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Shifting the geo-risk management paradigm through early screening

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ABSTRACT: Historical project performance of capital works developments tells us that geo-risks continue to play a role in unwanted engineering business outcomes and lost economic opportunity. Characterisation of subsurface conditions in geotechnical engineering practice relies primarily on relatively late-stage intrusive explorations with limited use of geophysical methods: we challenge the industry to take a fresh look. We recognise that the construction sector would likely benefit from earlier, faster, and better representation of the near subsurface using screening techniques with a light footprint and low permitting requirements at the earliest stages of project development. We present a solution that densely populates the ground model space through ambient noise tomography and one that provides representation of subsurface conditions at an engineering scale portending a new paradigm in the management of geotechnical risk for capital works projects. An effective solution should also inform better early development decisions in an improved data-driven way, mitigating the effects of cognitive bias that is increasingly understood to contribute significantly to early cost underestimation that seeds overrun. Through screening case studies we show how pre-FID (final investment decision) feasibility and planning phase decisions can be better informed where the opportunity to influence project outcome is greatest and at lowest cost. Post-FID screening coupled with an optimised conventional investigation and performance testing can complete the information set for full project design at considerably reduced levels of subsurface uncertainty leading to improved engineering business outcomes. As with the recent revision to Eurocode 7 for geotechnical design, the industry is encouraged to promptly incorporate an early screening philosophy into feasibility and planning activities and into design codes for geotechnical design and construction.

KEYWORDS: Geo-risk, uncertainty, hybrid solution, screening, geophysics, ground modelling

1 INTRODUCTION

Most capital works projects tend to overrun both in time and cost (e.g. Flyvbjerg et al, 2004), little ground risk management occurs pre-FID (final investment decision) and there is significant uncertainty of ground conditions at the subsequent construction bid stage as owner investigations are absent or have very restricted scope. Ground risks therefore represent a relatively small element of the broader risk spectrum considered during the DEVEX (development expenditure) phase of infrastructure projects where asset design is typically progressed to about 25-30%.

Leading to FID, multi-factor site ranking, site selection, pre-FEED and FEED (Front End Engineering and Design), site optioneering and project alignment activities are today not well-informed with respect to below ground risk, neither are key early stakeholders including investors with varying risk appetites. Consequently, a lack of information available to construction project bidders leads inadvertently to unwanted outcomes for owners in the form of increased cost and extended schedules.

Design teams supporting construction bid processes are under significant time pressure and are concerned about the consequences of missing key aspects that could lead to increased cost of construction. It is understood that designers can overengineer bid designs to reduce the risk of future malicious claims for professional negligence – especially where contractors are expected to assume ground risk. Also, due to inadequately characterised ground conditions, contractors bidding for work incorporate large (geotechnical) risk contingencies into their bids (productivity, material quantities etc.), both of these factors potentially contributing to increased project CAPEX costs at the bid stage.

Subsequently, during project execution and commonly with significant time pressure, supplementary (or initial) conventional site characterisation can reveal unexpected / unforeseen ground conditions leading to a) redesign, b) emergency site characterisation, c) contractor claims and delays and d) construction changes – all of which represent increased CAPEX costs and lost economic opportunity for the owner as part of the status quo.

Looking beyond purely technical issues, there appears to be a converging view from researchers in behavioural science and economic geography (see for example, Flyvbjerg et al, 2018) that human or cognitive bias is the root cause of project underperformance, and that early decision-making, if not adequately informed using a data-driven approach, inevitably leads to early cost underestimation that results in downstream cost overrun and delays. We have to assume that decisions around geo-risk are not immune to cognitive bias and that an improved data-driven approach to early decision-making would likely be beneficial.

Reflecting on the status quo we challenge the industry to take a fresh look at managing geo-risk *and* to consider how to mitigate the impact of cognitive bias using a hybrid solution to recover some of the lost opportunity arising from an incomplete understanding of the state and behaviour of the subsurface. By hybrid solution we mean combining early screening with optimised direct geotechnical investigation and developing robust digital ground models supported by advanced analytics based on artificial intelligence and / or geostatistical approaches.

Intuitively, we all know that earlier actions are better than late actions where there is a time-dependency on outcomes and this is why, for example, we prefer early diagnosis of health issues before they become more serious.

Fundamentally, screening is any 'early' activity that provides information or data to inform timely decisions around managing current or future risk. Screening can also be defined as the systematic evaluation and assessment of various factors within an environment, process, or population to identify and mitigate potential risks or issues before they escalate into major problems or unwanted outcomes. The field of geophysics provides tools that are perfectly suited for screening

Screening is established as common and best practice across many industrial sectors including medicine, agriculture and environmental management and has led to quantifiable benefits. For example, in medicine, screening has brought about significant improvements in patient outcomes, mortality rates, and overall healthcare efficiency. In agriculture, screening plays a vital role in ensuring crop and livestock health, increasing yields, reducing chemical usage, and contributing to sustainable farming practices.

2 EARLY SCREENING FOR GEO-RISKS

Whether on land or in the ocean, subsurface risk arises from the state and behaviour of natural materials being more variable and less predictable than that of engineered materials (see Eddies et al., 2024 for definitions of *geo-risks* and *geo-data*).

In the context of geotechnical engineering, geo-risk arises from uncertainty, the absence of which would mean that all outcomes could be predicted and could be engineered well in advance of construction, albeit at varying scales of cost.

In the absence of prior subsurface data, the positioning of intrusive investigations executed relatively late in asset development is often dictated by the geometric footprint of the proposed structure or based on grid not informed by subsurface variability. As a result, variations in subsurface conditions between investigation points—undetectable through standard site investigation analysis—can lead to unexpected and adverse geological scenarios. These may escalate construction costs, cause delays, or, in severe cases, compromise structural integrity during the asset's service life.

The current standard practice for subsurface characterisation relies predominantly on intrusive investigation techniques such as boreholes and Cone Penetration Tests (CPTs). Data collected from these methods are often interpolated and at times extrapolated—across extensive areas, which can lead to overlooking critical variations in ground conditions. Such omissions may compromise the reliability of both design and construction. While geophysical methods are available for site characterization, their adoption remains limited. When employed, they are typically confined to downhole geophysics, shallow techniques aimed at detecting subsurface obstructions, and occasional use of two-dimensional approaches like Multi-Channel Analysis of Surface Waves (MASW), primarily for estimating Vs30 values (e.g. Park et al 1999; Park, 2013).

To reduce uncertainty and effectively manage geo-risks in the subsurface during construction, site characterisation in geotechnical engineering is typically undertaken after the project owner's final investment decision (FID). This process continues to rely heavily on conventional in situ and direct investigation methods—such as drilling, probing, down-hole testing and logging, sampling, and laboratory analysis—which provide critical data to inform both the geotechnical design and construction phases of infrastructure development.

Acquiring early insights into the site's broader geological framework—particularly the presence and location of anomalies such as infilled paleo-channels or cavities—through a preliminary screening programme enables more informed planning of initial investigations. This approach allows site characterisation to reflect both subsurface variability and the spatial layout of the development – with the result of improved value-add from intrusive investigations and associated sampling and testing.

Geo-risks For large onshore development and before the final investment decision (FID) are only partially addressed during the front-end engineering and design (FEED) phase, typically through sparse conventional investigations. These early results shape the project's initial risk profile, informing investment viability, insurance evaluations, mitigation strategies, and regulatory processes such as permitting and licensing.

By targeting intrusive investigation locations based on early screening data, engineers can better capture the actual variability and hence nearly the full range of stratigraphic conditions and engineering properties. This significantly improves the reliability of interpolations between widely spaced data points.

After the final investment decision (FID), when an owner opts for a design-and-build or Engineer, Procure, Construct (EPC) delivery model, much of the project's geotechnical risk shifts to contractors. With only limited subsurface data supplied to support bid pricing—and with that scope often perceived as insufficient—constructors face significant uncertainty, reducing the chance of value-for-money outcomes.

Designers confronted by this uncertainty typically default to conservative soil and rock parameters. The result is overengineered foundations and earthworks, higher expenditures, and extended construction timelines.

As Wood (2022) emphasizes, contractors also depend on reliable subsurface insights. To guard against unknown ground conditions, they build generous contingencies into their bids, down-rate expected productivity, and inflate material estimates—essentially pricing for worst-case scenarios.

Moreover, transferring ground risk does not eliminate post-award disputes. Time and effort are often wasted debating claims that unforeseen geological conditions could not have been anticipated from the limited early data provided at tender. These factors significantly impact project capital expenditure and critical path timelines for both design and construction schedules. While reliability-based design approaches are increasingly prevalent, preventing performance failure in most cases, if such designs are not locally calibrated to specific site conditions through adequate site investigation and characterisation, there is a risk of overengineering structures, leading to excessive factors of safety and the antithesis of value engineering. These hidden costs, though not necessarily apparent as overruns, contribute to systemic underperformance within the industry.

In the feasibility, planning, and conceptual design phases (DEVEX), geo-risks often receive limited attention. During execution, conventional site investigations—constrained by sparse spatial sampling—leave designers and estimators facing significant uncertainty. The resulting subsurface models are data-poor, frequently relying on subjective judgment or chance to bridge gaps. When actual conditions diverge from these simplified assumptions, the outcome can be elevated risk and costly consequences.

We see clear value for the construction sector in achieving earlier, faster, and better subsurface representation within the top 100 m. This can be enabled through low-impact, lightly permitted screening techniques applied at the earliest project stages.

- Earlier: screening conducted pre-FID or early in execution
- Faster: quicker turnaround of engineering insights after data acquisition.
- Better: enhanced spatial coverage to 3D (beyond traditional 1D/2D profiles) and stronger integration of geophysical outputs with geotechnical analyses, supporting safer, more economical design and planning

Although site characterisation typically accounts for less than 2% of construction costs (Clayton, 2001), the premiums caused by subsurface uncertainty often exceed this many times over. Early adoption of screening solutions, such as those described here, can significantly reduce these uncertainties at a fraction of the cost.

3 GEOPHYSICAL SCREENING

3.1 *Adapted Ambient Noise Tomography*

Adapted Ambient Noise Tomography (ANT) is a seismic technique (Campillo & Paul, 2003; Campillo et al., 2011) that forms part of Fugro's GroundIQ® solution for improved data-driven decision-making. Also known as passive noise interferometry, ANT is primarily a passive geophysical screening method that uses a 2D surface grid of seismic sensors to generate a 3D shear wave velocity model. This model is directly related to small-strain stiffness - a key geotechnical parameter important in for example foundation engineering and slope design. Fugro has adapted the original ANT methodology of Shapiro et al. (2005) for engineering-scale applications (Eddies et al., 2024), incorporating active-source seismic data to enhance near surface resolution.

The 3D shear wave velocity (Vs) distribution derived from adapted ANT is directly related to the small-strain shear modulus (Gmax or G0), a fundamental parameter in geotechnical engineering. Vs provides a non-destructive means to evaluate ground stiffness directly and assess strength parameters indirectly through empirical calculations. Ground stiffness and strength parameters are essential for designing foundations, retaining structures, slopes, and evaluating seismic site response. Vs varies with soil type, density, confining pressure, void ratio, stress history, and aging—denser, stiffer materials exhibit higher Vs values. Generally, denser and stiffer soils and rock have higher Vs values, while softer, looser soils have lower values (see Table 1 for soil profile types based on the mean shear wave velocity of the top 30 m)).

Table 1. NEHRP Building Code Soil Profile Types (FEMA, 2000)

Soil Types	Rock/Soil Description	Vs30 Value (m/s)
A	*Hard Rock*	>1500
B	*Rock*	760-1500
C	*Dense Soil / Soft Rock*	360-760
D	*Stiff Soil*	180-360
E	*Soft Soil*	<180

Ambient noise tomography (ANT) involves several key steps. Firstly, seismic data are acquired using a grid of surface sensors (100s to 1000s) over a period of days to weeks. Following data harvesting, seismic interferometry (Curtis et al., 2006; Wapenaar et al., 2010) reorganizes ambient seismic noise into interpretable signals by cross-correlating a reference station with others to obtain correlation Green's functions (CGFs). Stacking over long periods allows coherent surface waves to emerge while incoherent noise cancels out.

An initial 3D (x, y, frequency) Rayleigh phase velocity model is built using F-K array processing (Foti et al., 2011). Arrival time differences across receivers yield local phase velocities; otherwise, the grid is filled with averaged 1D functions from dispersion spectra. Shear-wave velocity (Vs) depth profiles are then derived by damped Gauss-Newton inversion of layered elastic models, with density tied to Vs. Group velocity dispersion, calculated from smoothed phase velocity, guides automatic picking of dispersion functions from virtual source gathers.

Traveltimes are extracted using frequency-time analysis and continuous wavelet transforms; combining both reduces mispicks. These picks are mapped onto the inversion grid via travel time tomography. The final ANT product at engineering scale is a 3D cube of group velocities, with each grid cell's dispersion curve inverted to yield a shear-wave velocity distribution. A more detailed explanation of ANT noise sources and an ANT data processing workflow can be found in Eddies et al. (2024).

4 CASE STUDY 1: SCREENING SOILS FOR FOUNDATION ENGINEERING

Ambient noise tomography adapted for engineering purposes (Eddies et al, 2024) was performed at a greenfield industrial facility site in South Texas, USA. The site is located in an area underlain by the Beaumont clay formation. Typically, this formation consists of poorly bedded, plastic clay interbedded with coarser grained layers of silt and sand. Sand layers of substantial thickness do occur along distributary channels of the ancient delta. ANT was performed at part of the site across an area of approximately 200 m x 70 m, as a pilot, to demonstrate the applicability and value of early screening for site characterization. The main purpose of the demonstration project was to reliably map the variability of subsurface soils across part of the site and identify the expected elevation of the sand layers which would provide an adequate bearing stratum for deep foundations planned across the site. Aside from the ANT demonstration project at part of the project site, the client's approach to site characterization followed a conventional approach where a combination of intrusive explorations consisting of boreholes and CPTs was used to characterise the subsurface conditions across the entire site with approximate dimensions of 330 m x 500 m.

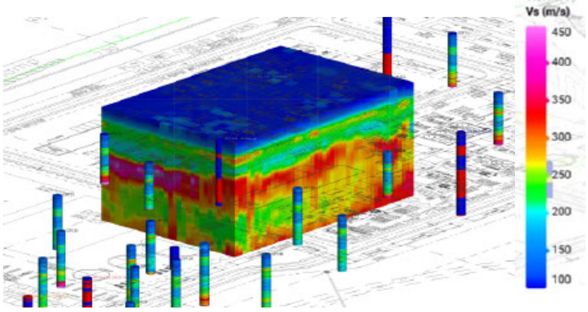

Figure 1. 3D shear wave velocity distribution in soils derived from adapted ANT screening. Red zones in boreholes represent sand, blue zones represent clay

The resulting 3D data volume is shown in Figure 1 and clearly shows the variations in the shear wave velocity down to approximately 70 m depth. The 3D shear wave velocity model from the ANT survey displays velocities less than 200 m/s (shaded blue), at the surface, which are indicative of soft clayey soils. The velocities then remain relatively low to moderate until a fast layer is encountered at approximately 20 m depth. This faster layer displays velocities between 300 and 400 m/s (shaded orange through pink) across the majority model and based on shear wave velocity alone; is likely to be related to stiff to dense soils. Comparisons of the 3D ground model from the ANT survey to geo-data and interpretations derived from intrusive explorations and downhole geophysics (Figure 2) reveals consistent findings. Figure 2 compares Vs contours from the 3D ANT model along a 2D section that includes projected boreholes (sands in yellow) and CPTs.

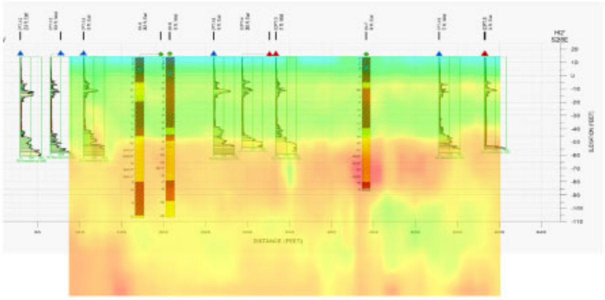

Figure 2. 2D slice of shear wave velocity derived from 3D ANT volume with CPT and borehole data

Figure 3 compares the Vs profile from downhole geophysics at one boring with the Vs profile derived from the ANT 3D model at that location. A thin fast shallow layer and a thick deeper one (~18 m depth) are imaged. This deeper layer correlates well with an increase in downhole Vs measurements and corresponds to a dense sandy layer observed in both CPTs and boreholes. There is excellent agreement between the increase in the Vs with the presence of both the medium dense silty sands at shallow depths and the dense sand bearing stratum at deeper depths.

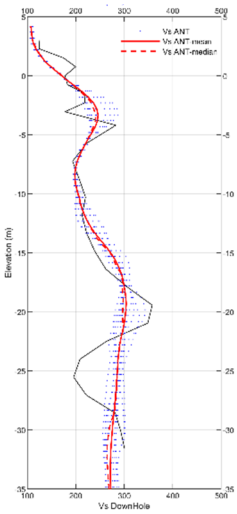

Figure 3. Vs profile from downhole geophysics at one borehole with the Vs profile derived from the ANT 3D model at that location

In a foundation engineering context, the case study demonstrated that for similar projects in relatively soft soils, a hybrid approach of combining geophysical screening and fewer, but better targeted CPTs and boreholes could have reduced the delivery schedule of key foundation design inputs by about 50% (i.e. CAPEX savings) and provided significantly more confidence in the design of pre-cut piles with reduced wasted time and materials for construction.

5 CASE STUDY 2: SCREENING ROCK FOR GEOHAZARDS

Fugro was commissioned by Stantec to carry out a screening investigation for planning the future Wakrah Pumping Station, Doha, State of Qatar. The aim of the exercise, ahead of planned deep excavations, was to screen the subsurface using an adapted ANT method to highlight the presence of adverse subsurface conditions associated with potential cavities (open or partially collapsed), and zones of extremely weak or fractured rocks, down to a depth of 100 m below the ground. A clear and coherent surface wavefield was retrieved from the data acquired at this site with an average Rayleigh wave velocity of around 1100 m/s. This recorded wavefield in combination with the high velocity in the subsurface allows for screening down to 120 m depth, which significantly surpasses the depth sensitivity of conventional tools. The 3D Vs volume resulting from the data processing (Figure 4) shows velocities (rock) between 800 m/s and 2000 m/s, a predictable velocity inversion caused by the presence of shale below the Simsima limestone, and, as a screening deliverable, no indications of adverse subsurface conditions.

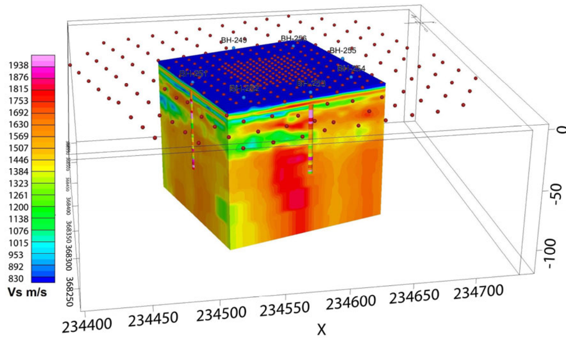

Figure 4. 3D shear wave velocity distribution in rock derived from adapted ANT screening

Borehole geophysical measurements (PS-logging) were carried out at the same location for comparison of shear wave velocities.

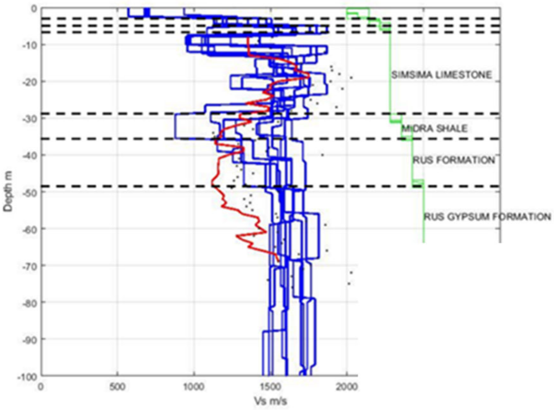

Figure 5. Plot showing the average of all PS-logging values (in red), 1D passive seismic Vs profiles extracted at PS-logging locations (in blue) and the vertical geological units with depth (in green). The black dashed lines map the geological transitions onto the passive seismic Vs profiles and the PS-logging results.

A good match between the Vs changes in the profiles derived from the 3D ANT distribution and the geological layering can be observed through the black dashed lines (Figure 5). Also, the general trend of Vs values of the PS-logging and ANT match up. Note that PS-logging provides a 1D high-resolution vertical distribution of shear wave velocity in an intrusive manner. The adapted ANT method provides a 3D Vs distribution over the area in a non-intrusive manner to a larger depth but with lower resolution. While a detailed description of the Wakrah pumping station development programme is beyond the scope of this paper, the case study highlights how a light footprint, low environmental impact screening approach applied sufficiently early can support risk-adjusted planning decisions for major infrastructure, in this case confirming an absence of adverse subsurface conditions and hazards such as cavities and weak zones.

The stratigraphy in the vicinity of the development site is well understood and relatively predictable other than the presence of karstic features that represent significant risks for excavations and foundation engineering. But had this screening approach been applied sufficiently early in the asset development, CAPEX savings equivalent to about 50% of the site characterisation schedule (which extended to several months) could have been achieved in the form of fewer boreholes as well as improved confidence for the developer that no surprises would be encountered during construction (no significant gaps in the ground model).

6 CASE STUDY 3: SCREENING ENGINEERED SOILS FOR SAFETY ASSESSMENT

There are over 3,500 tailings dams worldwide, and the stability of many poses a significant global concern—representing an existential threat to communities, governments, and mining organizations Tailings dam failures underscore the need to identify and assess hazards throughout their lifecycle. These linear structures are prone to localized distress, yet traditional assessments rely on 1D borehole or probe data, leaving significant residual uncertainty in unexamined areas. To address this, Codelco partnered with Fugro to pilot a new approach using 3D geophysical screening (ANT) and ground modeling at Dam A in the Colihues Tailings Deposit, El Teniente copper mine, Chile within the framework of a geotechnical investigation and instrumentation campaign. The study deployed around 1,000 seismic sensors in a 7-meter grid on the dam's front face, collecting passive and active seismic data.

The 3D shear wave velocity (Vs) model derived from adapted ANT comprising about 1 million data points is shown in Figure 6. Velocity values varied from about 300 m/s to 1300 m/s and represent an interval from surface to about 120 m depth. The 3D Vs model shows an increase of velocity with depth and the presence of lateral velocity/stiffness variations within the dam. The range of Vs was consistent with the presence of stiff / dense soils at low velocity through very dense soil / soft rock to rock at high velocity. Bedrock correlated well with the 900 m/s velocity contour (Figure 7) and the shear wave velocity derived from 3D ANT was very consistent with velocity data obtained from boreholes and from 2D MASW profiling (Figure 8). Localized velocity inversions were observed where velocity and therefore stiffness decreased with depth. However, the lowest velocities observed at Dam A below about 10 m depth were greater than 450 m/s equivalent to very dense soils and soft rock. Soft soils are characterised in commonly used classification schemes by shear wave velocities < 180 m/s; such low velocities were not observed at the Dam A site. No adverse geological/geotechnical features were therefore identified in the 3D velocity model requiring further investigation.

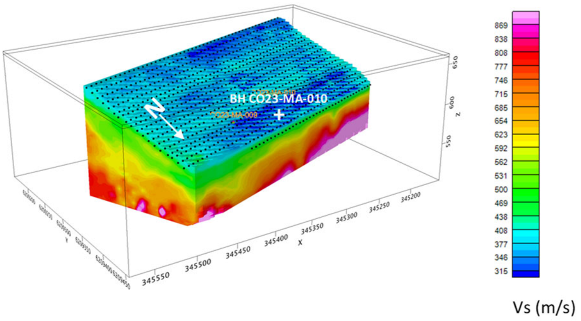

Figure 6. 3D model of shear wave velocity derived from 3D ambient noise tomography (ANT), Dam A

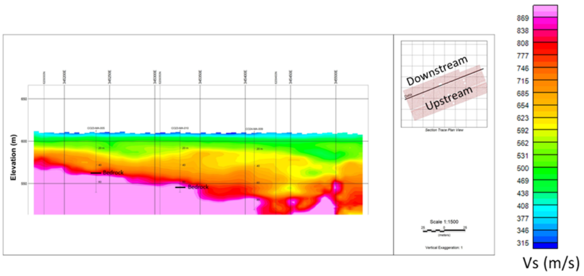

Figure 7. Slice through 3D model of shear wave velocity derived from 3D ANT, Dam A showing correlation between 900 m/s velocity contour and bedrock encountered in boreholes

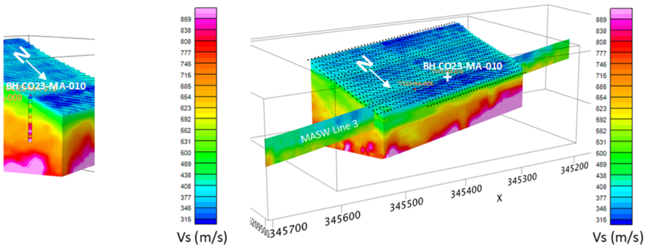

Figure 8. Comparison of 1D BH-derived and 3D ANT-derived shear wave velocity, Dam A (left) and comparison of 2D MASW-derived and 3D ANT-derived shear wave velocity, Dam A

As part of a geo-risk management solution, adapted ANT offers owner-operators a powerful tool for early-stage screening of tailings dams. It enables the construction of a high-resolution 3D geotechnical model that supports timely and informed risk management decisions. The ability to image internal dam characteristics and foundation soils allows for more accurate targeting of geotechnical profiles during subsequent intrusive investigations. The high fidelity and dense data coverage of the ANT-derived model allow for more reliable site zonation than is possible with widely spaced 1D or 2D data from conventional investigations. Furthermore, shear wave velocity and stiffness values derived from ANT can be directly integrated into numerical models for performance-based design assessments. Combining ANT screening with targeted intrusive investigations significantly enhances confidence in the characterization, engineering performance, and safety of tailings storage facilities.

Geotechnical engineers managing tailings dams' safety and engineering performance need to have confidence that the subsurface is well characterised – this case study demonstrates that a historical reliance on relatively sparse intrusive investigations alone no longer constitutes best practice in avoiding avoid costly and sometimes catastrophic failure.

7 CONCLUSIONS

The historical performance of construction projects justifies challenging the status quo of how geo-risk is managed and the building of a new paradigm to help recover ongoing lost economic opportunity for key stakeholders in infrastructure asset development and management.

Early screening similar to that highlighted in the case studies requires front-end loading of effort in the asset cycle and offers a small footprint with low-permitting requirements and an environmentally friendly, socially responsible, and low-risk means to obtain early subsurface characterisation. Executed sufficiently early in a pre-FID (DEVEX) or post-FID (CAPEX/OPEX) context, screening enables an initial, reconnaissance-level assessment of mechanical properties and subsurface risk.

A 3D screening solution including, but not limited to, adapted ambient noise tomography that provides dense characterisation at an engineering scale portends a new paradigm in the management of geotechnical risk for capital works developments. As partly highlighted by the case studies screening can help inform feasibility and planning studies, foundation engineering, geohazard assessment and slope engineering – saving time and cost and providing more confidence that the subsurface has been characterised well.

In addition to asset owners, key stakeholders typically involved early in asset development such as planners, permitting and certification authorities, insurers and investors stand to benefit from earlier reduction of uncertainty. Assessments of subsurface risk arising from screening could inform earlier and better, risk-adjusted, improved data-driven development decisions during planning phases (i.e., pre-FID) and could help mitigate the effects of human bias that is understood to be the root cause of early cost underestimation that effectively hard-wires overrun into projects.

During project execution phases (post-FID), informed targeting of the locations of intrusive investigations such that the full range of geotechnical properties encountered on the site relevant to engineering design can be defined without wasted effort. Indeed, savings in the extent of an un-targeted intrusive investigation will often more than offset the cost of the screening exercise itself. By significantly reducing epistemic uncertainty in the subsurface, geotechnical engineers have the possibility to build geotechnical construction, quicker, cheaper and to higher quality/safety shrinking the industry's 'triangle of compromise' which hitherto could only be distorted, for example desirous of improved quality, it would be suggested to build slower or at greater expense.

Effective reduction of uncertainty by the adoption of advanced screening techniques allows geotechnical construction for capital projects to be delivered with both value for money and certainty of outcome breaking what hitherto was considered a trade-off.

Dense, volumetric characterisation with screening technologies also opens up significant opportunities to leverage the power of unsupervised machine learning techniques for quantitative interpretation of geophysical data, but also to deploy supervised machine learning and probabilistic ground modelling to integrate screening and direct investigation data to produce maximum likelihood ground models to drive more timely and improved decision-making for design and construction.

As with the inclusion of light footprint screening approaches and ANT as an example geophysical screening technology in the revised, second-generation Eurocode 7: (Geotechnical Design), the industry is encouraged to promptly incorporate the screening philosophy as part of a hybrid geo-risk management solution into feasibility and planning activities and into design codes for geotechnical design and construction.

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