Toose Rd Geophysical Investigation

Passive Seismic Technical Memorandum

Kempsey Shire Council

29 June 2022

→ **The Power of Commitment**

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Executive Summary

GHD was contracted by Kempsey Shire Council to assess the depth to competent rock beneath a recent landslide event at Toose Road, Bellbrook, to inform remediation planning decisions. Given the unstable nature of the site, GHD utilised passive seismic technology to image the subsurface velocity interfaces associated with contacts between the landslide colluvium material, and the metasedimentary country rock. Beneath the active landslide, the dominant interface is imaged at depths of 17 – 34 m, suggesting colluvium and fractured rock fill above those depths. The major velocity interface is between 3 – 8 m beneath stable road sections adjacent to exposed rock, away from the active landslide. The western portion of the surveyed line transected an incised valley with older colluvium fill, and the major velocity interfaces were imaged at depths of 21 – 22 m in these regions, consistent with older landslide activity in this area.

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1. Introduction

A landslide event on 31 March 2022, following heavy rain in the preceding month, led to the closure of Toose Road, Bellbrook, in the Kempsey Shire.

The event restricted vehicle access for residents and due to ongoing ground movements and the risk to life, the road remains closed. Preliminary assessment of the site by GHD engineering geologists suggested remediation of the slope is problematic, given the recurrence of mass movement of the slope, including evidence of prior events, thickness of the landslide colluvium layer, and ongoing ground deformation.

Whilst an alternative road route has been proposed, cost and timeliness are factors for the client, and further investigations into the nature of the slope and thickness of the landslide colluvium are required before discounting remediation of the road.

GPR (ground penetrating radar) was deployed by GHD staff in a first-pass early assessment of the nature of the colluvium, and depth to bedrock (locally, the Nambucca Block Parrabel Beds, with the exposures on site a schistose metasedimentary member). The results of that survey showed no hard bedrock reflectors down to 15 m within the landslide area. The sections showed extensive evidence of buried boulders and irregular scree material down to those depths.

Given the uncertain stability of the site traditional geotechnical drilling was assessed as not suitable to assess the depth to rock. Further effort to constrain the geotechnical properties of the colluvium material, and its thickness, would require information from further geophysical investigations. Traditionally, methods such as seismic refraction would be deployed on-site to provide P-wave velocity models and define the limits of the (seismically fast) bedrock layers. However, this approach requires an active source – generally a sledgehammer striking a steel plate – and the risks involved of imparting a strong seismic signal on a currently failing slope were considered too significant for deployment.

Instead, GHD deployed a passive seismometer along line to develop seismic models of the subsurface, and mapped the boundary between the landslide colluvium and harder bedrock. The technique is non-disruptive, and significantly safer than active source seismics in a steep site of significant landslide risk. Passive seismic uses background microseismic noise in the environment to provide information about the subsurface. In this study we utilised an approach known as horizontal-vertical spectral ratios (HVSR) – which calculates the frequency spectrum of seismic accelerations in N-S, E-W and vertical directions, and uses the ratio of horizontal to vertical motion to determine the depth of major velocity interfaces, such as the landslide colluvium to country rock contact.

Approximately 220 m of Toose Rd were surveyed, bracketing the active landslide zone, and providing information on the subsurface in both stable road sections, and within the actively deforming zone.

2. Methodology and acquisition

2.1 Methodology

Seismic methods are commonly used to determine and map subsurface geotechnical information, including soil-rock contacts, and the elastic or strength properties of soil and rock. Traditional techniques such as refraction seismic are effective at determining P-wave velocity structure, and mapping subsurface variations.

At the Toose Rd site, ongoing ground motion introduces a significant element of risk to active-source refraction, and instead, a combination of Frequency Time Analysis (FTAN) of surface waves and Horizontal-Vertical Spectral Ratio (HVSR) of passive seismic signals methods were utilised. The FTAN was method was used to determine the velocity of the bedrock/colluvium, and HVSR to determine the depth to the bedrock contact based on the FTAN S-wave constraints. FTAN is a surface wave analysis technique, and was utilised in a single shot+receiver configuration to develop 1D profiles of the S-wave structure of the subsurface. The technique has the advantage of not needing extensive cabling, and can provide velocity information despite subsurface velocity inversions. FTAN was used in areas of minimal landslide risk to determine average velocities of colluvium and bedrock.

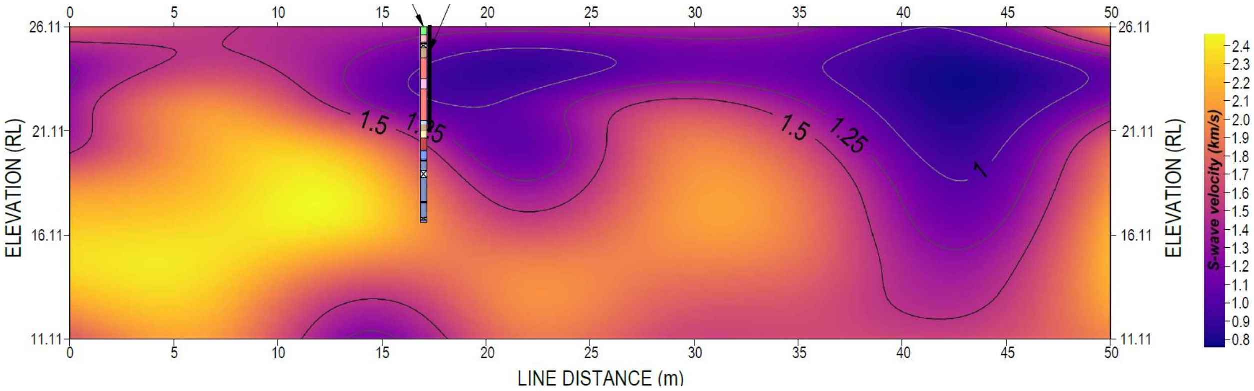


Figure 2.1 ***Example FTAN S-wave velocity section, with correlated borehole data***

In addition to FTAN, we also suggest utilising passive seismic techniques – specifically determining the HVSR. The technique can be used as an individual station, and uses background seismic noise (microtremors, traffic noise, etc) as a source, and records a long (approximately 30 min) record. This is inverted for spectral power, and harmonic peaks identified. The primary harmonic (f_0) in such data is related to the thickness of overlying sediment layer (h), via the relationship:

$$f_0 = \frac{V_s}{4h}$$

(Equation 1)

Thus, given constraints of sediment Vs (which can come from local FTAN shots), the thickness of the sedimentary layer can be mapped. An example is shown in Figure 2.2.

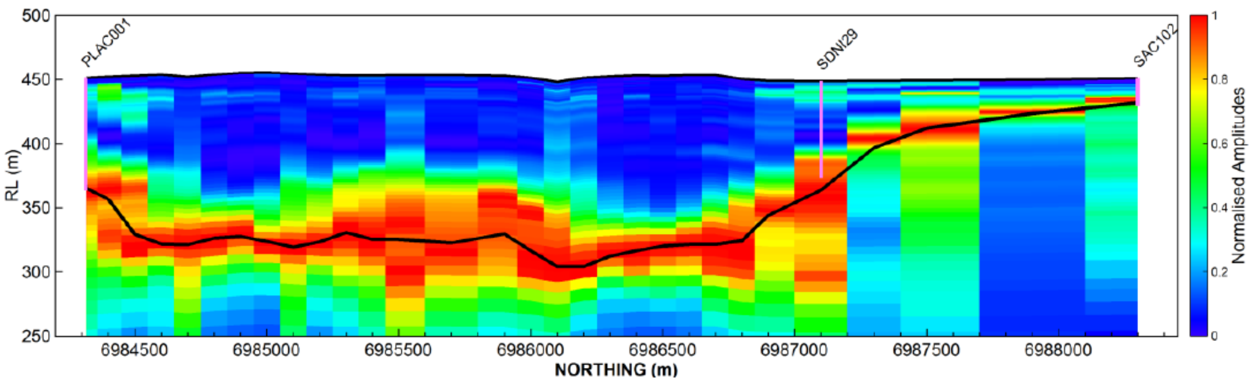


Figure 2.2 ***An example HVSR section, showing mapped soil – hard rock interface depths***

Seismic velocity generally increases with increasing density. The main factors controlling seismic velocity are porosity, mineral/soil type, grain-size, level of compaction/consolidation, pore pressure and saturation.

2.2 Acquisition

A 220 m length section of Toose Rd was surveyed over 2 days (7 and 8 June 2022) with HVSR, an additional two short recordings were acquired with an active source to be used for FTAN analysis. The active shots were spaced at 28 and 25 m between sledgehammer source and receiver, with individual shots targeting the metasedimentary country rock, and the landslide colluvium, respectively.

The core section of the survey encapsulating the active current landslide between 10 m and 100 m chainage was surveyed with 5 m spacing. The rest of the line had 10 m spacing, with off-end recordings (-20 m and 200 m) at a 20 m spacing.

The HVSR data collection used a 3-axis Tromino seismometer, with a default recording length of > 24 min per station (extended up to 45 min in test cases over the landslide). The Tromino was levelled and good ground coupling was ensured for each measurement. Wind and some anthropometric noise (local vehicles and dogs) were factors in some recordings, and the final data was assessed against these noise sources.

Due to ongoing landslide and rockfall, an assistant was provided to act as a spotter during the recording, and standard slope stability risk minimisation procedures were followed (including hard hats and parking distal to rockfall risk).

3. Data processing

3.1 Introduction

The following section describes the processing procedures implemented by GHD to produce final deliverable geophysical results.

3.2 Frequency-Time Analysis processing

3.2.1 FTAN overview

Frequency-time analysis (FTAN) utilises vertical components of seismic surface waves to derive their dispersion characteristics, and invert for S-wave velocity (Vs) structure. Typically, surface waves (here, primarily Rayleigh waves) are the largest amplitude waveform of the seismic wave packet, and can be measured on a fixed geophone a set distance from seismic source. FTAN utilises group-velocity dispersion (in contrast to more diffuse phase velocity dispersion approaches such as MASW), and the highest amplitude signals generally allow identification of the fundamental mode, and higher order modes.

The FTAN method deploys narrow-band Gaussian filters, with varying central frequency that do not introduce phase distortion and give a good resolution in the time-frequency domain, and these frequency filters are able to isolate the fundamental mode from higher modes.

The dispersion of these surface wave modes is sensitive to the Vs structure beneath the surface, and these dispersion curves may be inverted to obtain integrated Vs structure over the surface waves path.

3.2.2 FTAN processing workflow

FTAN was used in a stand-alone single shot-receiver configuration, utilising a wi-fi-enabled seismic recorder (the Tromino Blue) and wireless trigger. The recordings are triggered with a hammer source, generating surface waves which are detectable along a spread or single receiver. We require a minimum distance of approximately 20 m (optimally 25 m) between the source and receiver to allow dispersion of the surface wave packet, depending on local noise sources and logistics of shot positioning. The midpoint of the source and selected geophone or seismometer is set as the measurement point in later plotting.

The code utilised for processing is CPS (Computer Programs in Seismology, from The University of St Louis Earthquake Centre), which is a mature and well-tested community standard (Hermann, 2013). The recorded Tromino files (exported in ascii format from Grilla) are processed using ObsPy, and the traces extracted and exported to SAC format. These are loaded in CPS in a bash-scripting environment, where the FTAN analysis was performed using the sub-program do_mft, and the inversion using surf96.

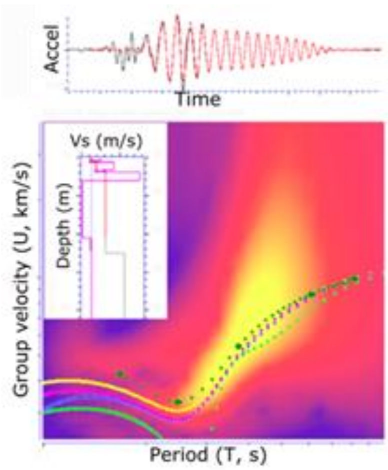


Figure 3.1 ***Example of FTAN processing workflow. An initial waveform (top) is transformed into Group velocity – Period space, and the fundamental digitised and inverted into a Vs-depth section (inset)***

3.3 HVSR analysis processing

3.3.1 HVSR overview

The HVSR method utilises ambient seismic noise and microtremors, it records a long-period of the harmonic characteristics of a site. The depth of the upper (sediment) layer strongly controls the characteristics of surface wave noise, and thus a difference is generally observed between horizontal and vertical wave amplitudes, at wavelengths (and thus frequencies) sensitive to the depth change. The effect is best shown by using a Fourier transform to convert the raw time-series data into a spectral plot of frequency vs amplitude, for each measured acceleration component. Then the quotient of the average horizontal response and the vertical response – the H/V ratio – is calculated. This allows the determination of the fundamental frequency.

The fundamental frequency may then be converted into depth using Equation 1, and the depth response plotted for each location along a profile, providing a cross section of H/V amplitude, which maps the rock-soil interface.

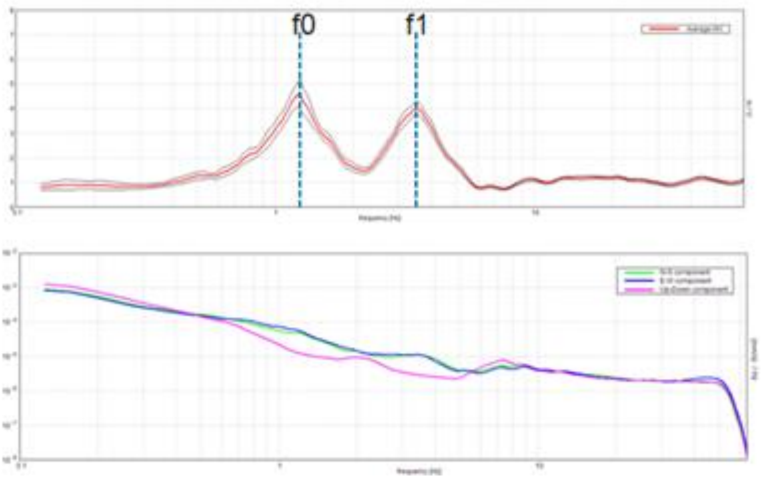


Figure 3.2 ***Spectral response curves (below) in horizontal and vertical (pink) directions. Top – the H/V quotient of these values, and the identified fundamental frequency f_0, and 1st overtone***

3.3.2 HVSR processing workflow

The data obtained from an approximately 30 minute deployment of the passive seismometer sensor is then downloaded via the Moho-provided software, Grilla. From here, the data trace can be exported as both a time series (for FTAN analysis) or frequency-domain spectral plot (for HSVR analysis).

The subsequent HSVR analysis was performed using in-house python scripts. Identification of the spectral peak of the H/V spectral data allows determination of the fundamental frequency f_0, from which the depth to rock interface can be determined using Equation 1.

4. Passive seismic results

To ascertain the Vs of the colluvium and underlying metasedimentary rocks, FTAN shot records were acquired both over the colluvium (with a shot placement at 40 m and a receiver at 68 m), and across reasonably intact rock (shot placement at 40 m and receiver at 15 m). Six to eight individual shots were acquired at each location, and the seismic records stacked to improve signal to noise. The surface waves were analysed for dispersion using an FTAN approach, and then inverted to give velocity structure. The FTAN results are shown in Figure 4.1.

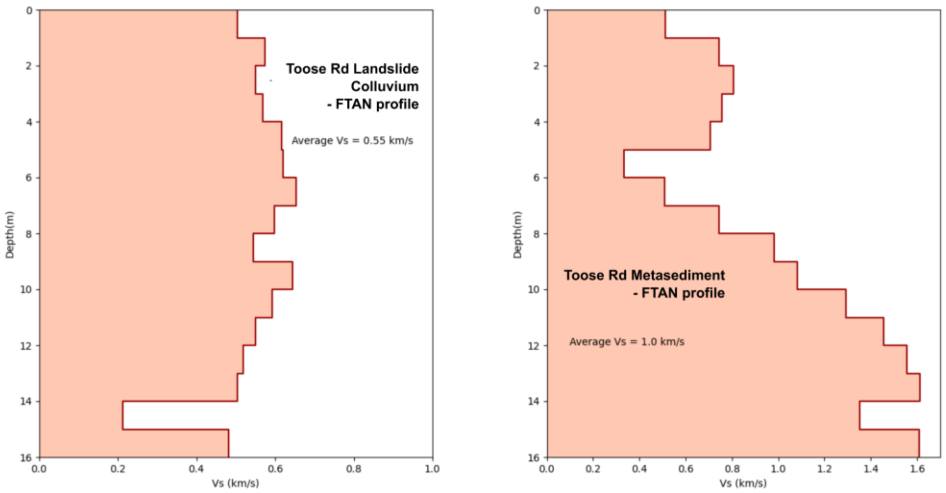


Figure 4.1 ***Shear wave velocity vs depth profiles for landslide colluvium and metasedimentary rock***

The colluvium shows are fairly constant slow velocity with depth, with an average value of 0.55 km/s. The FTAN show did not resolve the bedrock contact in this case. In contrast, the FTAN shot over the metasediments shows an increase in velocity with depth, probably related to the development of a weathering profile, or joint distribution. The top 6 m of the section shows velocities up to > 700 m/s, which is consistent with weathered, heavily jointed/fractured rock. Over the section covered by the shot, rock is exposed in the road base, but the foliations do not match those observed in the country rock, suggesting the rock is not in situ. From 6 m depth, the velocities increase steadily up to over 1500 m/s, which is consistent with a very hard, competent metamorphic rock. The average rock shear wave velocity for the section was 1.0 km/s.

We have used these values with the HVSR frequency spectrums to convert nominal frequency to depth via Equation 1. An example HVSR curve from the rock is shown in Figure 4.2.

The high frequency spectral peak observed in the example shown in Figure 4.2 is consistent with a shallow rock interface on this section of road, immediately below the compacted road base, and consistent with the FTAN velocity profile. The HVSR curves for each station are converted to equivalent depth, and then gridded to form a continuous section. The results are shown in Appendix A.

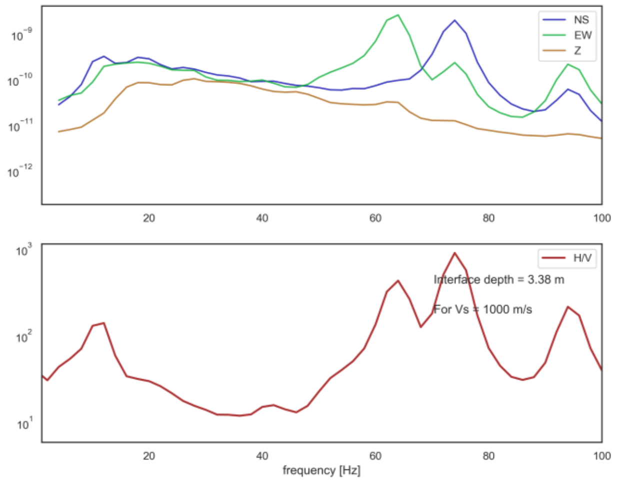


Figure 4.2 Example frequency spectrum from the Tromino (recorded on rock at 15 m chainage, top), and corresponding HVSR curve (bottom)

In Figure A1, the colour scheme corresponds to the peak in normalised spectral power of the HVSR curves, and the bright colours indicate hard interfaces in velocity. These may include interfaces between road base and rock (causing large, very shallow signal in the section), dislodged blocks and units basal to them (observed within the landslide zone), and the interface between colluvium and the underlying metasedimentary rocks.

Often the strongest signal in the sections is less than 6 m depth (which represents high frequencies of greater than 50 Hz). This shallow region of section is highly sensitive to ambient noise and wind, and associated surface tremors (and is often filtered out of HVSR data). As a result of this noise, it has a fairly high amplitude compared to the lower frequency signal. The FTAN profile in Figure 5 shows the development of a strong weathering front between the near surface, weathered, heavily jointed metasediments immediately beneath the road, and the fresh rock underneath. In the absence of sedimentary cover/colluvium – this fresh-to-weathered rock interface is the primary velocity contrast in the profile, and is what is primarily imaged in regions without well-developed colluvium (-20 – 40 m chainage, and < 160 m chainage).

In regions where the colluvium is present, deeper peaks in spectral power are imaged correlating to the colluvium – rock interface. The mapped interfaces, shown by crosses in Figure A1, show the spectral power peaks for frequencies greater than 30 Hz (if spectral peaks are observed at these depths, otherwise the shallow high frequency peaks noted previously are digitised). These features generally correspond to the rock interface below the surface.

Between the chainage of 20 to 30 m along the line, this interface is very shallow (less than 6 m) – consistent with the observation of adjacent rock proximal to the track, and the measured FTAN profile. The digitised crosses in Figure A1 along this part of the profile reflect the weathered rock - fresh rock boundary.

Approaching the landslide contact (chainage 35 to 40 m) a strong deep interface is imaged, at around 17 m. The surface expression of the most recent landslide occurs at around 42 m chainage, to 70 m chainage. Approaching 55 m chainage this interface drops precipitously, to around 34 m depth. The interface is smeared in this region – this is an effect of the surface slope of underlying rock dipping to the north to towards the river. The seismometer is recording signal not just from the shallowest intersection of colluvium-rock, but also the rock contact downslope, which is at greater effective distance. This is effectively a 3D effect of the slope, projecting onto the line profile, resulting in the observed harmonics at multiple depths. Additionally, the fragmentation of the ground surface may play a factor in the signal sharpness.

The deep interface trends upwards towards the west between chainage 55 m and 90 m. The survey continued on unaffected road surface from 75 m onwards to 110 m. Exposed rock is observed around the road bend at around 100 m, and some rock slide material is observed on the road around 80 m chainage. A very shallow interface of approximately 4 to 7 m depth is imaged in the section between 90 and 100 m. This interface again probably reflects the transition from surficial weathered/jointed metasediment, to strong competent rock, and is consistent with shallow rock below the road base.

From 120 m a second significant incised valley is entered, and the upslope material appears to be older colluvium material, which is observed at some road cuttings/gullies (e.g. at 160 m colluvium with large rock boulders is observed). Between 120 – 140 m chainage the data shows a deep interface approximately 21 to 22 m thick, consistent with a thick older colluvium cover.

From 150 m the depth to this interface shallows, and with some variation, is generally below 6 to 8 m depth from chainage 160 to 200 m. Chainage 200 m was located next to an exposed rocky slope adjacent to the road.

An example of the section shown in Appendix A1, with annotations highlighting the main features discussed in the text, is shown in Figure 7. The data has been compared to the previous GPR data, and it is noted that hard reflectors in GPR data correlate well with the passive seismic interfaces, within the depth range of the GPR. The GPR also picked up the weathered rock – rock interface, as mapped by the passives, along many sections of the line, giving some independent confirmation of the interpretation.

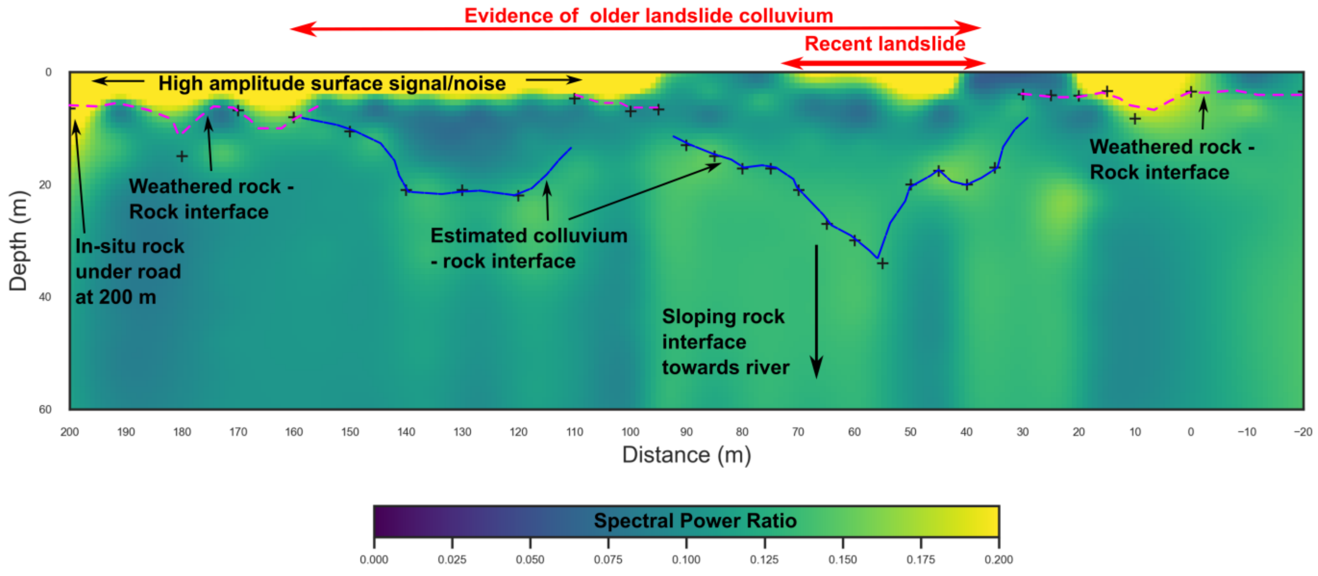


Figure 4.3 *Interpreted plot of the passive seismic section shown in Figure A1. Annotations indicate major interfaces and features*

5. Conclusions

The HVSR passive seismic conjunction successfully imaged the interface between colluvial materials/fill and metasedimentary country rock, along the active landslide site of Toose Road, Kempsey.

The peak interface observed in the data away from the landslide side is generally less 4 – 8 m deep, consistent with the measured FTAN profile, but which is near the surface resolving power of the technique, and probably represents the interface between road base/weathered rock and fill, and competent/slightly weathered to fresh rock beneath.

Beneath the recent landslide zone itself, the interface varies between 17 – 34 m depth, and probably represents the contact between the combined colluvium and fractured rock, and competent rock beneath. The spectral signal over the landslide is complicated, with signal observed from near-surface blocks, deep landslide-deformation related structures, and the sloping interface of the rock layer towards the river, which tends to smear the spectral signal in this zone. Away from the current landslide zone, the second incised valley to the west of the site also displays exposed colluvium near the road, and exhibits a deep interface of 21 – 22 m between 120 -140 m chainage, which may represent past slope instability events.

Appendix A

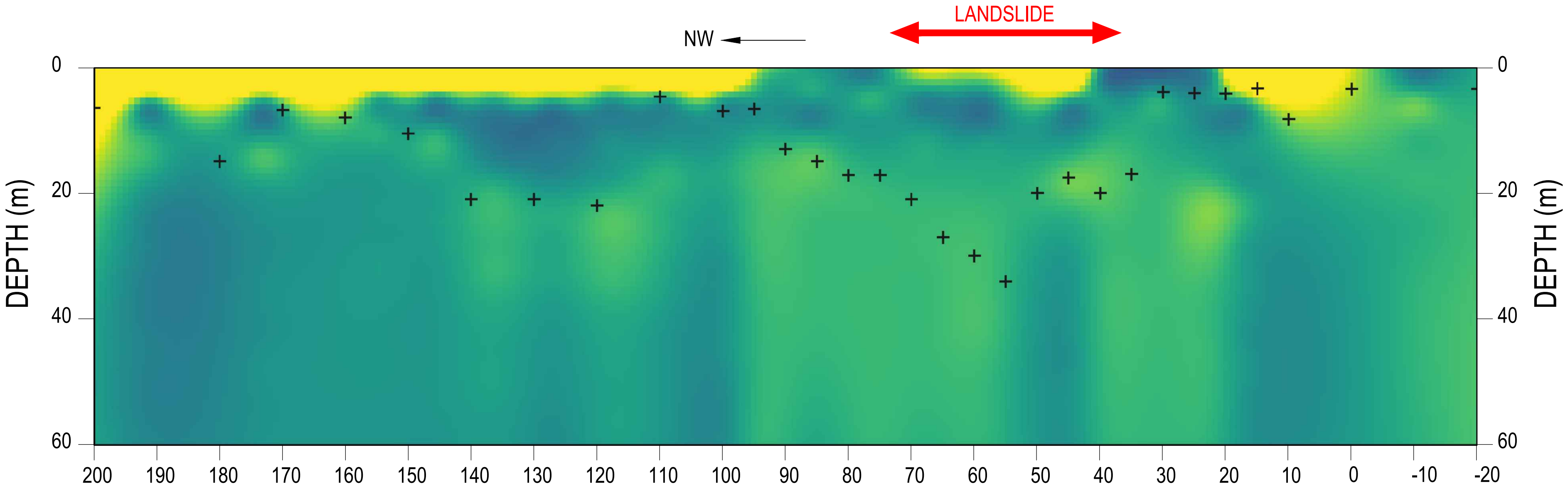
Geophysical Results

LEGEND:

- TOOSE ROAD PASSIVE SEISMIC LINE
- INTERPRETED VELOCITY INTERFACE

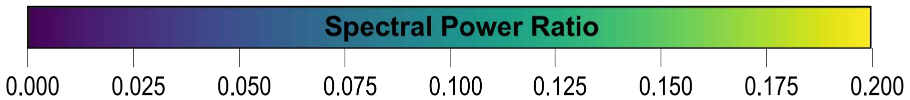
TOOSE ROAD PASSIVE SEISMIC LINE - PLAN

SCALE 1:5000



TOOSE ROAD PASSIVE SEISMIC LINE - PROFILE

SCALE 1:1000



0 50 100 150m

SCALE 1:5000 AT ORIGINAL SIZE

KEMPSEY SHIRE COUNCIL
TOOSE ROAD PASSIVE SEISMICS

GEOPHYSICAL INVESTIGATION
TOOSE ROAD PASSIVE SEISMIC - PLAN AND SECTION

Job Number	12554891
Revision	A
Date	JUNE 2022

Figure 01

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