century, European train operators noted substantial increases in vertical movements in the railtrack with increasing train speeds, even at speeds as low as 140 km/h (40 m/s) for some soil profiles (Dietermann & Metikine, 1997). The early twenty first century has seen increasing development of high-speed rail infrastructure across Asia, Europe and North America, with rail speed designations of 300 km/h and above (Taylor, 2007). The demand for train speeds up to 375 km/h on the foreseeable High Speed 2 (HS2) (The Engineer Q&A, 2013) calls for straighter network sections making the crossing of soft soil zones more unavoidable. Hence, there is great interest in the UK regarding the potential ground displacement distribution in relation to the ground conditions and line speed designation along the recently proposed HS2 route. Ground displacement amplification has occurred where train speeds approach a critical velocity that is equivalent to the fundamental Rayleigh mode associated with site specific soil profiles (Dietermann & Metikine, 1997; Madshus & Kaynia, 2000; Woodward et al., 2013). Rayleigh wave (phase velocity) dispersion curves aid identification of critical train speeds and the critical line speed-load frequencies associated with axial-bogie spacings that could further enhance site-specific amplification (Madshus & Kaynia, 2000). Recent studies have used simple layered track and subgrade structures, such as a finite layer over half-space to model this displacement amplification process using platforms such as VibTrain (Madshus & Kaynia, 2000) and DART3D (Woodward et al., 2013). While other models (Sheng et al., 1999 & Yang et al., 2003) have investigated multiple, infinitely extended layered ground, even these haven't captured the effects of laterally constrained boundaries associated with heterogeneous, shallow geology. So, to fully understand the wave propagation and amplification processes at specific locations requires ground models that capture site scale heterogeneity, especially where variable velocity profiles can be identified along a route, such as associated with river catchments.

Two-thirds of the total seismic wave energy generated by a vertically oriented load acting on a horizontal surface propagates as Rayleigh waves (Richart et al., 1970; Gunn et al., 2006; Gunn et al., 2011). Similarly, a significant proportion of the disturbance produced by rail wheel loading propagates in the form of a Rayleigh wave (Woodward et al., 2011; El-Kacimi et al., 2011), where the disturbance is mostly confined to the near surface in the form of ground roll affecting the engineered track, pavement, subgrade and shallow geology. While the Rayleigh wave velocity is required to model vehicle-induced ground displacements, it can be derived as a fraction of the shear wave velocity for rocks and soils (Woodward et al., 2011; El-Kacimi et al., 2011). Two very important parameters controlling shear (and hence Rayleigh) wave velocity are density and small strain stiffness (or modulus of shear), which are related to grain size, shape and grain-grain interactions (Gunn et al., 2003). Both density and stiffness are strongly influenced by the engineering geological characteristics of rocks and soils, hence vehicle-induced ground displacement will be significantly influenced by the geological distribution along the rail route. Ground displacement amplification can occur due to the development of ‘bow waves’ as train speeds approach a site-dependent critical Rayleigh wave velocity (Dietermann & Metikine, 1997; Woldringh & New, 1999; Heelis et al., 2000). The risk of amplification of ground displacements is increased when high speed vehicles travel over poorly consolidated, low density soft soils with low Rayleigh or shear wave velocities (Gunn et al. 2003). There is further risk of amplification due to interference effects from complex multiple wave propagation pathways through variable velocity changes caused by localised near surface structures. This risk is especially compounded at the interfaces between stiff soils of high velocity and soft soils of low velocities, for example such as associated with river terrace and alluvial deposits found at several river catchments along HS 2.

This paper presents a simple method for firstly, location of potentially low velocity route sections at network scale, and secondly, for the attribution of shear wave velocity route sections for input into local scale wave propagation modelling. Using the topical subject of planning strategic high speed rail transportation we provide an example of how a geological model framework can support multi-scaled assessment of surface wave propagation. While, this may not have been the original intention, the lithostratigraphical and especially engineering geological classes within modern digital geological information systems capture geotechnical and geophysical property data that are associated with the parameters that control surface wave propagation. In the absence of direct measurement of Rayleigh wave dispersion curves, maps and ground models can provide the framework for attribution of surface wave parameters onto the lithostratigraphic or engineering geological classes that is sufficiently robust for the localisation and initial characterisation of Rayleigh wave velocity-depth profiles and wave propagation processes at locations with potential for ground motion amplification. Also, ground models can be constructed that capture the site heterogeneity required to study additional amplification caused by localised interference of refracted and reflected wave propagation pathways.

Geotechnical properties controlling surface wave velocity

While the Rayleigh wave velocity is required to model vehicle-induced ground displacements, it can be derived as a fraction of the shear wave velocity for rocks and soils, using (Woodward et al., 2011; El-Kacimi et al., 2011):

$$V_R = \frac{(0.87+1.12\upsilon)}{(1+\upsilon)} V_S \qquad 1$$

where ν is Poisson's Ratio. Poisson's ratios for rocks are commonly within the range 0.2 - 0.3. Soils tend to have higher Poisson's ratios of 0.3 - 0.4, which can be even higher in very soft, fully saturated fine grained materials. So, Rayleigh wave velocities are generally a factor of 0.9 - 0.95 of shear wave velocities. The bulk density, ρ_b, is the volumetric sum of the densities of the solid rock/soil particles, ρ_s, pore fluid, ρ_w, and the remaining unsaturated air voids, ρ_a.

The contribution of the air component is negligible because of its very low density, so the bulk density of a soil approximates to:

$$\rho_b \cong (1-n)\rho_s + nS_w\rho_w \qquad 2$$

where S_w, the proportion of pore fluid saturation varies from zero to one, and n is the soil porosity. If a density - depth relationship can be established, effective stress, σ' can be derived by considering the total submerged weight acting per unit area which is related to the density differences (Gunn et al. 2002) as follows:

$$\sigma' = g\,d\,(\rho_b - \rho_w) \qquad 3$$

where: $g = 9.81ms^{-2}$, d = burial depth. The shear wave velocity, V_S is related to the strength of the soil solid framework matrix, which increases with burial depth and increasing effective stress. Lithology controls the grain friction and interactions within the framework matrix, and thus, controls the propagation velocity of a shear wave through a rock or soil (Gunn et al. 2003). Like density, lithology determines a specific effective stress dependent relationship applied to derive the velocity at a specific depth. These can take the form of V_S changing on the basis of a power law of effective stress (Richart et al., 1970; Gunn et al. 2003, Robertson et al., 1995; Shibuya et al., 1997) such as:

$$V_S = A.\sigma'^B + C \qquad 4$$

where A, B and C are constants (and B is an exponent of effective stress) influenced by lithology, porosity and density.

Outcrop maps for strategic scale route planning

Geotechnical property estimates from digital geological maps

Corridor overlays onto small scale 2D digital geological maps (e.g. 1:250, 000 or 1: 625, 000) can identify the lithostratigraphical framework useful in the early stages of route planning. However, identification of low velocity zones and initial works designation plans require information relating to engineering characteristics of the ground. This can be derived via reclassification of lithostratigraphy into associated engineering geological classes (Smith &

Ellison, 1999; Rosenbaum, 2003; Dobbs et al., 2012). Reclassification includes assessment of the influence of lithological attributes on geotechnical properties and behaviour, beginning with consideration of genetic origin into sedimentary, metamorphic or igneous classes, followed by attributes affecting mechanical behaviour (Dobbs et al., 2012). Metamorphic and igneous classes generally include hard rocks which are likely to be associated with very high shear (and Rayleigh) wave velocities. Whereas, the sedimentary class includes hard and soft rocks and soils of varying density or compaction onto which broad velocity ranges can be mapped for use in identifying low velocity zones during initial route network planning.

An engineering geological classification differentiates soils and rocks on the basis of the dominant grain size range, whether fine or coarse and possibly very coarse (first column in Table 1). A further differentiation is on the basis of compaction for fine grained materials and relative density for coarse grained materials. Broad shear wave velocity classes can be mapped on to the engineering geological characteristics of fine and coarse grained soils by applying porosity-density characteristics associated with their respective compaction or density indices into the effective stress algorithms (2 - 4 above). Table 1 presents the density and shear wave velocity ranges mapped onto the indices for normally consolidated fine and variable density coarse grained soils that could be within the upper 2 m interval and outcrop on small scale maps.

These classifications enable use of 1:1,000,000 series Engineering Geology Maps of the UK (British Geological Survey, 2011a, b, c) for general assessment of ground conditions and of shear wave velocity as part of initial route corridor planning over a strategic UK scale. While planning over network sub-routes would benefit from the greater resolution of engineering geological classifications based upon 1: 250,000 digital geological map series. However, the assumption that material at outcrop persists with depth in these outcrop-based approaches limits them to small scale strategic planning applications, for example at 1:250, 000 scale and below.

Grain Size Class		Fine Soils: Compaction				
Fine Soils		Very Soft	Soft	Firm	Stiff	Very Stiff Soil grading to Very Weak Mudstone
CLAY and SILT	Bulk Density (Mgm^{-3})	1.5	1.7	1.9	2.1	2.3
	Shear wave velocity ms^{-1} and ($kmhr^{-1}$)	62 (223)	89 (320)	115 (414)	140 (504)	164 (590)
SAND and GRAVEL	Dry Density (Mgm^{-3})	1.5	1.6	1.75	1.9	2
	Shear wave velocity ms^{-1} and ($kmhr^{-1}$)	113 (407)	139 (500)	161 (580)	180 (648)	197 (709)
Coarse Soils		Very Loose	Loose	Medium Dense	Dense	Very Dense
Grain Size Class		Coarse Soils: Relative Density				

Table 1: Site shear wave velocity classes mapped onto compaction and relative density engineering geological characteristics for soils. Velocities derived via application of Robertson *et al.*, 1995 and Shibuya *et al.*, 1997 to estimated densities for each soil strength class.

Small scale location of potential low wave velocity sections

Assessment of the outcrop along the HS2 Phase 1 route is of interest regarding the location of sites where the estimated shear or Rayleigh wave velocities assigned to the near surface materials are comparable to the designated maximum line speeds. Low velocity sections will be particularly associated where very soft and soft fine grained soils and possibly very loose coarse grained soils persist at outcrop and in the near surface. These characteristics are likely to occur at many locations along sections designated at grade where alluvial deposits outcrop, such as at Perivale, Aylesbury Parkway and Hampton in Arden, Figure 1. Line speed designations at Perivale could possibly be up to 250 km/h (69 m/s) and at Aylesbury Parkway and Hampton up to 400 km/hr (111 m/s) (ARUP, 2012).

Figure 1: Example geological information for locations of very soft or soft fine soils along HS 2.

At Perivale, the superficial geology comprises alluvium, glaciofluvial deposits and the bedrock is London Clay. Aylesbury comprises alluvium, head deposits and Ampthill Clay and Hampton comprises alluvium, glaciofluvial deposits and Mercia Mudstone. Alluvium can comprise many grain sizes including clay, silt, sand and gravel in variable amounts but clay and silt often dominate. Glaciofluvial deposits can comprise variable grain sizes but sand and gravel often dominate, while head can also be highly variable. The identification of these potentially low velocity locations represents the limit of the outcrop-based assessment. Hereafter, assessment of displacement amplification at greater scale relates to understanding the lateral variation in Rayleigh wave velocities with depth in the different geological profiles along a section. Hence, further assessment of this process requires more detailed subcrop information leading ultimately to site investigations to establish the exact ground conditions at depth.

Ground models attributed with wave properties

Site specific velocity profiles

Two fundamentally different displacement fields are caused by the loading of a moving train, which are dependent upon train speed, V_{Train} relative to the site specific 'critical speed', which is equivalent to the velocity of the fundamental Rayleigh mode, V_R (Madshus & Kaynia, 2000; Woodward et al., 2013). A quasi-static displacement field comprising downward strains caused by surface load-stresses acting through the bogies and axles of the train, which occurs at relatively low speeds with respect to a site specific 'critical speed', and a dynamic displacement field, which has both upward and downward strains, which increasingly develops as the train speed approaches the site specific 'critical speed'. The quasi-static displacement field maintains a pattern that is consistent with the train load point geometry and moves along with the train. The dynamic displacement field exhibits larger strains and comprises a rapid build-up under the front of the train and a decaying oscillation behind the train. Amplification of ground displacement or, the dynamic amplification factor, A_D (Dietermann & Metikine, 1997; Madshus & Kaynia, 2000; Woodward et al., 2013; Esveld, 2001; Verruijt, 1999) is dependent upon ratio of the train speed, V_{Train} to the 'critical speed', V_R and has its maximum value when the train speed is equal to V_R. In the undamped case, the dynamic amplification factor can be approximated by:

$$A_D = \frac{1}{\sqrt{\left(\left|1-\left(V_{Train}/V_R\right)^2\right|\right)}} \qquad 5$$

Using the effective stress controlled models (algorithms 2 - 4), surface wave velocities can be attributed onto 1, 2 or 3D geological ground models that can be constructed using all available outcrop and subcrop information, such as from nearby boreholes and ground investigations. 1D site soil velocity profiles can be constructed from individual borehole logs representative of site conditions. Of interest in our examples will be the potentially close matches to the designated line speeds of velocities associated with very soft and soft fine grained soils at Perivale, and the very soft fine soils and the very loose coarse soils at Aylesbury and Hampton, Figure 2a. Figures 2b, 2c show the maximum potential undamped A_D calculated for train speeds (V_{Train}) of 250, 300 and 400 km/hr using Rayleigh wave velocities of 93% of the shear wave velocities in the soft fine and the very loose coarse grained soil profiles in Figure 2a. The maximum A_D occurs where the ratio $V_{Train}/V_{Rayleigh}$ is closest to unity, which occurs at depths increasing with V_{Train} in Figures 2b, c. A significant proportion of the particle motion in the reverse ellipsoids of the Rayleigh wave phase associated with maximum A_D occurs within a fraction of one wavelength from the surface, considered to be between 0.25 – 0.5 of the wavelength (Gunn et al., 2006, 2011a, 2011b, 2013). Taking an approximate mid-range of one third wavelength, then Rayleigh waves are more likely to be induced as the train load frequencies, F_{Train} approach the ratio:

$$F_{Train} \approx V_{Train}/\left(3.D_{AD}\right) \qquad 6$$

where D_{AD} = depth of maximum A_D. In the case of a train traveling at 400 km/hr (111 m/s), with a D_{AD} of approximately 6 m in soft soils at Hampton or Aylesbury, Rayleigh waves are more likely to be induced at around 6 Hz.

Figure 2. Shear wave velocity- and potential displacement amplification-depth profiles for soft fine and loose coarse grained soils.

Dynamic amplification occurs due to excitation of a site specific resonance condition induced by the load frequencies associated with the various bogie-axle spacing combinations and the train speed. The actual amplification at site will be less than the maximum potential amplification shown in Figure 2. It will depend upon the vibration losses or damping in the soils, but more importantly how much the frequency-wavelength characteristics of the train-induced loads excite natural resonant modes related to the site velocity structure. For a single layer over half space of much greater velocity, Yang *et al*. (2003) showed that the attenuation of ground vibration with distance from a moving load was dependent upon layer thickness. At speeds below the critical velocity, attenuation increased with decreasing layer thickness, but the difference in the rates of attenuation reduced with increasing train speeds. Table 2 summarises the frequencies associated with typical bogie and axle load spacings on Asian and European high speed trains travelling at different speeds.

Load Centre Spacings			
Bogies	**17.5 m**	**Axles**	**2.5 m**
Train Speed		**Load Frequencies**	
		Bogies	**Axles**
km/hr	**m/s**	**Hz**	**Hz**
100	28	1.6	11.1
150	42	2.4	16.7
200	56	3.2	22.2
250	69	4.0	27.8
300	83	4.8	33.3
350	97	5.6	38.9
400	111	6.3	44.4

Table 2. Estimated load frequencies for high speed bogie and axle load centres.
[Overall approximate spacings for Chinese (CRH 380) and European (SF 500) bogies.]

Figure 3 compares train speeds of 250, 300 and 400 km/hr and the wave number equivalent to the typical bogie spacing of a high speed train to the Rayleigh wave (93% of the shear wave) velocity profiles of the soft, fine and the very loose, coarse grained soils in frequency-wave number space. The Rayleigh wave velocity curves form the locus for the maximum potential dynamic amplification at the site. The potential for amplification increases as the line speed designation approaches (and crosses) the Rayleigh wave curve for the site, such as at wave numbers 0.36, 0.73 and 1.22 on the soft fine soil profile for line speeds of 400, 300 and 250 km/hr respectively. The closer the intersection is to a wave number associated with any of the load centres, the more vulnerable the site is to dynamic amplification. Fine, soft soils associated with alluvium at Aylesbury and Hampton are likely to be vulnerable to dynamic amplification from trains travelling at 400 km/hr because the line speed intersects the soil Rayleigh profile very close to the wave number associated with the bogie spacing (0.35 m^{-1}). This intersection can be seen at approximately 38.5 rads/s or 6 Hz, which is very close to the frequency related to the bogie load centres. However, Figure 2 shows that the maximum amplification potential will occur where alluvium persists to beyond 6 m depth, which seems quite deep and would have to be confirmed by site investigations. With the variability of alluvial and terrace deposits, it is also possible for a softer, lower velocity interval to underlie stiffer or denser, higher velocity soils at outcrop (Gunn et al., 2011a). Intervals of soft, fine silts originally deposited in ephemeral lakes subcrop in many terraces and can produce non-normally dispersive velocity profiles, with a low velocity, silty layer underlying loose sands at the surface (e.g. variable terrace profile in Figure. 2a). This soil velocity profile would also be susceptible to similar levels of dynamic amplification as the fine, soft soil profile; but again, would have to be confirmed by site investigations. Such investigations could, for example, include invasive cone penetration resistance testing (CPT) or seismic CPT to establish ground truth combined with non-invasive surface wave surveys to attain sufficient ground coverage (Gunn et al., 2006, 2011a, 2011b, 2013).

Figure 3. Frequency - wave number comparison of train speeds, bogie centres and shear wave velocity for very loose and soft soils.

Site scale ground models for wave propagation visualisation

One dimensional soil velocity profiles are not sufficient to understand the wave propagation processes through the heterogeneous material and property distributions within Quaternary and Holocene structures as found in river terraces, glacial outwash and flood plains associated with recent river systems. Fuller 2D and 3D analyses are required that use attributed ground models to visualise the effects of laterally variable property distributions (along and across rail corridors) upon the propagation pathways of wavefronts within these structures. Very localised, high ground displacements could occur due to interference of wavefronts that have propagated via different pathways due to refraction and reflection of the original load disturbance within the ground. Process modelling and monitoring would benefit from a ground model that best captures the true site heterogeneity of the ground. This can be achieved by using property distributions based upon integrated geotechnical and geophysical ground investigation data as input matrices. 3D models of shear wave velocity or small strain stiffness can be constructed from surveys employing continuous surface wave or multi-channel analysis of surface wave methods to support an interpretation of the materials, variability and overall condition along the route (Gunn et al., 2011b, 2013). However, this will require extensive fieldwork and interpretation; activities that are likely as part of secondary route-site evaluation phases during project development. Again, in the absence of these detailed field data, a lithological framework model of subcrop can be used to develop representative engineering geological and geophysical property sections along a transportation route.

Figure 4a shows the engineering geological properties of the materials in a representative 2D section along the proposed HS2 route at Perivale. The ground model was constructed using available digital terrain models (DTM), outcrop information from 1:50k digital geological data (DiGMap-GB50) and outcrop information from major site investigation boreholes surrounding the HS2 transport corridor. Borehole subcrop is correlated with surface line work to produce a network of 2D sections for the made ground, superficial and bedrock geology, which are interpolated (using Delaunay triangulation) to produce a 3D ground model (Kessler et al., 2009). Thereafter, the 3D ground model can be interrogated to generate 2D pseudo-sections along any route, such as along HS2. The made ground has been modelled as loose sand and gravel, the alluvium as soft clay, the terrace gravels, the Kempton Park and the Taplow Park sands and gravels as dense coarse soils, (but noting that *in situ*, they can contain localised lenses of silt, clay or peat) and the London Clay as a stiff fine soil. Figures 4b and c show the simplified model sections of density and shear wave velocity equivalent to the succession of made ground, alluvium and terrace gravel overlying the London Clay between 150 and 450 m in the engineering geology section in Figure 4a.

Figure 4. Ground models attributed with geophysical properties for input into wave propagation modelling

A finite difference package was used to model the propagation of a Ricker wavelet caused by a vertical impulse of nominal 10 Hz frequency through the shear wave velocity and density structures representing part of the Perivale section along HS2. The model also required a compressional wave velocity input matrix, which was set to a single value of 1500 m/s over the whole section (e.g. fully saturated soils). The side and lower boundaries were made to be absorbing over at least 20 nodes, whereas the surface boundary was set to be stress free. Simulations were up to 2 seconds duration with a 25 microseconds interval between finite difference calculations. The first model relates to wave (stress field) propagation from a source location at x = 0 m, z = 0 m through a geophysical property model representing the London Clay, where the density and shear wave velocity gradually increase with depth, Figure 5a. This first model serves as a benchmark for comparison to the second model, which relates to the localized propagation within the made ground-alluvium-terrace gravel structure from a second source on the upper, made ground gravel, 10 m from the interface with the alluvium. In the London Clay model, with increasing distance from the initial impulse, body shear waves travel via shorter duration pathways, through deeper, higher velocity zones at increasing depths. These continuously refracted wavefronts can be identified on seismic field records as the upwardly curving first wave arrivals. The Rayleigh wave arrivals follow after the shear wave front, where the difference in arrival times due to slightly lower Rayleigh wave velocities increases with distance, Figure 5a. Field records over the alluvial and terrace structure reveal more complex propagation. For example, the fast event between 0 - 250 ms from x = 100 m to 150 m is caused by waves that propagated through the upper made ground gravel (1 in Figure 5b). Corresponding slower events between 0 and around 400 ms result from waves that propagated through the underlying alluvium (2), where at x = 100 m they refract into the higher velocity terrace gravels (3). Also, near the source, waves refract from the made ground gravel into the slower alluvium (4).

Figure 5. Seismic field records of inline displacement due to wave propagation from a vertical impulse source.

A series of stills show the wavefront propagation at different times after the initial vertical impulse of the second source on the upper, made ground gravel, Figure 6.. The body P-waves, traveling at far greater velocities appear as faint fronts well advanced of the body shear and surface waves, Figure 6, Frame 3. The shallow, left going wavefront is distorted as it advances more rapidly through the higher velocity made ground gravel than the underlying alluvium, Figure 6, Frame 3. Wavefront advance is slower through the alluvium than through the higher velocity coarse soils above and below resulting in further refraction of the wavefront into the low velocity alluvial layer, between 150 ms and 300 ms, Figure 6, Frame 6. The right going waves from the upper made ground and lower terrace gravel propagate more quickly into the alluvium than through the alluvium and on into the London Clay, Figure 6, Frames 3 and 6. Also, waves propagating from the lower terrace gravel into the alluvium and the London Clay refract along the alluvium-London Clay boundary and bend upwards towards the alluvium outcrop. The different propagation modes that are channeled into the alluvium result in a series of ground displacements, from around 250 ms to 600 ms, that grow and decay in a beating pattern as they interfere constructively and destructively, Figure 6, Frames 6 and 9.

Figure 6. Wave front propagation pathway through representative geophysical ground model section at Perivale.

The simulated seismic field records were constructed by aligning the displacement-time traces that would be recorded across the surface by individual sensors spaced at 2 m intervals across the models. Comparison of individual sensor traces from the two ground models in Figures 4 and 5 provides an indication of the additional displacement amplification arising from localized interference of waves propagating through the alluvial-terrace structure rather than through the London Clay bedrock. The examples in Figure 7 use the trace from a sensor located 26 m away from the impulse sources in each model to compare ground displacement in the outcropping soft, fine soil of the alluvium to a baseline reference trace through the London Clay at the same offset. The wave sequence through the alluvium arriving around 250 milliseconds after the vertical impulse (Figure 6), produces the series of large amplitude peaks on the horizontal displacement trace in the alluvium-terrace model over the interval from 250 - 600 milliseconds, Figure 7b. This trace exhibits a low frequency growth and decay of amplitudes over what appears to be around a beat period of around 500 milliseconds. Localised interference of the different wave pathways contributing to this sequence results in peak amplitudes up to 2.5 times greater than the waves that propagate in the baseline London Clay model at similar time delays (Figure 7a). These increased peaks occur where constructive interference occurs, whereas low amplitudes (such as at around 1.0 s on the alluvium-terrace: Horizontal trace, Figure 7b) result from destructive interference. The largest peaks (troughs) in the vertical displacement in the alluvium are also around 2 times greater than the London Clay baseline arriving after around 600 milliseconds delay. Train-induced vibration studies using more representative ground models will improve visualisation of site ground motion and show how local structure influences potentially large ground motion, such as on the alluvium in the Perivale model. In turn, these modelling outcomes will better inform local track design, for example, identifying sections requiring ground stiffening treatment or more robust trackbed design.

Figure 7. Relative surface displacements at location 26 m away from vertical impulse for London Clay baseline and Perivale ground models.

Conclusions

Depending upon the vehicle speed, loads associated with moving trains cause quasi-static or dynamic displacement fields. Compared to the static field, amplification of ground displacements occurs in the dynamic field as the train speed approaches a critical velocity that is related to a site specific Rayleigh wave velocity. However, dynamic amplification of displacement is also influenced by the load frequencies induced into the ground by the load centres of the moving train, which is controlled by the train speed. Susceptibility to amplification increases in locations where the train induced ground motion occurs within an interval of up to half the wavelength of a Rayleigh wave of the same frequency (phase) induced by the train load centres.

Engineering geology influences shear wave and Rayleigh wave velocity and hence the route engineering geology will strongly influence the locations of potential dynamic displacement amplification along a high speed rail network. For route planning and evaluation purposes, the influence of engineering geology and ground condition on the Rayleigh wave velocity can be modelled using effective stress controlled algorithms. Subsequently, the route engineering geology can be attributed with geophysical properties sufficient to model surface wave propagation caused by impulsive vertical loading. Lithology, compaction and density provide the parametric control on the stiffness, and hence, shear and Rayleigh wave velocity profiles. Comparison of the train speed to the Rayleigh wave velocity-depth profile can provide an estimate of site dynamic displacement amplification potential. Low velocity materials such as, very soft and soft fine and very loose coarse soils are particularly susceptible to high amplification potential. Shallow structures in superficial deposits are also highly susceptible to further amplification, especially at the interfaces between very soft or very loose soils with stiff or very dense soils. This shallow heterogeneity leads to variable density, velocity and acoustic impedance structures that will cause reflection and refraction of propagating surface waves and lead to variable, complex pathways. Additional amplification occurs during constructive interference of wavefronts that have been affected by refraction and propagated along different pathways. In most modelling studies of high speed train-induced ground vibration, the ground is assumed to be uniformly, horizontally stratified. However, over one third of outcrop along the HS 2 route is on superficial geology, which exhibits a highly heterogeneous distribution of materials. In turn, the geotechnical and geophysical property distributions throughout these materials will also be highly variable. Hence, in certain environments, such as river catchments, where soft fine and or coarse loose soils occur, the assumption of uniform, horizontal stratification breaks down. In these situations, vibration and displacement modelling about the train load points would benefit from use of ground property models that more closely resemble local variability. In the absence of property data gathered from site survey, ground property models can be constructed via attribution of engineering geological maps or models. The benefit of this approach is that it utilizes the state of the art geological ground model available and hence can be tuned to become fit for purpose at greater scales of planning as more relevant ground information becomes available.

The effects of wave attenuation were not included in this study, which would serve to reduce the dynamic displacement. However, it should also be noted that the effects of strain softening were also beyond the scope of this study, but which would act to increase the dynamic amplification. Hence, such processes should be investigated as part of a fuller study of the true impact of local geology on site specific wave propagation. The effects of attenuation can be studied using the existing FD platform, whereby absorption can be included via attribution of seismic quality factors into the model materials.

Practical Relevance and Potential Applications

This methodology can provide the framework for assessment of the surface wave propagation along a transportation corridor based upon route engineering geology. Locations particularly susceptible to high displacement amplification potential will coincide with high line speeds over river catchments and floodplains where alluvium, terrace or wetland deposits occur. This methodology can inform site evaluation planning and the ultimate design of track works. It is envisaged that future track design will benefit from the improved outcomes of vibration and ground displacement model studies that combine track elements with more realistic ground models, such as constructed in this way.

Acknowledgement

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Figure captions:

Figure 1: Example geological information for locations of very soft or soft fine soils along HS 2.

Figure 2. Shear wave velocity- and potential displacement amplification-depth profiles for soft fine and loose coarse grained soils.

a. Shear wave velocity profiles for fine and coarse soils. Fine; Shibuya *et al*. 1997; Coarse Robertson *et al.* 1995
b. Amplification with depth for soft fine soil. Potential amplification using Esveld 2001.
c. Amplification with depth for very loose coarse soil. Rayleigh wave velocity 93% shear velocity.

Figure 3. Frequency - wave number comparison of train speeds, bogie centres and shear wave velocity for very loose and soft soils.

Figure 4. Ground models attributed with geophysical properties for input into wave propagation modelling.

a. Engineering geology section along HS2 route at grade at Perivale.
b. Geophysical property models along section at Perivale based on the engineering geology.

Figure 5. Seismic field records of inline displacement due to wave propagation from a vertical impulse source.

a. London Clay bedrock: vertical white dashed line at 26 m. Shot gather field record shows shear wave first arrival followed by surface waves. Source at 0,0 on London Clay.
b. Alluvial-terrace structure: white line at 176 m in outcropping alluvium. Relatively large displacements between 250 ms – 600 ms across alluvium. Source at 150,0 on sand/gravel comprising made ground, 10 m from alluvium.

Figure 6. Wavefront propagation pathway through representative geophysical ground model section at Perivale.

Frame 1: Source in loose gravel; 10 m from gravel-alluvium boundary
Relative shear wave velocities: gravel > London Clay > alluvium.
50 milliseconds after impulse

Frame 3: Waves from made ground / terrace gravels travel more quickly to the alluvium than they travel through the alluvium and on into London Clay.
150 milliseconds after impulse

Frame 6: Wave refraction, reflection and interference into alluvium
results in large displacements in middle of alluvium outcrop.
300 milliseconds after impulse

Frame 9: Wave refract out of alluvium into higher velocity gravels and
London Clay; large amplitude, low frequency ground roll in London Clay.
450m seconds after impulse

Figure 7. Relative surface displacements at location 26 m away from vertical impulse for London Clay baseline and Perivale ground models.

a. London Clay bedrock ground model: Stiff, fine soil / shear wave velocity increasing with depth.
b. Ground model with alluvial / terrace structure: Alluvium-soft, fine soil; Terrace-dense, coarse soil.

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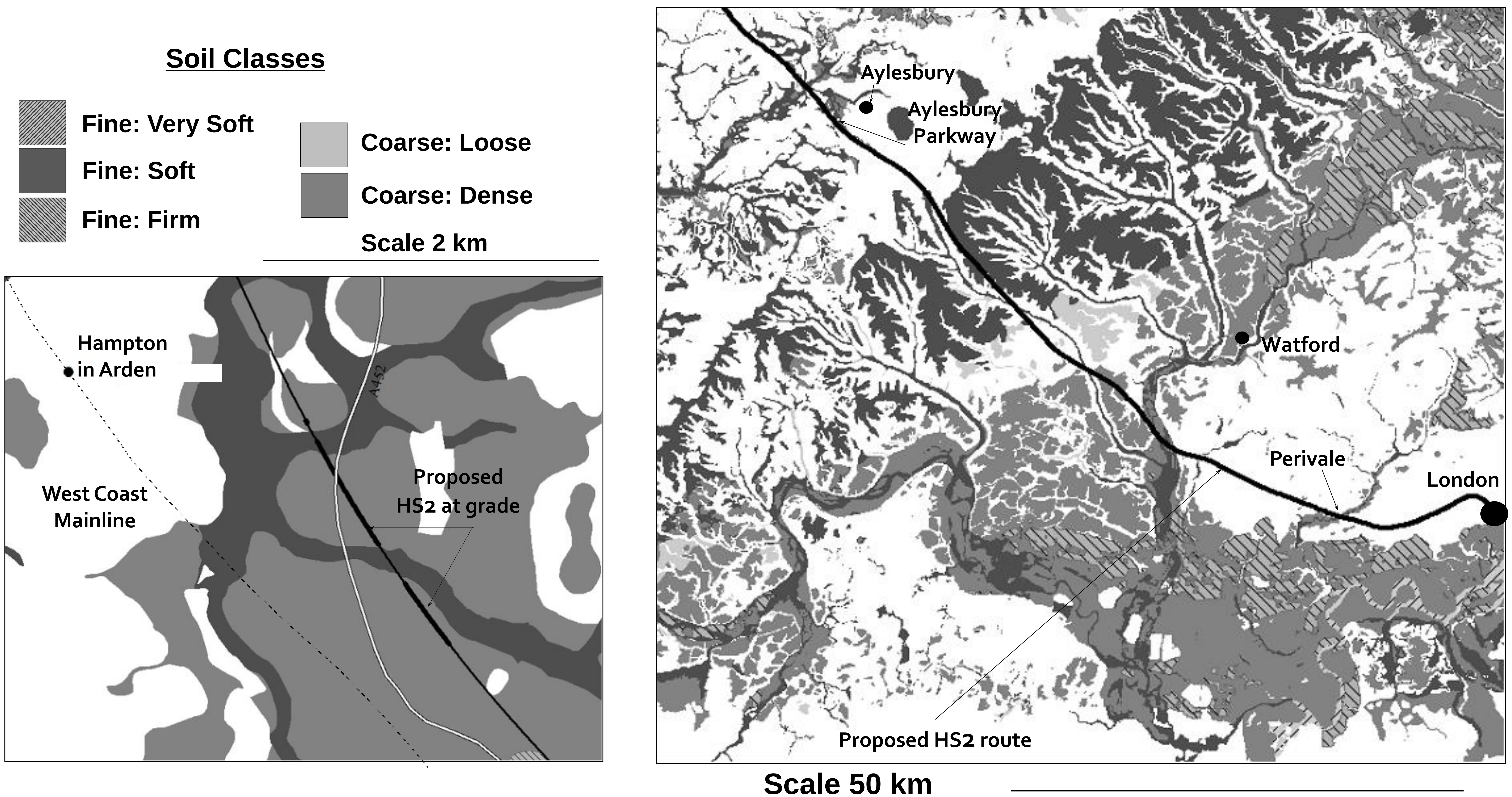
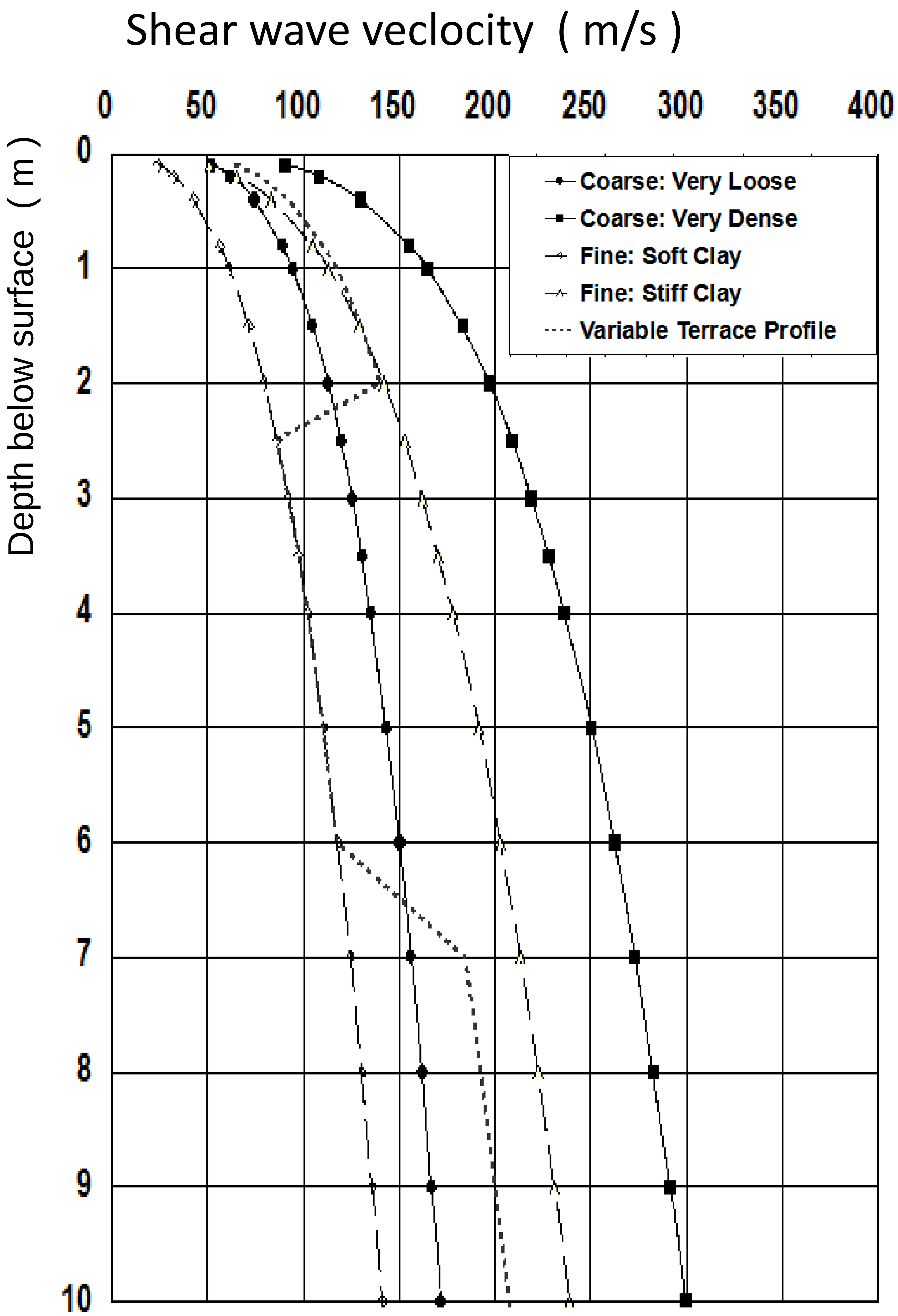
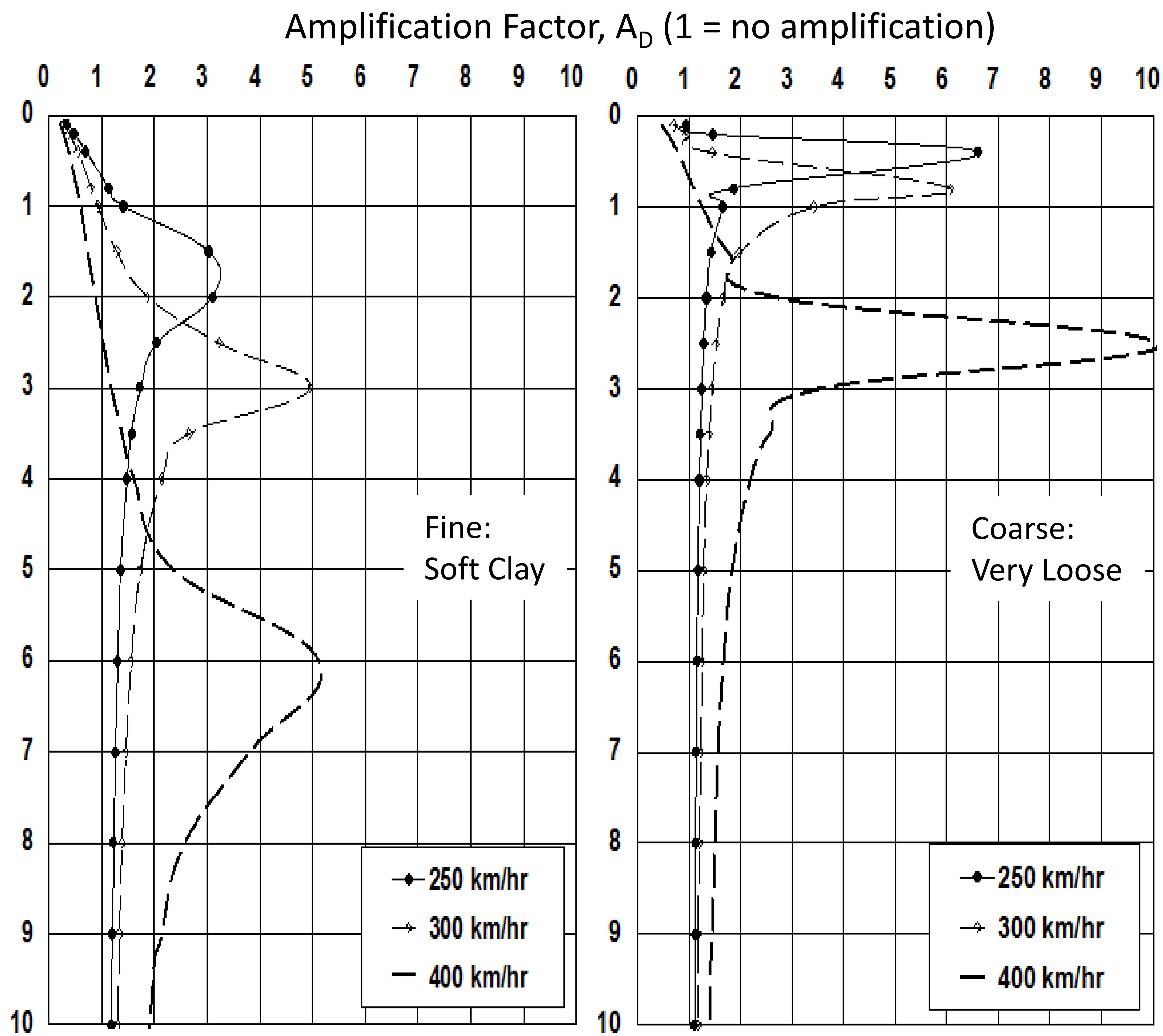

Soil Classes
Fine: Very Soft
Fine: Soft
Fine: Firm
Coarse: Loose
Coarse: Dense
Scale 2 km
Hampton in Arden
A452
West Coast Mainline
Proposed HS2 at grade
Aylesbury
Aylesbury Parkway
Watford
Perivale
London
Proposed HS2 route
Scale 50 km

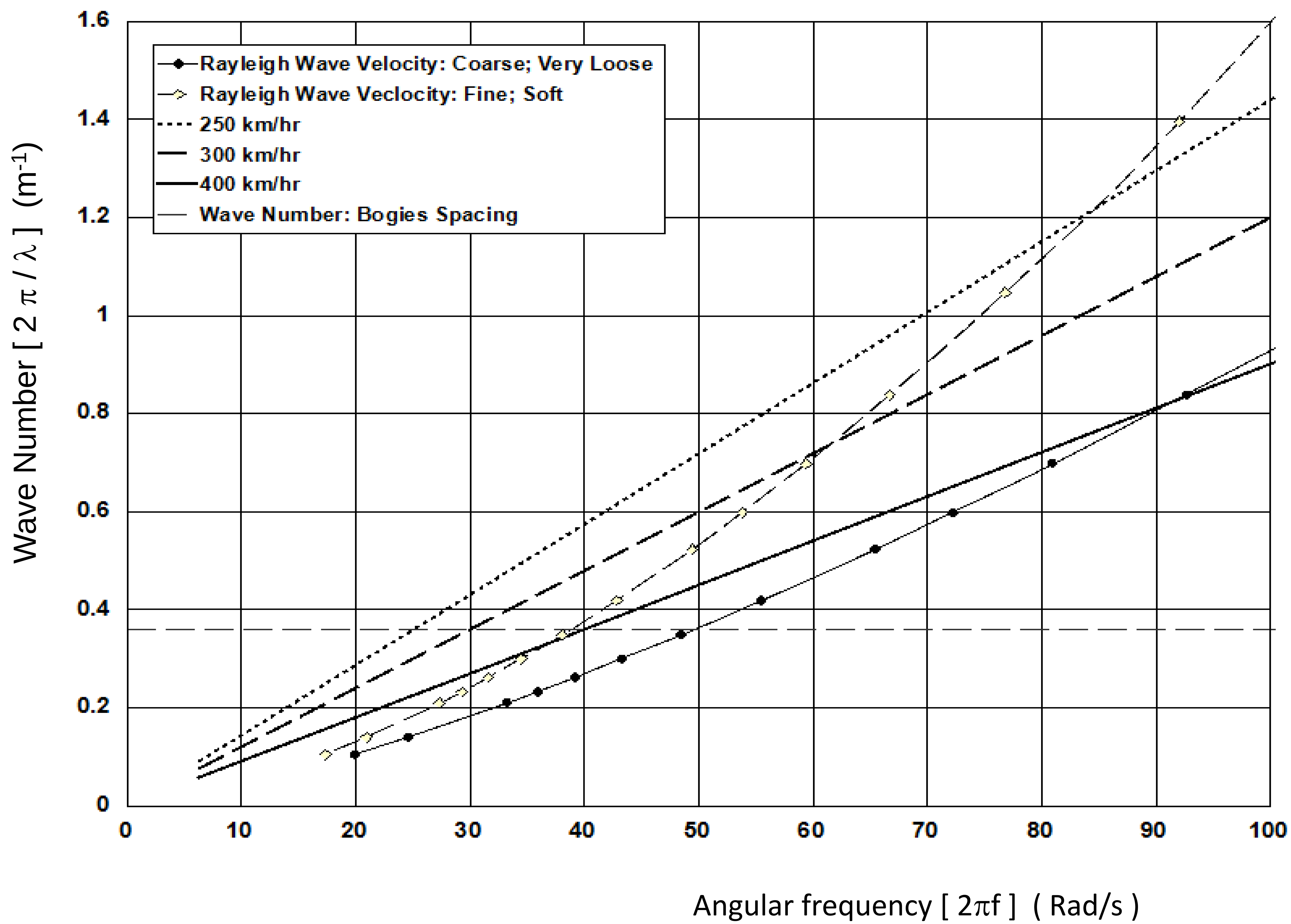


Shear wave velocity profiles for fine and coarse soils.
Fine; Shibuya et al 1997; Coarse Robertson et al. 1995.

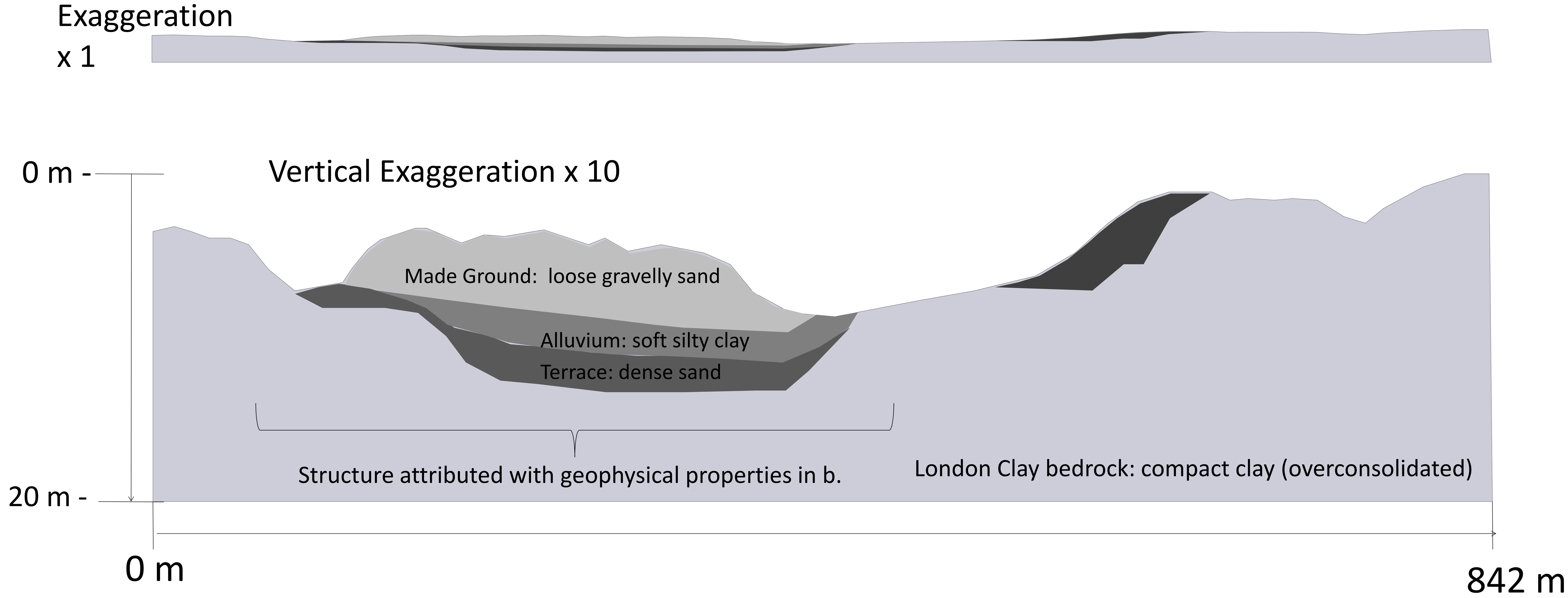


Amplification with depth for soft fine soil.
Potential amplification using Esveld 2001

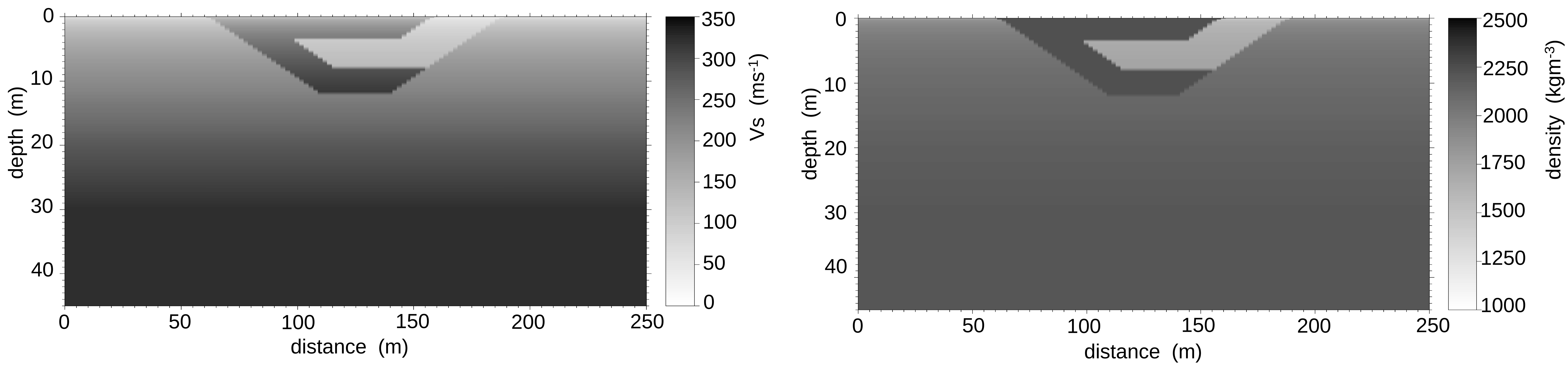
Amplification with depth for very loose coarse soil.
Rayleigh wave velocity 93% shear velocity.

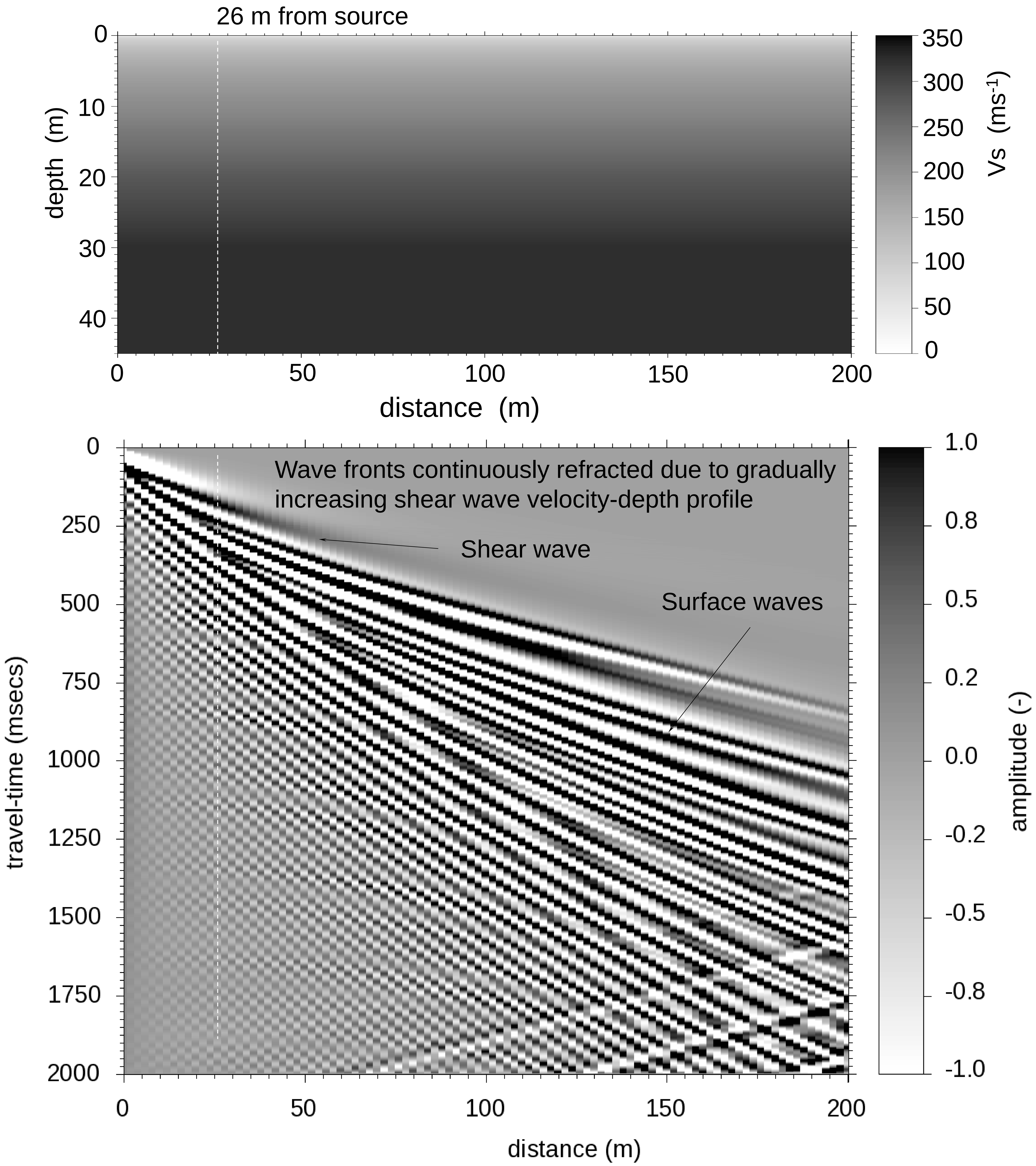

Rayleigh Wave Velocity: Coarse; Very Loose
Rayleigh Wave Veclocity: Fine; Soft
250 km/hr
300 km/hr
400 km/hr
Wave Number: Bogies Spacing
Wave Number [2 π / λ] (m-1)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
Angular frequency [2πf] (Rad/s)

a. Engineering geology section along HS2 route at grade at Perivale.

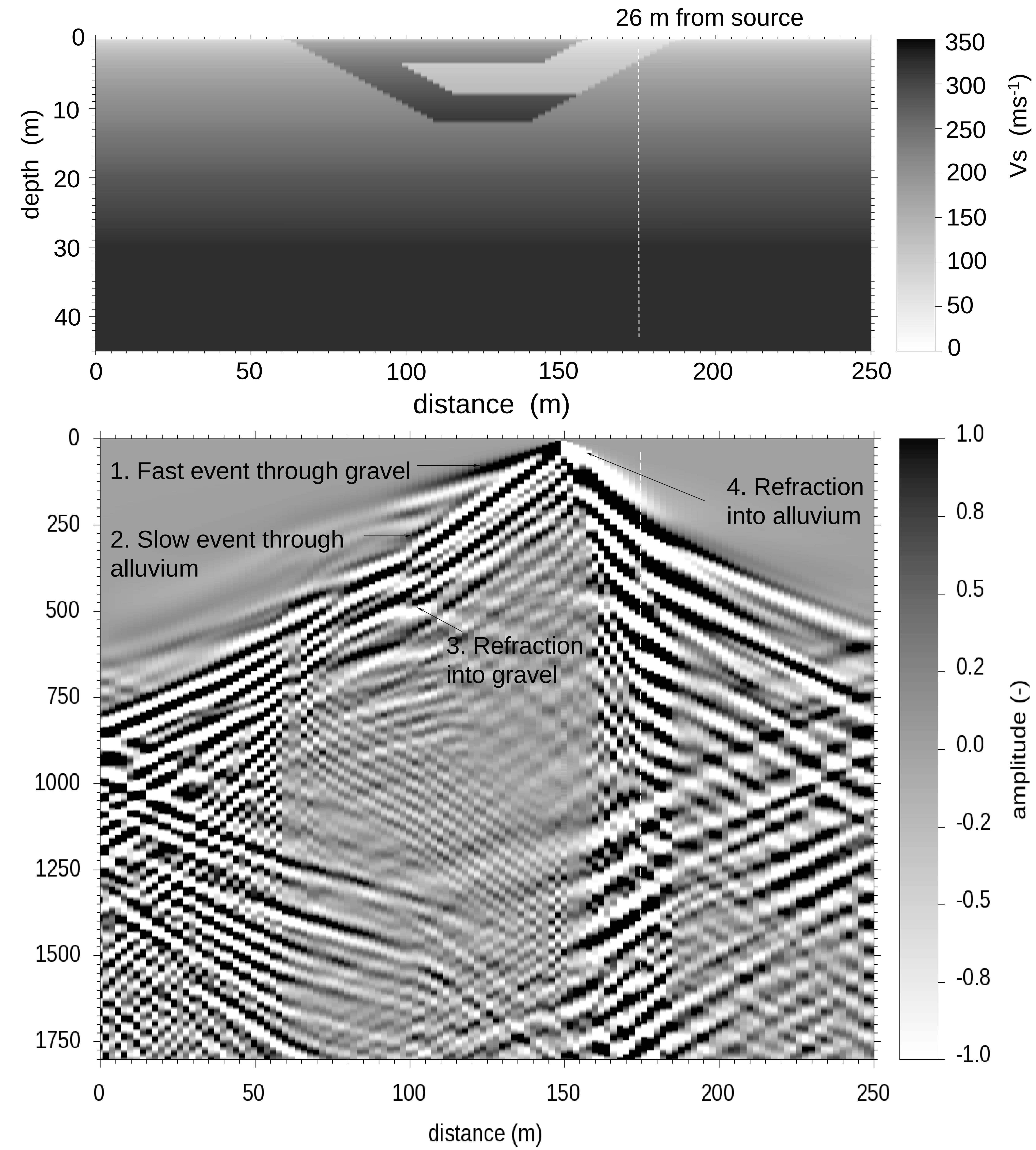


b. Geophysical property models along section at Perivale based on the engineering geology.

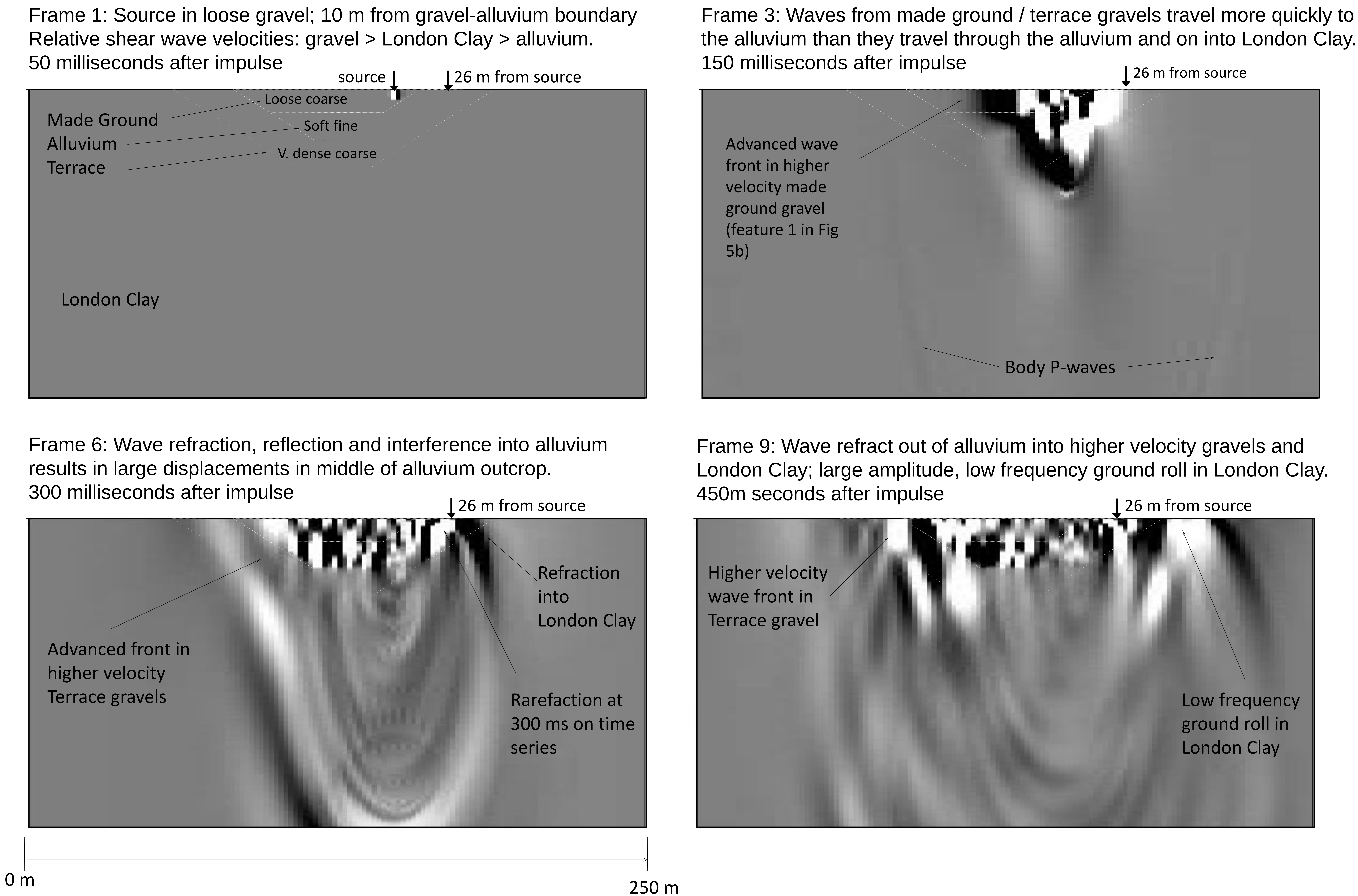


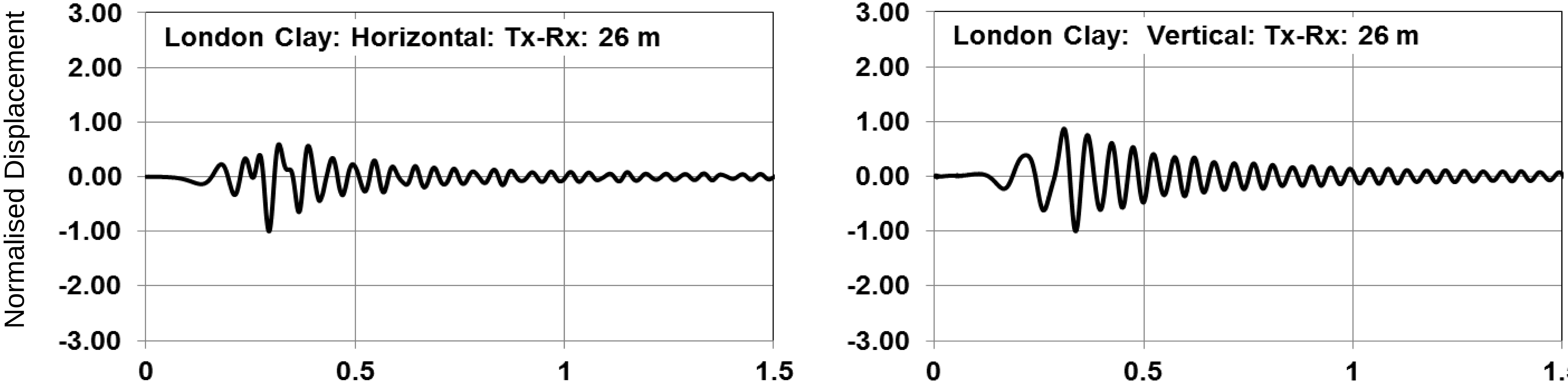


a.London Clay bedrock: vertical white dashed line at 26 m.
Shot gather field record shows shear wave first arrival followed by surface waves. Source at 0,0 on the London Clay.

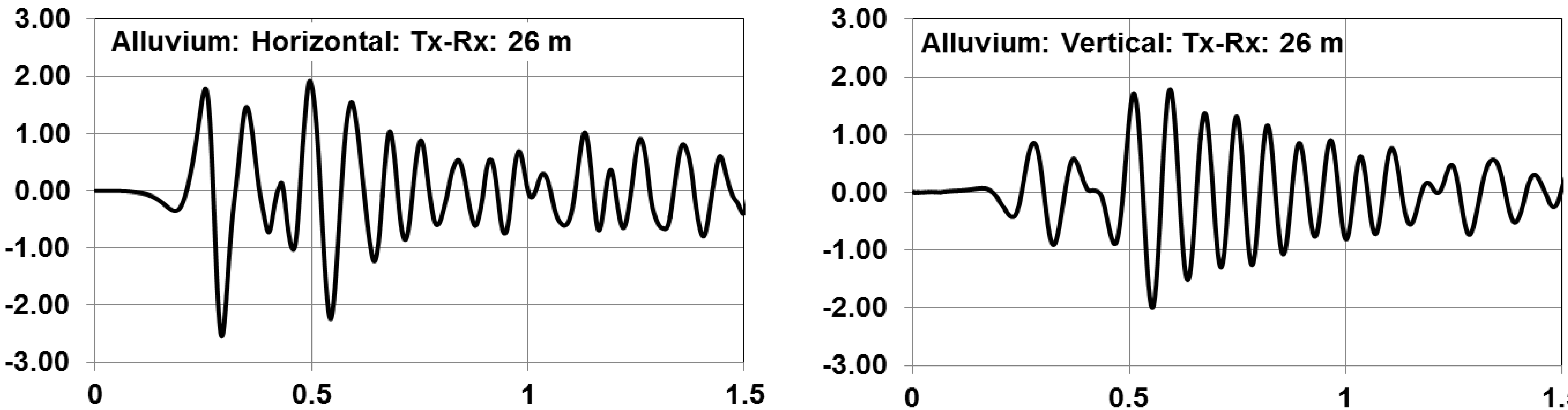


b. Alluvial-terrace structure: white line at 176 m in outcropping alluvium.
Relatively large displacement between 250 ms-600 ms across alluvium.
Source at 150,0 on sand-gravel comprising made ground 10 m from alluvium.


Frame 1: Source in loose gravel; 10 m from gravel-alluvium boundary
Relative shear wave velocities: gravel > London Clay > alluvium.
50 milliseconds after impulse
source
26 m from source
Loose coarse
Soft fine
V. dense coarse
Made Ground
Alluvium
Terrace
London Clay
Frame 3: Waves from made ground / terrace gravels travel more quickly to the alluvium than they travel through the alluvium and on into London Clay.
150 milliseconds after impulse
26 m from source
Advanced wave front in higher velocity made ground gravel (feature 1 in Fig 5b)
Body P-waves
Frame 6: Wave refraction, reflection and interference into alluvium results in large displacements in middle of alluvium outcrop.
300 milliseconds after impulse
26 m from source
Refraction into London Clay
Advanced front in higher velocity Terrace gravels
Rarefaction at 300 ms on time series
0 m
250 m
Frame 9: Wave refract out of alluvium into higher velocity gravels and London Clay; large amplitude, low frequency ground roll in London Clay.
450m seconds after impulse
26 m from source
Higher velocity wave front in Terrace gravel
Low frequency ground roll in London Clay



a. London Clay bedrock ground model: Stiff, fine soil / shear wave velocity increasing with depth.



b. Ground model with alluvial / terrace structure: Alluvium-soft, fine soil; Terrace-dense, coarse soil.