Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Early Screening for Improved Management of Geo-risks

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ABSTRACT

Across several sectors including medicine and agriculture and the extractive industries, availability of early information from screening delivers disproportionate downstream benefit to key stakeholders. With the aim of reducing uncertainty to manage geo-risks in the subsurface, site characterisation for geotechnical engineering is mainly executed following a project owner's final investment decision (FID) and continues to rely predominantly on conventional investigation techniques that inform both the geotechnical design and construction phases of infrastructure development. However, historical project performance of capital works developments tells us that geo-risks continue to play a role in unwanted engineering business outcomes in the form of schedule and cost overrun associated with earlier cost underestimation. Fundamentally, we recognise that the construction sector would benefit from earlier, faster, and better representation of the subsurface in the top 50 m to 100 m using techniques with a light footprint and low permitting requirements at the earliest stages of project development. We describe an example early-phase screening solution based on adapted ambient noise tomography. Screening at feasibility and planning phases can help to mitigate the impact of human bias arising from epistemic uncertainty in the subsurface and can improve early decision-making where the opportunity to influence project outcome is greatest and at lowest cost. Screening coupled with an optimised conventional intrusive investigation during the execution phase can complete the information set for full project design at considerably reduced levels of subsurface uncertainty leading to improved engineering business outcomes. The industry is encouraged to promptly incorporate the screening philosophy into feasibility and planning activities and into design codes for geotechnical design and construction.

Keywords: screening; uncertainty; geo-risks; geophysics; geotechnical engineering

1. Introduction

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.

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.

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 and in agriculture, screening plays a vital role in ensuring crop and livestock health, increasing yields, reducing chemical usage, and contributing to sustainable farming practices. The integration of advanced technologies has further augmented its effectiveness, making it an essential component of modern agricultural management. Early screening in environmental management plays a crucial role in the timely identification of environmental risks and issues, allowing the implementation of measures to prevent or mitigate the adverse effects on the environment before they become severe. It enables better planning and execution of environmental policies and can lead to significant long-term savings by avoiding the costs associated with remediation of environmental damage. Additionally, it helps in maintaining compliance with environmental regulations and can improve the sustainability of projects and activities.

2. Screening for Geo-Risks

The success of screening across a number of sectors can be seen as the identification of desirable outcomes or endgames and then implementation of an efficient decision process around risk to meet those objectives. 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. 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. We define the term *geo-risks* as those risks associated with natural environments and their processes, and the state and behaviour of natural and engineered earthen materials and, structures built on and in the ground, or above and below water. So, we can see that *ground risk* or *geotechnical risk* (e.g., Clayton, 2001) is a subset of a broader family of geo-risks that need to be managed for successful capital works development. We use the term *geo-data* to describe the increasingly digital information needed to reduce uncertainty and manage geo-risk. Geo-data generally fall into one or more broad types including geological, geotechnical, geophysical, geospatial, geochemical, hydrogeological metocean and hydrographic, though this is not an exhaustive list.

With the aim of reducing uncertainty to manage geo-risks in the subsurface, site characterisation for geotechnical engineering is mainly executed following a project owner's final investment decision (FID) and continues to rely predominantly on conventional investigation techniques (drilling, probing, down-hole testing and logging, sampling, and laboratory testing) that inform both geotechnical design and construction phases of infrastructure development.

Often by necessity in the absence of any other information, the layout of intrusive investigation positions is defined based on the geometrical footprint of the structure. Consequently, subsurface conditions that vary between investigation positions, which cannot be inferred from analysis of the site investigation data, can lead to unforeseen and adverse geological conditions which can result in increased construction costs or delays or worse, structures suffering distress or failure during their service life. Early information defining the overall geological structure underlying the site (through a screening programme), particularly the presence and location of anomalies, such as infilled paleo-channels would allow initial site investigations to be defined by reference to both the subsurface variability and layout/location of the development. For larger onshore projects, pre-FID geo-risks are partially addressed during the front-end engineering and design (FEED) phase, often utilising sparsely spaced conventional site investigations. These results contribute to an initial project risk profile and thereby influence attractiveness for investment/development, project insurance, risk mitigation, permitting, licensing, and accreditation. Targeting of the intrusive investigation locations based on early screening activity allows the full range of relevant stratigraphic conditions and engineering properties to be defined together with better constrained interpolation between sparse locations.

Post-FID, where the owner adopts a 'design and build' or 'Engineer, Procure, Construct (EPC)' project delivery method, the owner/developer transfers many risks to other organisations. Limited geotechnical information obtained to allow constructors to price the design and construction of the project, that is perceived to include many uncertainties due to its limited scope is unlikely to deliver value for money construction. Designers when faced with uncertainty tend to adopt more conservative design input data which often leads to overengineering of the construction, higher costs and longer construction schedules. However, as highlighted by Wood (2022), it is not only designers who require subsurface insights. Construction contractors, faced with geotechnical uncertainty, tend to adopt a conservative approach in estimating productivity, construction material requirements, and risk contingencies within their bid prices, often preparing pricing for 'worse case' ground conditions. Transferring ground risk to a constructor does not always eliminate claims for unforeseen ground conditions and effort and time can be wasted arguing for and against claims that actual ground conditions could not have been reasonably foreseen from early data provided at the time of bid.

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.

At feasibility, planning and conceptual design phases, there may be little attention to geo-risks. During the execution phase, limited spatial sampling presents a recognised limitation of conventional site investigation, leading to uncertainty for designers and construction estimators. This results in subsurface models containing sparse data, relying on subjective judgment or chance occurrences to fill the gaps. Such an approach can introduce risks and undesired consequences when the subsurface deviates from simplistic scenarios.

Fundamentally, we recognise that the construction sector would benefit from earlier, faster and better representation of the subsurface in the top 50 m to 100 m using screening techniques with a light footprint and low permitting requirements at the earliest stages of project development. By earlier we mean screening that can be executed earlier in the asset cycle, either pre-FID or early in the execution phase. By faster we mean reduced delivery time of insights following data acquisition. By better we mean improved spatial coverage to 3D (engineering geophysics typically derives 1D or 2D profiles) and improved interoperability between geophysical deliverables and geotechnical analyses required for better planning and economic and safe design.

When typically less than 2% of project construction cost is expended on site characterisation (e.g., Clayton, 2001), construction cost premiums arising from subsurface uncertainty are many, many times the cost of reducing this uncertainty, particularly if screening solutions of the type described here are adopted early.

3. Adapted ambient noise tomography as a screening solution component

As one possible component of a screening solution, ambient noise tomography (Shapiro et al., 2005) or ANT sometimes referred to as passive seismic interferometry and adapted for use at engineering scales, is a non-intrusive technique that uses ambient noise ever-present in most environments. Ambient seismic noise originates from both natural (ocean waves, wind) and anthropogenic (traffic, industrial processes) mechanisms. These mechanisms are frequency-dependent with a spectral boundary between natural and cultural noise around 1 Hz (Bonnefoy-Claudet et al., 2006). Knowing that we would like to focus on (foundation) depths of 0-100 m for engineering purposes, the cultural noise range (1 Hz to 100 Hz) is most suitable for our purposes. Cultural or anthropogenic seismic noise primarily originates from activities that occur at or near the surface, for example, traffic or industrial processes. Therefore, it is reasonable to assume that the noise wavefield mainly consists of surface waves. There are two types of surface waves: Rayleigh waves and Love waves. According to Yamanaka et al. (1994), noise at frequencies above 1 Hz primarily consist of Rayleigh waves. These waves consist of different propagating modes in layered media (a typical subsurface), where the fundamental mode is typically the strongest. Fundamental mode surface waves are an approximate solution to the 2D wave equation with a frequency-dependent propagation velocity (Wapenaar et al., 2010). Therefore, reconstructing these Rayleigh waves from the recorded cultural noise is expected to be adequate to obtain a high-resolution shear wave velocity model of the subsurface (Picozzi et al., 2009).

The shear wave velocity (V_s) measured by shallow seismic techniques is directly related to the maximum (or initial) shear modulus (G_{max} or G_0) of soil or rock in geotechnical engineering. The relationship between shear wave velocity and the shear modulus is fundamental in the field of geotechnics, as it provides a non-destructive means to evaluate the stiffness of the ground materials, which is crucial for understanding soil behaviour under loading conditions. The shear modulus is a measure of the material's ability to resist shear deformation – it is especially important in the analysis and design of foundations, retaining structures, and slopes, as well as in the assessment of seismic site response.

Adapted ANT data acquisition involves the setting out of seismic sensors over a 2D surface grid that are sensitive to and can record low frequency ambient noise down to a frequency of 1 Hz over a period from days to weeks. The number of sensors can vary between a few hundred to several thousand as a function of the investigation objective. The ambient field can also be augmented using an active seismic source (such as a sledgehammer, small vibrating source or weight drop) that can sometimes provide higher frequency signals to improve near-surface information.

Ambient noise tomography data processing involves a number of key steps. The first processing step uses seismic interferometry (Curtis et al., 2006), a data-driven method that reorganizes recorded ambient seismic noise into interpretable seismic signals. This method cross-correlates a reference station with all other stations to obtain correlation Green's functions (CGFs) that are organized into virtual source gathers. When stacked over a relatively long amount of time (active seismic surveys typically record a few seconds after each shot, but passive seismic surveys typically record for days or weeks that are correlated and stacked per hour), surface waves that have been traversing the site emerge as signal whereas uncorrelated incoherent noise and transient signals stack out.

Where available, a 3D (x, y, frequency) starting model of gridded Rayleigh phase velocities is created using F-K array processing (Foti et al., 2011). For every receiver, the analysis selects the surrounding receivers and uses the arrival time differences of the surface wave fronts to obtain local phase velocities at each frequency. Otherwise the inversion grid is filled in by an average 1D phase velocity function generated by stacking individual phase dispersion spectra generated by frequency-wavenumber (F-K) or frequency-slowness transforms. The initial shear-wave velocity (V_s)-depth function is then obtained by damped Gauss-Newton (gradient-descent) inversion parameterized as a layered elastic model with variable V_s, V_p (compressional wave velocity) and layer thickness, and density fixed by an empirical relationship with V_s. A group velocity dispersion function calculated from the (smoothed) phase velocity serves as a guide function for the automatic picking of individual group dispersion functions from each virtual source gather. Group velocity is calculated as the ratio of traveltime and virtual source-receiver distance of the energy peak of the surface wave wavelet split up into narrow frequency bands. Two established methods are used to transform the time-domain correlation data for energy traveltime picking: frequency-time analysis and continuous wavelet transform. Since the two methods are sensitive to noise and transform artifacts in different ways, inverting both datasets together reduces the influence of individual mispicks. The resulting travel time picks are projected onto the inversion grid for each frequency band using travel time tomography.

The result of applying a form of ANT adapted for use at an engineering scale is a 3D (x, y, frequency) cube of group velocities. In each (x, y) grid cell, the group velocity dispersion curve is then inverted to obtain a shear wave velocity for each cell as part of a 3D shear wave velocity distribution.

4. Screening: a case study in rock, Doha, Qatar

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.

Figure 1 shows the acquisition design that was used to capture ambient seismic noise for 4 days using 349 sensors installed in 3 nested grids (red markings). A grid with 6 m sensor spacing was placed directly on top of the target area, with surrounding grids of 12 m and 24 m spacing to record the long wavelength information to ensure sufficient depth penetration. Since the site is located in a relatively quiet area (in contrast to a city or industrial environment), there were concerns regarding the retrieval of higher frequency surface waves that are needed to resolve the near-surface. To ensure sufficient resolution in the near surface, the passive recording phase was supplemented with an active seismic survey using a weightdrop source (see Figure 1 for the shot locations in blue).

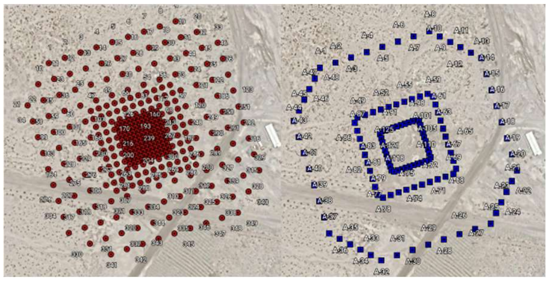

Figure 1: left) Adapted ANT acquisition design with 3 nested grids, right) active seismic design for the shot locations using a weightdrop source.

Figure 2 shows a beamforming plot (phase velocity vs. frequency) generated by stacking all (virtual) source gathers (coming from both the active and passive acquisition phase) and performing a Radon transform.

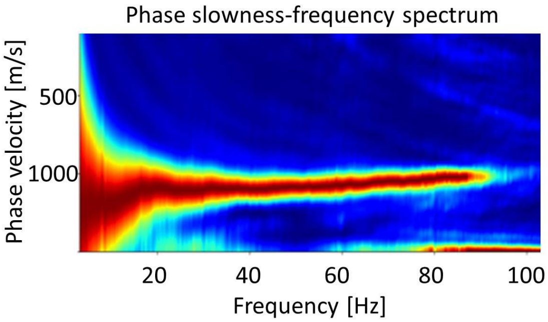

Figure 2: Beamforming plot (phase velocity in m/s (Y) vs. frequency in Hz (X)) generated from a stack of all virtual source gathers retrieved from both active and passive ANT data. The data show a very wide bandwidth to more than 90 Hz

A clear and coherent surface wavefield with a bandwidth of about 2-90 Hz 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 bgl, which significantly surpasses the depth sensitivity of conventional tools. The 3D Vs block resulting from the data processing (Figure 3) shows velocities 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.

Geotechnical measurements (PS-logging) were carried out at the same location for comparison. Figure 4 shows the comparison of the average of all PS-logging data (red line), their geological interpretation (green line), and the Vs profiles from ANT data at the logging locations (blue lines). A good match between the Vs changes in the profiles derived from the 3D ANT distribution and the geological interpretation can be observed through the black dashed lines. 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. This allows for following the medical analogy of first performing non-intrusive 3D screening before commencing with targeted intrusive investigations. 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

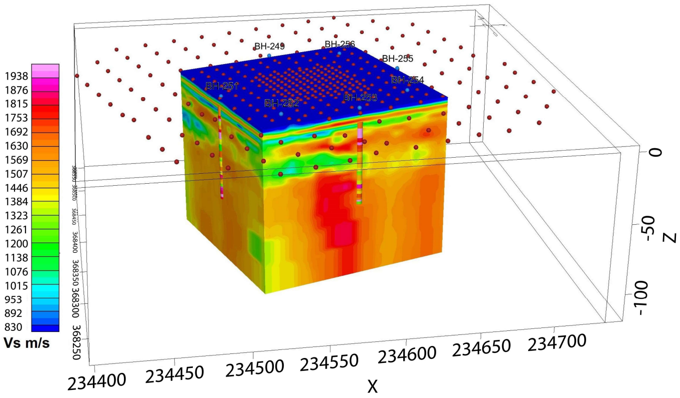

Figure 3: 3D Vs block from from the data processing of adapted ANT data. The receivers (dots) and PS-logs (vertical cylinders) are also depicted.

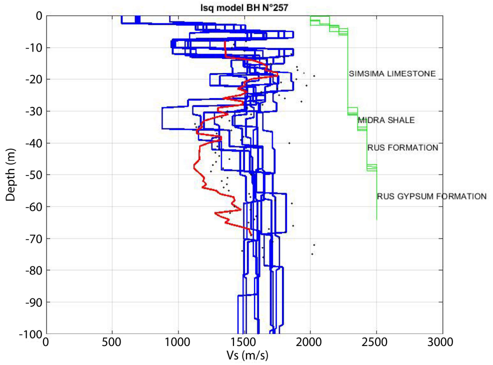

Figure 4: plot showing the average of all PS-logging values (in red), adapted ANT Vs profiles extracted at PS-logging locations (in blue) and the vertical geological units with depth (in green) based on the interpretation of borehole data.

5. Screening: a case study in soil, Nootdorp, Netherlands

For several decades, CPT (cone penetration testing) has been a key component of conventional approaches to understanding the geotechnical properties of soils across the world and to provide insights for foundation engineering. CPTs are relatively inexpensive and can deliver high resolution data albeit from a highly localised zone of the subsurface. CPTs deliver quantitative information broadly based on a measured resistance to pushing a cone into the ground at a constant rate and also to frictional forces on the cone generated by the pushing process. These physical measurements are translated to stiffness and strength properties through the use of empirical correlation formulae. Similar to downhole seismic methods in boreholes, seismic CPT investigation (sCPT) provides a direct means to measure Vs using an impulsive surface source and a pair of geophones located 0.5 m apart above the CPT cone.

A number of formulae (e.g., Mayne, Robertson et al, Kruiver et al.) relating CPT data to shear wave velocity have been developed for general, regional and lithology-specific use. These empirical methods represented a significant advancement in geotechnical engineering, providing tools for estimating shear wave velocity from CPT data without direct V_s measure measurements. By utilizing the cone resistance and friction ratio, engineers can infer the dynamic properties of the soil, critical for designing foundations and evaluating seismic response. The choice between for example Mayne's, Robertson's and Kruiver et al.'s methodologies depends on the available data, soil conditions, and the specific requirements of the project. These empirical correlations have been validated through numerous studies and are instrumental in preliminary site investigation phases, offering a cost-effective and efficient approach to understanding subsurface conditions. Furthermore, supervised machine learning techniques have been adopted for interpreting soil stratigraphy and deriving shear wave velocity from CPT data to estimate soil properties for design (Tsiaousi et al., 2018) – pointing to the future possibility of deriving CPT parameters from Vs data, albeit with resolution considerations.

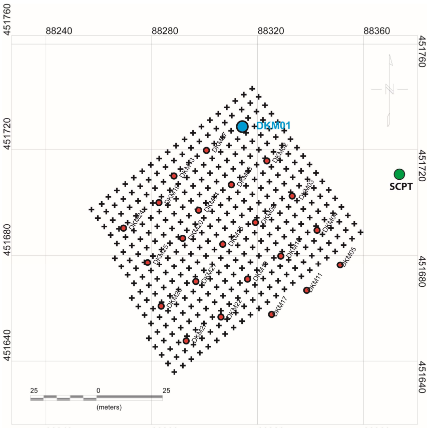

Figure 5: Adapted ANT sensor location plan: sensors (crosses), CPTs (red), reference CPT location DKM01 (blue) and sCPT location (green)

The Nootdorp case study centres around a new infrastructure development project at a level site (- 4 m elevation) for which, and typical of construction in the Netherlands, a CPT investigation was originally designed to about 35 m depth in geology comprising unconsolidated clays, underlain by sands at about -22 m elevation. CPTs would provide information around stiffness, strength, and stratigraphy to inform the foundation design process. To enable a comparison with Vs derived empirically from CPT using the formula of Kruiver et al. (2021) and directly from seismic CPT (sCPT) and Vs derived from a combined active/passive-source MASW, an adapted ANT geophysical investigation was carried out over the footprint of existing CPTs using 387 seismic sensors (vertical uniaxial accelerometers with a 1-125 Hz flat frequency response) spaced 4 m apart as a surface grid (Figure 5) with ambient surface wave data acquired over a one-week period. A 3D Vs (Vs^{ANT}) distribution was derived through interferometry, phase and group velocity analysis followed by tomographic inversion (Figure 6).

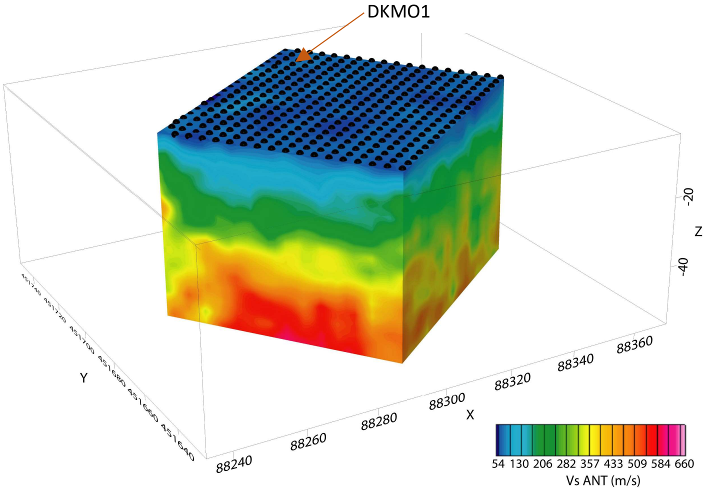

Figure 6: 3D volume of Vs to about 55 m depth derived from an adapted ambient noise tomography approach, Nootdorp, Netherlands.

Figure 7 provides a comparison between four sources of Vs from the Nootdorp site:

1. Vs derived from CPT at location DKM01 (Figure 6) using Kruiver et al. (2021) empirical correlation formula (chosen as applicable to cohesive and non-cohesive Dutch soils), Vs^{CPT}
2. Vs derived from an sCPT location offset about 50 m from DKM01, Vs^{sCPT}
3. Vs derived from active and passive MASW centred on location DKM01, Vs^{MASW}
4. Vs derived from the adapted ANT investigation at the site, Vs^{ANT} with no processing constraints or inputs provided by other data sources

The Vs^{ANT} data represent a mean of grid values within a 2 m radius of DKM01 derived from the 3D Vs^{ANT} distribution (Figure 6). The Vs^{MASW} data represent active source values to about -15 m elevation plus the addition of passive energy recorded along the 2D MASW line, adding low frequency energy for the inversion process and extending the depth of investigation to about -35 m elevation. The active and passive MASW data are shown in Figure 7.

All Vs data sources show a general increase of shear wave velocity with depth and as expected, show a scatter of Vs values for a given depth. This is no surprise given the differences in how Vs is derived i.e., directly through seismic transmission of shear waves (sCPT) or indirectly from inversion of Rayleigh waves (MASW and ANT) or empirically through CPT correlation formulae (e.g. Kruiver et al., 2021). Each data source has uncertainties, for example applicability of specific CPT correlation formulae for a particular lithology. Errors in time-picking and geometry can impact sCPT-derived velocities and initial velocity models and dispersion curve mispicks can impact Vs derived from inversion for both MASW and ANT. MASW also has strong azimuthal bias relative to ANT. There are also fundamental differences in the volume of ground sampled say between highly localised CPT measurements and the ground sampled by seismic waves using MASW, ANT and sCPT. The SCPT data were also derived from a location some 50 m from DKM01, beyond the ANT grid (Figure 5).

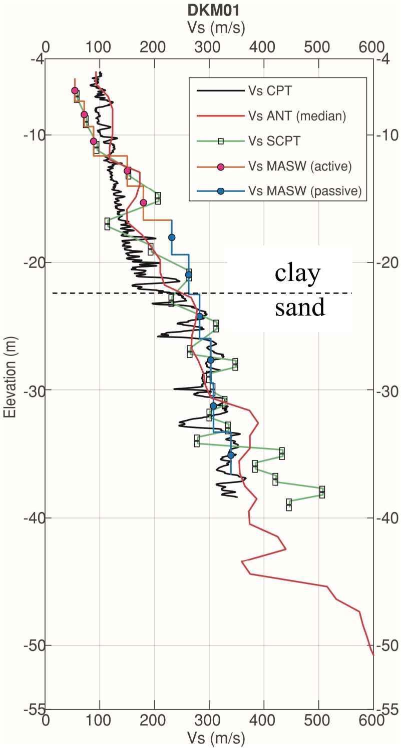

Figure 7: A comparison at location DKM01 between shear wave velocity estimates derived from i) emprical CPT correlation (Kruiver et al. (2021) formula), ii) an offset sCPT, iii) adapted ANT median Vs derived from a 2 m radius of DKM01 iv) MASW (active and passive) centred on location of offset sCPT, Nootdorp site.

A detailed comparison of the results from the different data sources is beyond the scope of this paper but the data highlight the ability of the adapted ANT approach to capture, quickly, in 3D, and at least to a reconnaissance level and down to about -33 m elevation or 30 m depth, the geotechnical characteristics of a soils environment (<750 m/s) that is comparable to existing conventional approaches. And then to extend the depth of investigation generally beyond that achievable using established geophysical methods (MASW +/- passive components) and beyond that achievable through sCPT and CPT methods. The key boundary between overlying clays and underlying sands (a potential source of pile end bearing capacity) is known to be at about -22 m elevation below the site. $Vs^{CPT/SCPT}$, Vs^{MASW} and Vs^{ANT} data show a change of response at this depth (higher Vs but lower velocity gradient below about -22 m elevation).

Between about -33 m and -38 m elevation (limitation of CPT), Vs values derived from correlation formulae were lower than those derived from sCPT and ANT and this could be due to a number of factors such as the 50 m sCPT offset or inaccuracies of applying CPT correlation formula or possibly a lack of sensitivity of ANT to a low-contrast velocity structure at depth. This requires investigation including further benchmarking of the ANT technique with other data sources capable of providing Vs to greater depths than CPT, such as PS logging in a borehole. PS logging is a further means of correlation, but this was not available at the site. Below -40 m elevation, only the ANT technique was able to provide Vs estimates for this site.

For rapid screening of sites comprising soils, an adapted 3D ANT approach as part of a screening solution applied early in the project execution phase (in this example) would provide an early means (model) to assess the variability of geotechnical properties of a site such that follow-on conventional investigation can be optimised (driving both efficiency and sufficiency – how much conventional investigation is needed?) and in turn a more representative (and far more dense) ground and geotechnical model can be built to inform and optimise the design process.

In this way the models derived from early screening initiate evolving representations of the structure and properties of the subsurface through the asset cycle. This provides the basis for a digital twin that can capture all below and above-ground characteristics for risk management during the operational life of the asset.

6. Discussion

Ground conditions beneath development sites can be geologically complex with significant changes from a design perspective occurring over relatively short distances. We know from case histories and failure back analyses that linear structures such as levees, dams, viaducts, roads etc offer suffer distress or failure locally and over limited lateral extent. Although limited in extent such failures can have catastrophic consequences, for example the 2014 Mount Polley tailings dam failure in British Columbia when failure of less than 2% of the length of the dam led to the release of over 24 million cubic metres of wastewater and tailings into a nearby creek and lake causing significant environmental damage (Morgenstern et al., 2015) The presence and likely behaviour of the stratum responsible for the dam failure had not been adequately identified or characterised in earlier subsurface investigations. Failure to identify such adverse geological features provides false confidence in the stability and safety of civil engineering structures. Safe and responsible design requires that all significant geological features below the site are appropriately identified and characterised.

Geotechnical designers have long recognised that they must design foundations and geotechnical construction based on information derived from a tiny volume of the soil and rocks beneath the site. Their main desire is to develop a three-dimensional representation of the subsurface in terms of stratigraphy and engineering properties to allow the design of geotechnical construction for all areas of the site. They use engineering judgement to develop subsurface models by interpolation based on 'sticks' of geotechnical data (boreholes, CPTs, etc) and occasionally 'slices' (geophysics such as electrical resistivity tomography, seismic refraction etc.), but recognise that these models are sparse, i.e., mainly empty of data. Accordingly, good practice requires that construction specifications and acceptance criteria are developed to confirm design assumptions and amend designs when encountered ground conditions are different to those assumed. Whilst this approach goes far to assure public safety it can lead to schedule delays and increased costs that have contributed to more than half a century of underperformance in capital works projects (Flyvbjerg et al., 2004). Cost overrun appears downstream of cost underestimation and cost underestimation (say at the feasibility or planning stage of a development) is a consequence of human bias as a root cause (Flyvbjerg et al., 2018). Screening reduces epistemic uncertainty relating to the subsurface, so we see screening as a mechanism to provide early insights around geo-risk as one means to possibly manage that element of human bias that arises from a lack of information, data, or knowledge.

The three-dimensional screening technique described in this paper, adapted ambient noise tomography, an example of a significant and scalable screening solution component, defines a new paradigm in the development of subsurface models whereby a 'block' of data is generated containing both stratigraphic and engineering parameters at a spatial resolution sufficient for the optimisation of engineering design. Scaling of geophysical techniques to larger sites can be a challenge, and normally larger sites require either more resources and/or more time. One significant advantage of the adapted ANT technique is that the time required to capture the ambient noise field is largely independent of site size. More surface sensors are required for larger sites but setting-out of sensors is generally much shorter than the time require for recording and miniaturisation of sensor technology is likely far from complete meaning easier field logistics in the future. Another advantage of passive 3D seismic approaches over 2D approaches is data redundancy – with N surface sensors the number of data pairs scales up approximately as N^2 and so this should lead, all other factors being equal, to reduced uncertainty in 3D approaches such as ANT over 2D approaches such as passive ReMi (Louie, 2001) and active MASW (Park et al., 1999).

As with other geophysical techniques, limitations such as spatial resolution and sensitivity to subsurface velocity changes and complex surface topography must be well understood as to build confidence in any geotechnical screening approach. Ambient noise tomography (with or without active source components), as an example of an effective screening solution component can exceed the depth penetration of most conventional geophysical methods (for example, MASW) by providing screening down to 100 m or more in faster strata, which is sufficient for the very deepest foundation and for most subsurface excavations in infrastructure development. In slower strata (say Vs< 300 m/s) very low frequencies will need to be recorded in the ambient wavefield, possibly requiring longer 'listening time' to investigate to similar depths and the understanding of the sensitivity of dispersion curves to velocity changes at such depths requires more investigation. Increased use of, for example, Monte Carlo simulation methods could also provide better estimations of statistical uncertainty in velocity estimation derived from ANT and similar surface wave methods – meaning that in the future we could see geophysical parameters presented as probability distributions that could be ingested into reliability based design methods.

Carefully targeted intrusive investigation to calibrate the model will reveal the range of parameters present for the site relevant for design. Careful correlation of the high-resolution subsurface model obtained from the geophysical screening with the relevant design parameters, noting that shear stiffness on a site-by-site and empirical basis can be a good proxy for many engineering design parameters allows micro-zonation of the site for foundation design. Future advances in machine learning and Artificial Intelligence will only increase the value of three-dimensional screening of shear stiffness. The accelerating development of cloud computing will also drive data throughput to enable rapid delivery of better subsurface representation in the form of digital models readily ingestible into geotechnical design software, particularly as sensor count increases with sensor miniaturisation and ease of mobilisation and data volume increases with greater adoption of techniques such as ANT at an engineering scale.

All geotechnical design methods are essentially reliability based and statistically will deliver higher than intended factors of safety, i.e., will overengineer the solution for the majority of sites. Once ground conditions on a site are known with greater fidelity it becomes more worthwhile to perform site specific calibration of design methods using semi-full-scale or full-scale foundation testing.

Often capital works projects during their early feasibility stages consider alternative site locations, route alignments and plot plan layouts. Ranking of alternatives often takes place based on more factors than subsurface conditions. At the earliest stages of a project, it is often challenging to accomplish permitting for an intrusive investigation and cost considerations make these investigations so limited in scope that they might misinform risks either positively or negatively. Light-footprint, three-dimensional subsurface screening as described here will often provide sufficient information for multi factor ranking assessments and site optioneering in a more time and cost-effective way than intrusive investigation. It also opens the possibility of performing intrusive investigation in the more accessible areas of a site to provide correlating information.

Screening offers a small footprint with low-permitting requirements and an environmentally friendly, socially responsible, and low-risk means to obtain early subsurface characterisation, optimising and targeting subsequent conventional site investigation activities. This approach translates to increased value generation per borehole, CPT, in situ test, and laboratory analysis. The broader acceptance of early screening approaches within a hybrid framework could be facilitated by revising engineering design codes and guidance.

7. Conclusion

Screening requires front-end loading of effort 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 or post-FID context, screening enables an initial, reconnaissance-level assessment of subsurface risk.

A screening solution including adapted ambient noise tomography that provides high spatial resolution of subsurface conditions at an engineering scale portends a new paradigm in the management of geotechnical risk for capital works developments and projects. 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 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 cost underestimation.

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 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.

The industry is encouraged to promptly incorporate the screening philosophy into feasibility and planning activities and into design codes for geotechnical design and construction.

Acknowledgements

The authors are very grateful for the technical support of Dr Moritz Fliedner, Teus van Dam, Dr Francois Janod, Dr Alexandre Boleve, Dr Stephane Sol and Nico Parasie and for their significant contributions to Fugro's geotechnical and geophysical innovation programmes. We are grateful to Stantec for permission to publish the Wakrah Pumping Station case study and for the comments of an anonymous reviewer.

References

Bonnefoy-Claudet, S., Cotton, F., & Bard, P. Y. 2006. The nature of noise wavefield and its applications for site effects studies: A literature review. *Earth-Science Reviews*, *79*(3-4), 205-227.

Clayton, C.R.I. 2001. Managing Geotechnical Risk: Improving Productivity in UK Building and Construction. Thomas Telford, London

Curtis, A., Gerstoft, P., Sato, H., Snieder, R., & Wapenaar, K. 2006. Seismic interferometry—Turning noise into signal. *The Leading Edge*, *25*(9), 1082-1092.

Foti, S., Parolai, S., Albarello, D., & Picozzi, M. 2011. Application of surface-wave methods for seismic site characterization. *Surveys in geophysics*, *32*, 777-825.

Flyvbjerg, Bent, Holm, Mette K. Skamris, Buhl, Søren L., 2004. What causes cost overrun in transport infrastructure projects? Transp. Rev. 24 (1), 3–18.

Flyvbjerg, B., Ansar, A., Budzier, A., Buhl, S., Cantarelli, C., Garbuio, M., Glenting, C., Holm, M. S., Lovallo, D., Lunn, D., Molin, E., Rønnest, A., Stewart, A., & van Wee, B. 2018. Five things you should know about cost overrun. Transportation Research Part A: Policy and Practice, 118, 174-190. https://doi.org/10.1016/j.tra.2018.07.013

Kruiver, Pauline & Lange, Ger & Kloosterman, Fred & Korff, Mandy & van Elk, Jan & Doornhof, Dirk. (2021). Rigorous test of the performance of shear-wave velocity correlations derived from CPT soundings: A case study for Groningen, the Netherlands. Soil Dynamics and Earthquake Engineering. 140. 106471. 10.1016/j.soildyn.2020.106471

Louie, J. N. 2001. Faster, better: shear-wave velocity to 100 meters depth from refraction microtremor arrays, Bull. Seism. Soc. Am., 91, 347–364.

Morgenstern, N., Van Zyl, D. and Vick, S.G., 2015. Independent expert engineering investigation and review panel. *Report on Mount Polley Tailings Storage Facility Breach*.

Park, C. B., R. D. Miller, and J. Xia. 1999. Multichannel analysis of surface waves, Geophysics, 64, 800–808.

Picozzi, M., Parolai, S., Bindi, D., & Strollo, A. 2009. Characterization of shallow geology by high-frequency seismic noise tomography. *Geophysical Journal International*, *176*(1), 164-174.

Shapiro N.M. Campillo M. Stehly L. Ritzwoller M.H. , 2005. High resolution surface wave tomography from ambient seismic noise, Science, 307, 1615–1618.

Tsiaousi, D. Travasarou, T., Drosos, V., Ugalde J., and Chacko, J. 2018. Earthquake Engineering and Soil Dynamics Machine learning applications for site characterization based on CPT data.

Wapenaar, K., Draganov, D., Snieder, R., Campman, X., & Verdel, A. 2010. Tutorial on seismic interferometry: Part 1—Basic principles and applications. *Geophysics*, *75*(5), 75A195-75A209.

Wood, R.W. 2021, Integrating recent advances in industry site characterisation capabilities to improve foreseeability in sub-surface conditions for capital works projects, 6th International Conference on Geotechnical and Geophysical Site Characterisation, Budapest.

Yamanaka, H., Takemura, M., Ishida, H., & Niwa, M. 1994. Characteristics of long period microtremors and their applicability in exploration of deep sedimentary layers. Bulletin of the Seismological Society of America, 84(6), 1831-1841