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Multidisciplinary site investigations: geophysical techniques for comprehensive site characterisation and assessment

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ABSTRACT: We present three case studies from recent site investigations that have utilised geophysical data to supplement traditional geotechnical investigations. Use of the Refraction Microtremor (ReMi) method is described, which measures the shear-wave velocity of the subsurface soil profile, to enhance our overall understanding of geotechnical site conditions. Lateral variations in shear-wave velocity beneath a site are characterised by 2D velocity-versus-depth representations. Case studies demonstrate the benefits of incorporating the shear-wave velocity estimates from ReMi into the geotechnical investigations. These include identifying the thickness of basalt flows, identifying the location of buried stream channels, characterising palaeo-topographical features, identifying areas of low velocity which may be prone to liquefaction, and assessing the thickness and velocity variations within geological units between borehole and test pit locations. ReMi is less costly than other geophysical investigations, and therefore is an effective reconnaissance tool for targeting key areas for further, more expensive intrusive investigation methods.

1 INTRODUCTION

Refraction Microtremor (ReMi) is a non-intrusive geophysical technique which uses ambient vibrations, (background noise) generated by anything from vehicle traffic to the wind blowing nearby trees, to determine the underlying sub-surface velocity structure. The method involves the deployment of a linear array of instruments to record ground motion generated by these ambient signals. This differs from other, similar, geophysical techniques that utilise active sources, requiring background noise to be at a minimum. Noisy urban environments provide an ideal setting for the ReMi technique, providing a fast and often cost-beneficial method for obtaining subsurface information. ReMi has been widely used for engineering applications to image very shallow subsurface material structure in the upper 10 m to 100m, as well as deep basin structure down to 1 km depth.

A primary benefit of utilising the geophysical measurements is the ability to extrapolate geotechnical knowledge between sparsely distributed and more costly investigation methods (e.g. boreholes, CPT's and test pits) towards increasing spatial sampling density so that background and anomalous conditions can be identified early in the investigation.

Shear wave velocities obtained using ReMi allows for the determination of the site period and subsequent assessment of the site subsoil class in accordance with NZS1170.5. ReMi makes use of the same 0.5-10 Hz frequencies that cause damaging earthquake ground shaking, which for soft soil with a

typical shear-wave velocity of 200 m/s, the nonlinear wave effects are occurring over volumes at least 60 m in diameter, at these frequencies. Thus, some of the most troublesome nonlinear effects in earthquake risk evaluation are best evaluated with techniques that yield velocities averaged over similar-sized volumes as opposed to traditional borehole founded approaches (i.e. SPT N Count or Nakamura Methods). We demonstrate how use of ReMi enhances the ability to obtain a thorough geological understanding of sites, hence minimizing geotechnical risks. We show how the complementary method allows better characterisation of subsurface material properties. Use of multiple methods supports thorough understanding of subsurface conditions enabling adoption of appropriate geotechnical design parameters to support the fundamentals of “good design”.

2 GEOPHYSICAL TECHNIQUES

Geophysics provides an efficient and cost-effective means of collecting geologic and hydrogeologic information. A primary benefit of utilising geophysical measurements is the ability to increase spatial sampling density so that background and anomalous conditions can be identified early in the investigation. Geophysical surveys are not intended to replace traditional subsurface sampling and boring investigations. However, they aid in quickly and economically

extending subsurface characterisation over larger areas, correlating between the boreholes, test pits, and other investigation data points to characterise lateral changes in geology and/or material properties. By providing details regarding different material properties of the sub-surface ground conditions, geophysical investigations contribute towards the development of an integrated site model. However, geophysical surveys should not be a substitute for such investigations.

Towards better characterisation of geotechnical soil properties across a site, several seismic geophysical methods can be applied. Geophysical data enhances the overall geotechnical investigation by providing a means of assessing soil cyclic resistance and liquefaction potential, and estimates of soil engineering properties such as low strain elastic and shear moduli. These methods can be separated into two categories, surface array techniques and vertical array techniques. Surface array methods involve the deployment of recording instruments along linear arrays, while vertical arrays are those deployed down investigation holes.

2.1 Surface Array Techniques

Geophysical seismic surface array techniques involve the deployment of a series of ground motion instruments (called geophones) at equal spacing along the ground surface. The most common seismic methods are reflection and refraction. Other geophysical techniques useful for site characterisation include, soil resistivity/conductivity, magnetic surveys, electromagnetic surveys, micro-gravity and electrical resistivity tomography. Seismic reflection uses the properties of acoustic waves to obtain highly detailed images of subsurface layers and bedding planes to significant depths from reflected seismic waves. The method requires a controlled seismic source of energy, such as dynamite, a specialized air gun or a seismic vibrator. In contrast, seismic refraction involves measuring the travel time of the component of seismic energy which travels down to the top of rock (or other distinct density contrast), is refracted along the top of rock, and returns to the surface. The method identifies layers in rocks and provides information on wave speeds in each layer. This differs from seismic reflection that provides good geometry of the subsurface but limited data on the wave speeds. One disadvantage of seismic refraction is that the method is unable to detect softer soils which lie underneath harder material, or material layers that are very thin.

The multichannel analysis of surface waves (MASW) method is another seismic survey method that evaluates the elastic condition (stiffness) of the ground using seismic waves. MASW is based on analysing the frequency-dispersion characteristics of Rayleigh waves generated by active sources. The data acquisition involves deployment of an array of

receivers which is left in-place while active sources are recorded at different distances from the array. Analysis of the Rayleigh dispersion characteristics allows the determination of a shear-wave velocity versus depth profile beneath the ground surface. The resultant velocity-versus-depth models are non-unique, which will be further discussed later in this section.

In urban settings, use of these active source methods can be challenging. For reflection surveys, local vibrational noise will reduce the signal-to-noise ratio and make the resulting seismic section less definitive.

Likewise, for refraction data acquiring first arrival would be hard to detect and may obscure the refractions from the bedrock if active source recordings were superimposed with background noise generated by urban activity. For MASW, due to the need to record active sources from hammer shots or weight-drop, data acquisition is most suited to the time of day when pedestrian and vehicle traffic are at a minimum.

To overcome these urban issues and allow the use of seismic data to characterise subsurface conditions for seismic hazard and engineering applications, the Refraction Microtremor (ReMi) technique was developed (Louie, 2001). ReMi is a surface performed geophysical technique which uses ambient vibrations and noise generated by cultural and natural sources caused mainly by human activities (e.g. trucks, trains, airplanes, machinery, tree movements, and wave action to determine the sub-surface velocity structure. Microtremor noise from these sources excite surface Rayleigh waves, which are then used to create a shear-wave velocity versus depth profile beneath the ground surface. Results have extensively been blind-tested against results from borehole measurements, multichannel analysis of surface waves (MASW), and spectral analysis of surface waves (e.g. 2005; Stephenson *et al.*, 2005; Thelen *et al.*, 2006). This differs from other methods that utilise the signals from active sources that requires background noise to be at a minimum.

The advantages of ReMi from a seismic surveying point of view include: it requires only standard, commonly used seismic refraction equipment; it requires no triggered source of wave energy; and it will work best in a seismically noisy urban setting. ReMi is therefore less costly than other investigation methods with rapid data acquisition, especially on active construction sites. The method is thus an effective tool for both reconnaissance for and extrapolation of site conditions between more-costly traditional investigation methods such as boreholes.

As with all surface-wave measurements, refraction microtremor is a volume-averaging measurement, summing interval travel times for which geology is laterally variable, as concluded by Raptakis (2012). ReMi measurements thus differ from the single-point measurements obtained by downhole logs. Downhole shear-wave velocity measurements average over far smaller volumes of the subsurface and may well be

less appropriate for predicting earthquake shaking. In comparison, the volume averaging of velocity using the ReMi technique is on the scale of building footprints and the wavelength of the seismic waves that cause damage.

However, like the MASW surface wave method, ReMi also suffers from non-unique interpretations, meaning that a given data set can be represented by multiple subsurface geological models. Trade-off between layer thickness and the material property generates the issue of non-unique modelling results. Neither the thickness nor the material property of the layer can be independently determined. Towards obtaining a valid model, independent physical evidence and constraints are incorporated into the interpretation of the data to narrow the range of possible subsurface models.

Aurecon New Zealand Ltd (Aurecon) have utilised ReMi towards supplementing data between geotechnical spot measurements. Results allow the correlation and extrapolation of geotechnical knowledge between geotechnical investigation locations, and the further assessment of subsurface material properties. More importantly, the method allows assessment of soil conditions to deeper depths than the shallow geotechnical boreholes, test pits and in some instances MASW.

Interpolation of closely spaced 1D velocity–depth profiles along transects allow 2D velocity-versus-depth representations to be produced, which map the lateral velocity heterogeneity. These 2D representations enable changes in the soil profile and geological structure to be characterised. Results also provide information that can be used as a first order reconnaissance tool targeting key areas for furthermore costly investigation methods (e.g. boreholes, CPT's and test pits).

2.2 Vertical Array Techniques

Vertical seismic arrays involve the deployment of instrumentation and recording of measurements perpendicular to the ground surface, usually taking place down geotechnical boreholes. The most common methods are downhole and cross hole seismic velocity testing. Downhole testing, measures vertical changes in seismic velocity by placing a source at the top of a borehole and measuring S- or P-wave travel-times at multiple intervals in the borehole.

The cross-hole method measures the S- or P-wave travel-time between the source and one or two receivers, which are located at the same depth in different boreholes. A downhole impact source generates a horizontally propagating, vertically polarized S-wave, and the interval travel-time between two receivers positioned at the same elevation is used to calculate the seismic velocities with depth.

Cone Penetration Test (CPT) based shear wave velocity profiles are obtained in similar fashion to

downhole testing, however they utilise a seismic cone advanced directly into the soil, rather than a pre-drilled borehole. These cones are mounted on a rig, operated from the ground surface.

In this paper, only downhole seismic S-wave velocity measurements are discussed.

3 CASE STUDIES IN GROUND ENGINEERING

3.1 City Rail Link – Auckland, New Zealand

ReMi was used to supplement the existing borehole investigation towards mapping basalt depths in Auckland, New Zealand. The scope of the investigation included better characterisation of the basalt (part of the Auckland Volcanic Field) and gaining insight into the overall shape and thickness of the basalt flows. The aim of the investigation was to identify locations where the pipe-jack route for a storm-water realignment would potentially encounter basalt. The avoidance of basalt intrusions was imperative to avoid major project delay and associated financial ramifications. Array locations, shown in Figure 1, were selected to provide information on basalt depths between widely spaced boreholes, and to gain further insight into the overall shape and extent of the palaeo-flow channels.



Figure 1. Locations of the ReMi seismic arrays (red) near Mt Eden Train Station. Green dots show boreholes nearest the seismic survey locations at the time of the investigations. The cyan dots show boreholes drilled after the ReMi investigations. Labels refer to the boreholes shown in Figure 2.

Towards obtaining a valid shear-wave velocity model, the initial borehole information allowed calibration of the velocity structure and assisted in the verification of the derived models. The 2D shear-wave velocity profile below Line C, shown in Figure 2(a), maps the lateral variation in basalt depth and thickness. Depth to the top of the basalt flow abruptly changes in depth at 21m along the array. The recorded surface-waves warranted this change, dictating the need for the shallowing and thickening of the basalt flow to match the data. The ReMi technique was also able to ‘see through’ the basalt intrusion to delineate

both an upper and lower basalt surface, and the softer materials that lay beneath. Depicted features along the base of the basalt flows are interpreted as a geo-morphic characteristic of the alluvial valley that was being infilled by the lava.

Results beneath Line F, which are presented in Figure 2(b), helped constrain basalt depths towards initial reconnaissance prior to selection of further borehole locations for a later stage of the geotechnical investigations. Boreholes drilled during this later stage are circled in Figure 2(b). The borehole results demonstrated that the investigation using ReMi was able to correctly estimate the general shape of the basalt flow. The model highlighted the location of the thickest portion of the basalt, as well as the thinning of the flow towards the south-east.

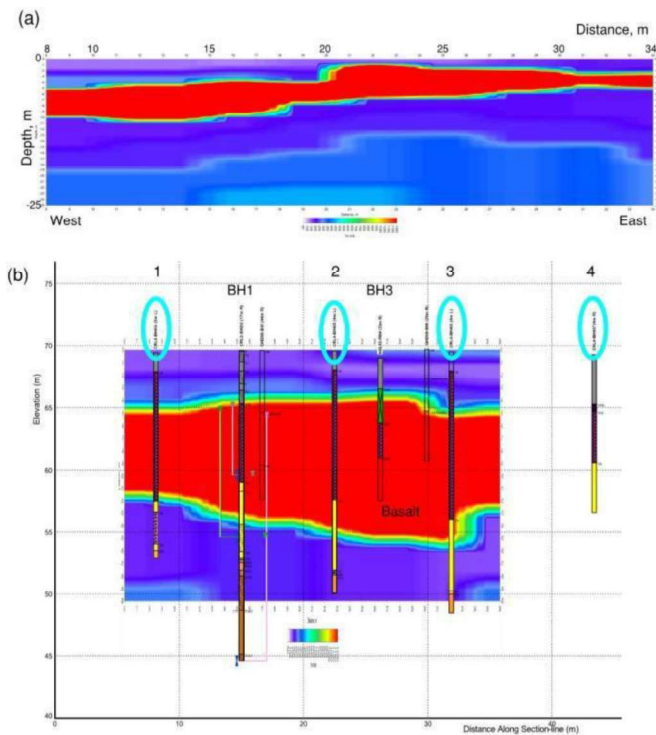


Figure 2. Delineation of a basalt flow beneath (a) Line C and (b) Line F using the ReMi technique. Results from this investigation were used to strategically place an additional four borehole (circled in cyan) to verify these findings. Figure 1 shows the location of these boreholes. The shear-wave velocity scales displayed below each figure range from 50m/s to +1200 m/s. Warm colours indicate high velocities, while cooler colours indicate low velocities. The basalt was found to have a shear-wave velocity of >1200m/s (red).

3.2 Bowen Campus/Parliament Precinct – Wellington, New Zealand

Parliamentary Service were proposing construction of two buildings, a four-storey extension and a new six storey block to the west of the Beehive at their Parliament Precinct, located off Bowen Street, Wellington (Figure 3). This site is located directly adjacent to Bowen Campus, which is currently undergoing seismic strengthening and redevelopment of a 15-storey and 9-storey building. For this publication, we shall consider these as a single site.

Geotechnical information was required to determine foundation design parameters, liquefaction potential and Site Subsoil Classification. Initial geotechnical investigations comprised boreholes with Standard Penetration Tests (SPT), including down-hole shear-wave velocity testing. ReMi was then used to supplement the initial geotechnical investigation, correlating between the borehole data and determining lateral changes in bedrock depth across the site.

Wellington region is a seismically active region with potential for a high level of ground shaking. In accordance with NZS1170.5:2004 “Earthquake Design Actions” (Standards New Zealand, 2004), a seismic site classification based on geological and geotechnical properties is used in the calculation of seismic loading of buildings and structures. The site subsoil classes are defined as Class A (strong rock), Class B (rock), Class C (shallow soil site), Class D (Deep or soft soil), and Class E (very soft soils). Each class quantifies the soil’s propensity to amplify, or in some cases attenuate, surface ground motion from underlying rock, where rupture occurs during earthquakes. They are based on physical soil properties, including the site period. Site period is defined as four times the shear-wave travel time from the surface to bedrock (Larkin and Van Houtte, 2014), and is a measure of the period of vibration corresponding to the fundamental frequency of the column of soil.

Amendments to NZS1170.5 in 2016 now make interpolated design shape factors between Class C and Class D based on site period an acceptable solution. Assessment of the interpolated curves demands that accurate determination of bedrock depths together with robust measurement of shear-wave velocity to bedrock are required for site period calculation. Site Subsoil Classifications for these development sites were assessed in accordance with NZS1170.5:2004 using Unconfined Compressive Strength (UCS) testing of the bedrock, down-hole shear wave velocity testing and ReMi investigation data.

Using the shear-wave velocity and depth information obtained from both methods, site period measurements were mapped across the site, as shown in Figure 3. Bedrock depths varied from 16m depth below ground surface to 80m depth, with prominent deepening of the bedrock surface towards the east. The detailed mapping of bedrock depth, coupled with the 2D shear-wave velocity information allowed comprehensive assessment of both the site subsoil conditions and the variability of the fundamental period of the soil column.

Constraints from the borehole descriptions, SPT, laboratory testing and downhole velocity measurements were used to constrain the velocity profiles determined from the ReMi data. The resultant 2D seismic profiles were able to provide vital information on bedrock depths, characterising the nature of the change. Most importantly, the ReMi investigation allowed the 1D point measurements from the vertical

boreholes to be extrapolated across the entire development site.



Figure 3. Locations of the ReMi seismic arrays and boreholes (red) at Bowen Campus/Parliament Precinct, Wellington, New Zealand. Site period measurement values across the site are displayed, with estimates from the seismic ReMi data shown as cyan circles. Aerial photograph sourced from LINZ Data Service (<https://data.linz.govt.nz/data/category/aerial>) and licenced under the Creative Commons Attribution 4.0 New Zealand.

A identified the location of a buried stream channel, which spot borehole test investigations failed to target. More importantly, the technique permitted the assessment of material properties to deeper depths than the shallow test pits.

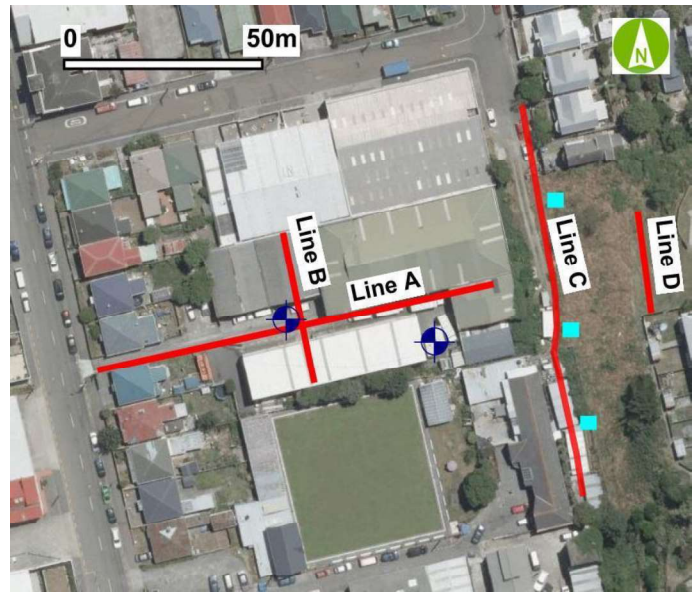


Figure 4. Locations of the ReMi seismic arrays (red lines) undertaken for the geotechnical investigation for a Terrace Townhouse development. Borehole (blue symbols) and test pit (cyan squares) locations are displayed. Aerial photograph sourced from LINZ Data Service (<https://data.linz.govt.nz/data/category/aerial>) and licenced under the Creative Commons Attribution 4.0 New Zealand.

3.3 Terrace Townhouses – Wellington, New Zealand

Towards supplementing data between geotechnical borehole and test pit investigations, ReMi investigations were undertaken to determine the subsurface velocity structure beneath the site of the proposed Terrace Townhouses (Figure 4). 2D velocity-versus-depth representations mapping the lateral velocity heterogeneity beneath Line A and Line C are presented in Figure 5.

Borehole data from two locations along Line A were used to constrain the velocity profile. Both boreholes terminate at the bedrock interface. As seen from Figure 5(a), there were notable lateral changes that were important for the liquefaction assessment of the site, with interbedded zones of low velocity sediments depicted. The non-intrusive technique was also able to define the location of a historical buried stream channel along Line A, documented to have run through the site during the mid-1800's.

Interpretations along Line C, shown in Figure 5(b), were controlled by stratigraphy from three test pits. Bedrock was only encountered in TP-02. An abrupt change in bedrock depth and soil thickness was revealed through the investigation. The development site was the location of a historic brick factory (circa 1895), which utilized clay material in the immediate vicinity. The increase in bedrock depth observed along Line C is interpreted to be anthropogenic in nature and was undetected and unforeseen by the geotechnical investigation.

The ReMi investigations allowed the correlation and extrapolation of geotechnical data between investigation locations, and the further assessment of material properties. The 2D velocity profile beneath Line

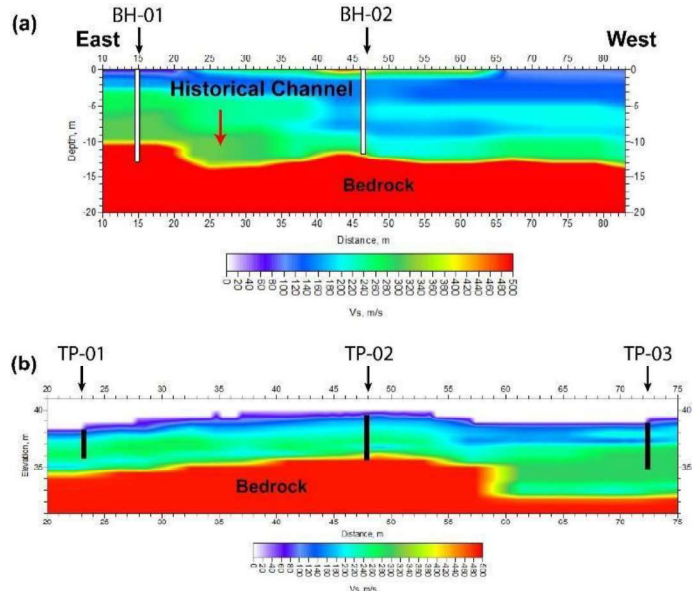


Figure 5. 2D shear-wave velocity representations beneath (a) Line A and (b) Line C. Borehole BH-02 and BH-01 terminated at the weathered bedrock interface. Relative locations of the seismic arrays are displayed in Figure 4. The shear-wave velocity scale displayed below each figure range from 0m/s to +500 m/s, with bedrock velocities > 500m/s. Warm colours indicate high velocities, while cooler colours indicate low velocities. Test pit locations and depth extent are displayed as back lines in figure (c).

4 CONCLUSIONS

Results from the City Rail Link investigation demonstrate how the ReMi technique is a valuable reconnaissance tool. For large-area geotechnical investigations, geophysical data can be acquired over much of the site at relatively low cost to identify areas to target with traditional, but more expensive geotechnical investigation methods. The preliminary ReMi investigations identify general characteristics of the subsurface bedrock topography, regions of lower velocity soils, areas of thicker low velocity material, areas of stiffer materials, buried low velocity zones, and other important subsurface features. These details can then be used to plan the location of boreholes, test pits, and CPT measurements to verify and quantify the properties of these features.

In areas of complex geology, particularly where bedrock depth is variable in seismically active regions, there is often uncertainty in whether a borehole or downhole shear wave velocity investigation has been carried out where bedrock depths are greatest. This was true for the Parliamentary Precinct site investigation. Establishing bedrock depths together with material shear-wave velocity profiles are now crucial for the determination of site period towards Site Subsoil Classification in accordance with NZS1170.5. However, with depth to bedrock exceeding 60m beneath many urban areas, boreholes to bedrock are very costly to drill. This poses a major issue in correctly determining site period and thus site classifications for building code implementation. ReMi allowed the extension of shallow borehole information to bedrock depths, adding a cost-effective assessment tool, providing information regarding the variability of both shear-wave velocity and bedrock depths across large sites.

Use of ReMi in conjunction with boreholes and test pits for the Princess Terrace project enabled the ability to acquire a more comprehensive assessment of site conditions than traditional methods allowed. Shear-wave velocity profiles from the ReMi analysis that were co-located with boreholes and test pits were constrained using physical observations that included SPT and geological soil descriptions. These constraints were then used to produce 2D velocity-depth representations beneath each seismic array and extrapolate site condition knowledge across the entire investigation site. These 2D velocity profiles helped to identify the location of a buried stream channel and palaeo-topographical features that would otherwise be unknown. The geophysical ReMi data also aided in assessing the liquefaction potential of the site by identifying areas of low velocity between borehole locations, as well as assessing the thickness and velocity variability of geological units between borehole and test pit locations. Most importantly for this case study, ReMi characterised an otherwise unknown dramatic increase in bedrock depth.

The three case studies have demonstrated the considerable contribution ReMi shear-wave velocity assessments can make towards a better understanding subsurface geological and geotechnical conditions beneath large development sites. At all three sites velocity measurements from ReMi were used to supplement data from geotechnical spot measurements. Because data can be obtained in very noisy urban environments, obtaining shear-wave velocity information using the ReMi method is less costly and allows for faster data acquisition than many other geo-physical investigation methods. Results presented here demonstrate how ReMi can be used as a cost-effective first order reconnaissance tool targeting key areas for intrusive investigations, and towards providing a comprehensive site characterisation and assessment.

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