Integrating recent advances in industry site characterization capabilities to improve foreseeability in sub-surface conditions for capital works projects

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ABSTRACT: Unforeseen conditions represent a significant risk to the delivery of major civil engineering and building projects often leading to overruns in cost and time. This paper examines the importance of a managed approach to reducing site characterization uncertainty and summarizes recent advances in the tools and techniques available to the geotechnical engineering industry to optimally plan and execute site characterization programs to the benefit of the key project stakeholders, namely owners/developers, designers and constructors. Recent developments in remote sensing, geophysical surveying, in-situ probing, continuous soil coring and geodata management are described.

Keywords: ground risk; geophysics; cpt; permeameters; geodata management

1. Introduction

For owners and developers of civil engineering and building projects, the subsurface conditions are merely a hindrance to them achieving their overall business objectives, be these more financial (rate of return) in the private sector or societal benefit for public agencies. The geotechnical designer's role is to minimize such hindrance whilst simultaneously delivering value for money in terms of effort (cost and time) for the geotechnical construction activities associated with the project.

Much of a construction project's risk lies within the subsurface and effective characterization of spatial and behavioral variability of the soils and rocks within the zone of influence of the project construction is essential for successful management of ground risk. Unforeseen rather than genuinely unforeseeable subsurface conditions often cause significant project cost overruns and delays to completion.

Studies conducted in the 1990s [1] for highways projects showed a positive correlation between project cost overrun and money saved on site characterization and at the typical levels of overall project spend on site characterization (~1% of total project cost), cost overruns of 20% of total project cost were not unusual. Increasing the amount invested in site characterization modestly to say 2% of overall project cost was shown to be effective in significantly reducing project cost overrun and clearly therefore the return on incremental investment of additional characterization effort is considerable.

Clayton [2] identified soil stratigraphy, soil behavior and ground water uncertainty as prominent components of foreseeability of project conditions and hence key contributors to project time and cost overruns. Since the work of the 1990s several studies [3-6] have confirmed the general relationship between effort devoted to site characterization and project overrun.

Studies of project economics and final outturn cost and schedule [7] indicate that major capital works project cost and schedule overrun continue to plague the civil engineering industry today, despite significant positive developments in overall procurement and contracting strategy.

2. The Costs of Geotechnical Uncertainty

Geotechnical site data are used by two distinct groups of stakeholders in the capital projects development process. It is important that the site characterization effort is appropriately scoped to fully meet the needs of both.

Most obviously, geotechnical designers need data to design the envisaged geotechnical construction. Sometimes less well served or even overlooked are the construction estimators who price the construction of the design. Uncertainty in site characterisation data drives project outturn cost in each of these two groups. When designers perceive increased uncertainty, they are generally more conservative in their design, leading to heavier construction, potential overengineering and increased construction cost. Estimators translate uncertainty into more cautious productivity estimates, increased time of resources on site and contingency items and hence increased bid prices for project owners to pay.

Geotechnical designers seek to manage uncertainties presented not only by the variability of subsurface conditions but also the uncertainties in how the subsurface materials respond and behave under the forces applied by the proposed development. Within our industry our design methods are largely reliability-based seeking to prevent failure in an acceptably large majority of instances. This approach whilst responsible and prudent, when uncalibrated for site specific conditions, generally assures overengineering of actual geotechnical construction, that is actual factors of safety achieved in construction often exceed, sometimes significantly those expected at the time of design. The cost of geotechnical construction significantly exceeds the cost of site characterisation and geotechnical design usually by a factor of 30x or much greater. This gearing means that small incremental investments in site characterization often generate a large return in terms of construction cost savings.

Site specific calibration of design methods, for example for drilled shafts have often documented construction cost savings of 20% or more [8]. Site specific calibration of geotechnical design methods is of greatest value when the variation of subsurface conditions across the site is well known.

Effective reduction of geotechnical uncertainty results in better value for money for the construction phase and increased certainty of project delivery outcomes. These two elements are seen by many as a trade off, but with effective site characterisation and planning they can be simultaneously achieved with the distinct business benefits for project stakeholders as summarised in Table 1

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Table 1: Project Stakeholder Business Benefits from well scoped and executed site characterisation

Stakeholder	**Business Benefit**	**Description**
Owner/Developer	Reduced Cost	Reduced ‘over-engineering’ of geotechnical design leading to lighter construction that is cheaper to build
Designer	Reduced Professional Risk Exposure	Reduced situations of missed subsurface variability that lead to reduced asset performance and claims in negligence
Owner	Risk Transfer	Management of geotechnical construction risk can be transferred to the Constructor (arguably the party best qualified to manage this risk) without the inclusion of exorbitant risk premiums in bid prices
Owner	Improved Outturn Cost/Schedule Certainty	Unforeseen subsurface conditions are minimised leading to the reduction/elimination of Constructor claims for time and money
Constructor	Reduced Commercial Risk	Projects are won at the ‘right price for the job’ sustaining constructors within the industry

3. Scoping Site Characterization Programs to Minimize Uncertainty

All too often in our industry, site characterisation programmes are scoped using only drilled and sampled boreholes, laid out uniformly by reference to the geometric footprint of the construction project. Such an approach does not take advantage of the many available proven techniques (such as geophysical survey and in-situ probing) to better characterise the subsurface and may miss significant subsurface features that are not penetrated by the sampled drillholes.

Construction industry economics and time scales mean that even the best ground investigations will only physically examine a miniscule proportion of the subsurface. Accordingly, a well scoped site characterisation study should first seek to identify the overall subsurface structure of the site and all features of geotechnical significance for the design, construction, and performance of the proposed development.

Such initial site screening (perhaps using geophysical techniques) is then used to better locate (or target) any intrusive investigation activity to confirm stratigraphy and its variability and provide engineering design and constructability parameters for the subsurface materials. It is of great value if any initial site screening techniques can also provide constraint of the interpolation of stratigraphic boundaries between intrusive investigation points. This integrated approach, by creating a high-fidelity representation of the subsurface conditions will often allow a more cost and time efficient and focussed programme of laboratory testing to best define engineering properties of the subsurface materials.

4. Recent Advances in Remote Sensing

Remote sensing from space using satellites has advanced greatly in recent years. Interferometric Synthetic Aperture Radar (InSAR) measurements can be used to monitor displacements of the earth’s surface and structures built upon it [9]. Advanced analytical techniques allow measurement of movements with millimetric precision. Synthetic aperture radargrams started to be collected in the 1990s and since that time coverage of the earth’s surface and the frequency of measurements have increased such that radargrams can now be obtained every few days over the same area. The library of radar images that exists provides a unique opportunity for the geotechnical engineer to look back in time to see how a structure (particularly earthen structures) might have experienced deformation over time. Essentially linear earthen structures (levees, dams, embankments) suffer distress locally due to conditions that are limited in spatial extent.

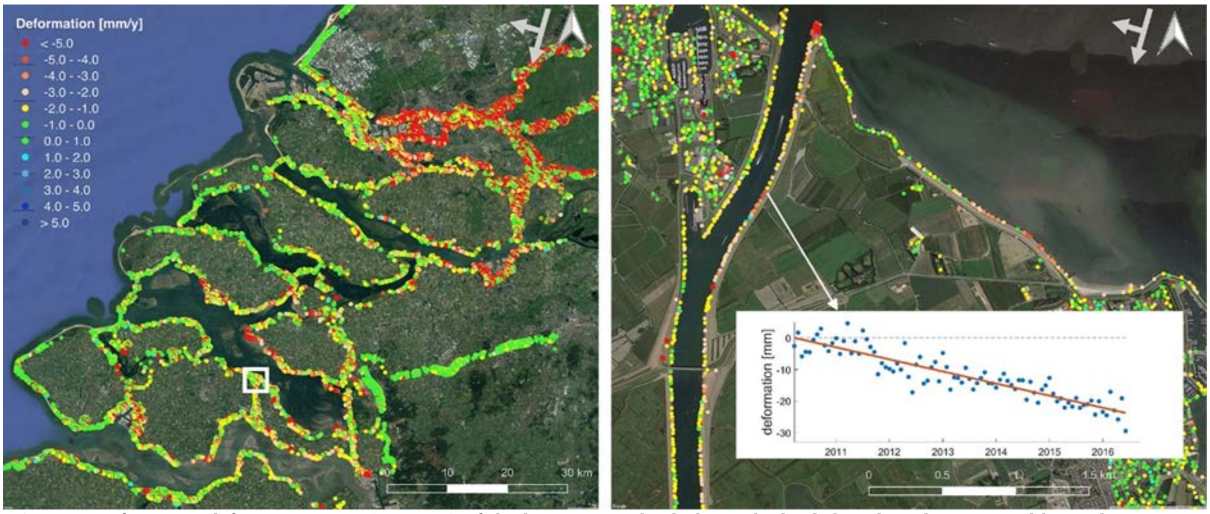

Figure 1. Left: Linear deformation rates (mm/year) of the levees in Zeeland, the Netherlands based on data acquired by RadarSAT-2, descending (2010–2017). Right: An example of deformation time-series with a linear velocity of 4.1 mm/year Özer et al 2018 [9]

InSAR analyses can now be undertaken quickly and inexpensively by any number of specialist service providers and any engineer contemplating, for example, reanalysis of a long levee structure would be advised to consider InSAR analysis (Figure 1) to identify any more critical sections of the structure to more effectively target subsequent field investigation.

5. Recent Advances in Geophysics

Conventional intrusive investigation methods (probings, sampled borings) and wireline logging methods produce 'sticks' of data within the subsurface volume. Whilst cone penetration tests (CPTs) for example provide continuous data along the 'stick'; sample boreholes, unless sampled continuously, require vertical interpolation between sampling locations to develop the subsurface profile. Most surface geophysics methods applied in the near surface produce either 2-D 'slices' that can be interpolated to 3D, or, infrequently, true 3-D representations of the subsurface. Early geophysical survey with appropriate techniques for the site provides valuable insights into the overall geological structure and geotechnical conditions beneath the site allowing subsequent intrusive investigation to be targeted in such a way as to characterize the full range of subsurface stratigraphy and conditions, significantly improving foreseeability of those conditions.

5.1. Passive Seismic Techniques

Non-intrusive 3D passive seismic tomography provides a light touch, low footprint means to obtain general subsurface stratigraphy and stiffness variations in complex urban locations where traditional geophysical methods are less successful. The Surface Wave Ambient Noise Seismology (SWANS) system [10] captures ambient ground vibration signals that are ever present in urban environments (such as those from transportation sources and industrial processes) with minimal environmental and community impact. Many small receivers (typically 100 to 1000+) are set out across the site, typically 5 meters to 50 meters apart and are left unattended for a few days to record the ambient seismic waves. Propagation of the ambient seismic waves is influenced by subsurface properties, particularly the shear modulus at small strains, and the recorded signals are analyzed to produce a dense 3D seismic velocity representation of the subsurface (Figure 2) typically to depths of 100 meters or more.

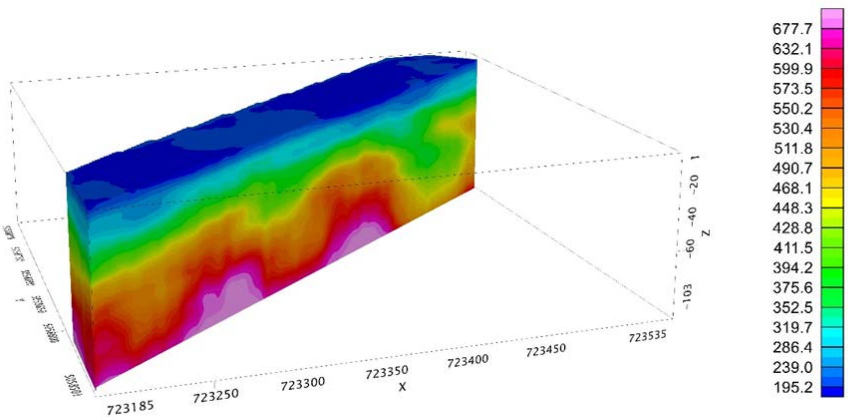

Figure 2. Passive seismic technologies such as Fugro's SWANS system derive 3D distributions of shear wave velocity (in m/s) that can be used to manage subsurface risk through inference of small-strain geotechnical conditions, stratigraphy and structure in otherwise noisy locations such as industrial and urban environments. Data example courtesy of Fugro.

5.2. Three Component (3C) Active Source Broadband Seismic Techniques

Seismic imaging using broadband three- component (3C) receivers [11] is a recent industry advance to overcome many of the challenges of using seismic methods in the near surface to inform civil engineering design and risk mitigation decisions.

The technique uses the latest generation of MEMS (Micro Electro Mechanical Systems) receiver technology (Figure 3) that provides a flat linear response across the complete seismic frequency spectrum delivering measurement fidelity advantages at low frequency for surface wave investigation and deeper reflection imaging and at high frequencies to avoid spurious noise for high resolution near surface imaging.

Figure 3. Modern compact sensors such as Sercel's DSU3-428 3-component broadband MEMS seismic sensor mean that much larger data volumes can be acquired efficiently in a single pass, simultaneously targeting geotechnical properties and structure.

During a single field data acquisition pass, measurements suitable for seismic reflection, seismic refraction and surface wave (MASW) analyses are obtained typically resulting in a 30% reduction in fieldwork schedules and lower data acquisition costs.

3C acquisition produces larger data volumes in less time compared to more traditional approaches providing higher interpretational confidence and more effective planning, scoping and targeting of follow on intrusive programmes.

5.3. Borehole Magnetic Resonance

Determining hydrogeological properties of the subsurface in a time and cost-effective way in boreholes has been challenging due the need to deploy hazardous radioactive sources or to carry out relatively slow and expensive borehole pumping tests. Originating in the 1950s and first adopted by the medical sector in the 1970s and well known to many through magnetic resonance imaging or MRI, nuclear magnetic resonance or NMR has recently been adapted for wireline borehole logging in the geoscience sector. The technique is well established in the resource exploration sector but has only recently been applied in civil engineering.

Magnetic resonance surveys effectively map porosity and permeability and can distinguish, by analysis of the measured data, between mobile, capillary-bound and clay-bound water (Figure 4).

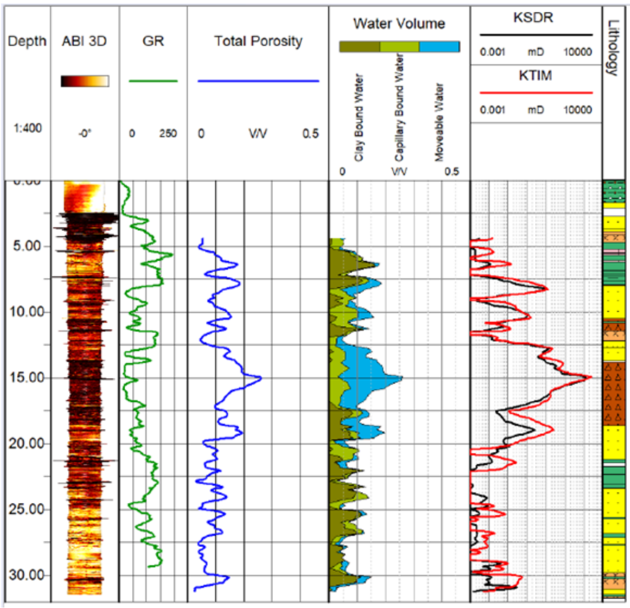

Figure 4. Downhole magnetic resonance (DMR) yields in-situ estimates of porosity, permeability and bound/moveable water that can be combined with other wireline logging data in composite logs to inform interpretation and provide better characterisation of the borehole environment and its associated risks (Rigler, 2018).

The downhole sensor operates at several frequencies to investigate concentric shells around the borehole to provide evaluation of in-situ conditions outside the zone of drilling disturbance.

Magnetic resonance measurements are particularly helpful for reducing ground risk associated with tunneling projects [12]. When used in conjunction with a carefully selected programme of in-situ permeability measurements, project uncertainty can be greatly reduced.

5.4. Looking Ahead

Advances in acquisition hardware including drone-based surveys, cloud-based data processing focused on capturing and deriving insights from more spatially dense data, data analytics and the migration of technological advances from seismology and hydrocarbon exploration will positively impact most sub-disciplines within the broader field of near-surface geophysics in the near future.

Developments of interferometric seismic surface wave methods will likely result in full 3D seismic wavefield capture and 3D imaging deliverables within the next few years, in addition to the current practice of deriving geophysical parameters through inversion. Optimised algorithms will soon allow processing of 2D surface wave seismic profiling data in near real time (real time seismic scanning) to provide rapid subsurface insights only previously available with ground penetrating radar technologies. Overall, seismic sensors will become much smaller allowing for more lightweight, lower impact field operations and dense spatial sampling and higher fidelity deliverables.

The near surface is frequently inherently complex, and this is sometime reflected in the complexity of near-surface geophysical data. Interpreting such complex responses remains a challenge but geophysical interpretation is starting to benefit from the application of machine learning in, for example, the identification of subsurface structures in GPR data – a trend likely to continue in parallel with AI advances across many other technical disciplines.

Communication and visualisation of insights from near-surface geophysical and other geo-data to manage ground risks will be facilitated by powerful 3D implicit modelling software developed within the mining and exploration sectors and migrated to near-surface infrastructure applications. This will allow not just the visualisation of 3D data volumes but the ability (through ground information modelling or GIM) to build robust, integrated digital subsurface representations during the early phase of the asset cycle. This should mean earlier characterisation of ground variability and earlier identification of key risks. Through better visualisation, such insights can be made available to key stakeholders at a time in the asset cycle when the cost of project changes are relatively low and the opportunity to positively influence project outcomes, through better risk management afforded by modern near surface geophysics, is high.

6. Recent Advances in In-Situ Testing

6.1. Cone Penetration Testing (CPT)

One of the challenges for the effectiveness of cone penetration testing is the ability to perform the test below the refusal depth of penetration using surface push systems. Refusal of the cone test is generally caused by either accumulated friction on the test string or end bearing refusal in a dense layer (sometimes causing the risk of buckling of the test string in weak layers near the surface). The offshore industry has driven many advances in cone penetration testing and two of these are now available for use in land site investigation.

6.1.1. *Downhole CPT*

The downhole CPT is a short stroke (often 1.5m) CPT unit deployed by wireline to latch into the bottom assembly of the drillstring with the test performed through the drill bit into the soil at the base of the borehole [13]. Such systems have been used offshore since the 70s and are highly effective for performing cone penetration tests below hard/dense strata causing refusal for surface push systems. A challenge for typical land drilling rigs is the maximum reaction that can be mobilized and in dense or very stiff strata insufficient reaction can limit the penetration that is achieved. The Deep Line system (Figure 5) recently developed by Fugro overcomes this by using a separate crawler machine to deploy the wireline CPT which can be mechanically coupled to the drillstring increasing the effective reaction beyond the 10-ton thrust capacity of the downhole CPT system. A 1.5m long CPT (Figure 6) from the base of the borehole provides excellent soils information and overcomes all the disadvantages of the Standard Penetration Test (SPT) such as energy losses in deep tests and disturbance at the base of the borehole affecting the results.

Figure 5. The Deep Line wireline CPT rig. Photograph courtesy of Fugro.

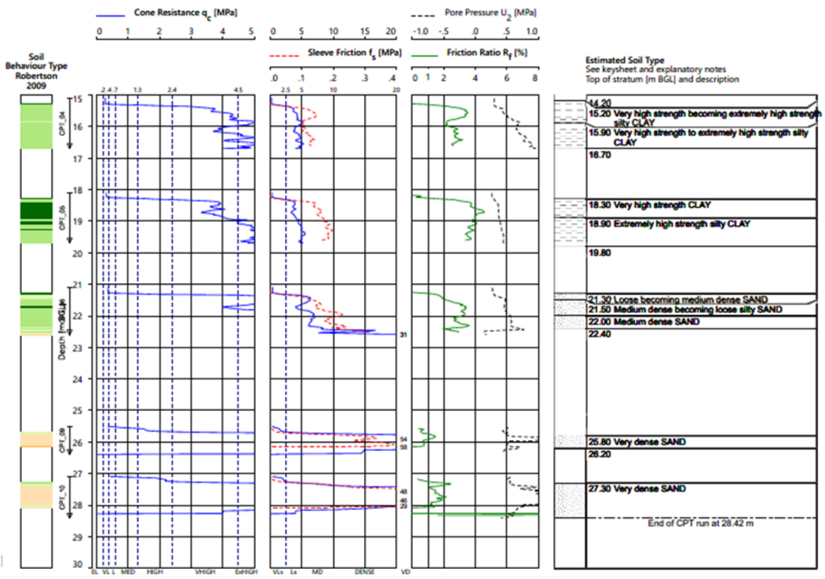

Figure 6. Typical Wireline CPT results at Various Depths in a Borehole (data courtesy of Fugro)

6.1.2. Continuous Penetration Systems

Most CPT systems used in land site investigation utilise short, one-metre-long test rods that are added as the test progresses. Most jacking systems are discontinuous, meaning that at the end of a one-metre-long push stroke, cone penetration is paused whilst the jacking system returns to the start of the stroke and the next rod is added, thus the cone penetration test is conducted in a series of one metre discrete pushes. Stress relaxation inevitably occurs at the end of each stroke to the potential detriment of the quality of the test result. A strong interest in the identification of thin drainage layers in the offshore industry led to the development of continuous jacking systems usually based on wheels or rollers clamped at high force on the CPT test string to achieve penetration and subsequent retraction. Initially such systems continued to utilise a CPT test string made up from one-metre-long rod sections, but more recently systems have been developed that use continuous coiled tubing as the CPT test string.

The coiled tubing is stored on a spool and is straightened using precisely aligned rollers just before entering the jacking system. Advances in electronic control of hydraulic systems now means that linear jacking systems moving a pair of clamps in harmony can reliably effect continuous penetration – whilst one clamp is penetrating the test string into the ground, the other is released from the test string and is undertaking its return stroke.

Techniques to increase penetration depths in cohesive materials (high friction) have been trialled using fluid injected at low pressure behind the cone penetrometer tip to lubricate the test string/ soil interface and reduce accumulated friction. Unfortunately, conventional land-based CPT systems based on short one-metre-long push rods mean that this approach is operationally challenging and time consuming. The continuous coil provides an easy conduit for the lubricating fluid and early trials suggest that lubricating the test string can reduce accumulated test string frictions by 50%. The use of a continuous coil makes remote operation of a CPT machine much easier and avoids the need for complex rod handling systems and challenging wireless data transmission from the cone.

Fugro have recently introduced their offshore Deep Drive coiled tubing CPT system (Figure 7) to the land sector by fitting the continuous cone thrust device onto a crawler vehicle that can be operated remotely by an operator up to 1km away from the machine itself. Remote operation is beneficial when tests need to be performed in locations deemed hazardous for personnel such as tailings dams. During field trials of the land Deep Drive system in early 2021 a lubricated cone test was performed to 105 metres depth in Nootdorp, the Netherlands.

Figure 7. Deep Drive Continuous Coil CPT Rig. Photograph courtesy of Fugro

6.2. *Permeability Profiling*

Knowledge of in-situ permeability is important for the design of excavations below the water table and for the assessment of the stability and performance of water retaining/flood defence structures such as levees. Typically, permeability is determined using pumping tests in boreholes (relatively expensive and time consuming to perform) or using laboratory tests on recovered samples. Since the 1990s there has been significant research interest in developing push or drive-in probes that can be used for in-situ permeability testing [14]. Few if any of these research devices have made the transition into widespread industry use.

Due to expectations of sea level rise and more frequent extreme weather events over the coming decades, billions will be spent building and upgrading the dykes and levees that provide river and coastal flood defence. A better understanding of the behaviour of the more permeable layers that are vulnerable to underseepage and piping will likely result in the design of reliable earthen structures that are less expensive to construct.

In its simplest form the Hydraulic Profile Tool (HPT) (Figure 8) comprises an output port through which clean water is pumped at a constant flow rate from a surface reservoir, whilst the probe penetrates the subsurface. The flow rate and injection pressure are continuously monitored and recorded and the quotient of flow rate and pressure with depth provides a measure of relative permeability. The HPT can be combined with other sensors such as the standard piezocone, an electrical conductivity sensor and/or the Membrane Interface Probe [15].

Figure 8. HPT water Injection Ports above Electrical Conductivity Sensor and standard piezocone. Photograph courtesy of Fugro

When combined with the standard piezocone the instantaneous pore pressure response during penetration can be used to identify zones of higher permeability that will likely be of interest for geotechnical design. Penetration is stopped when the injection port is in such a zone and a pumping test performed to measure absolute permeability. Such pumping tests typically take around an hour to perform and operationally are comparable to the time taken to perform pore pressure dissipation tests during a CPT in clay. Pumping tests performed in the range of permeable strata in the soil profile allow formation calibration factors to be determined to provide a continuous profile of interpreted absolute permeability (Figure 9).

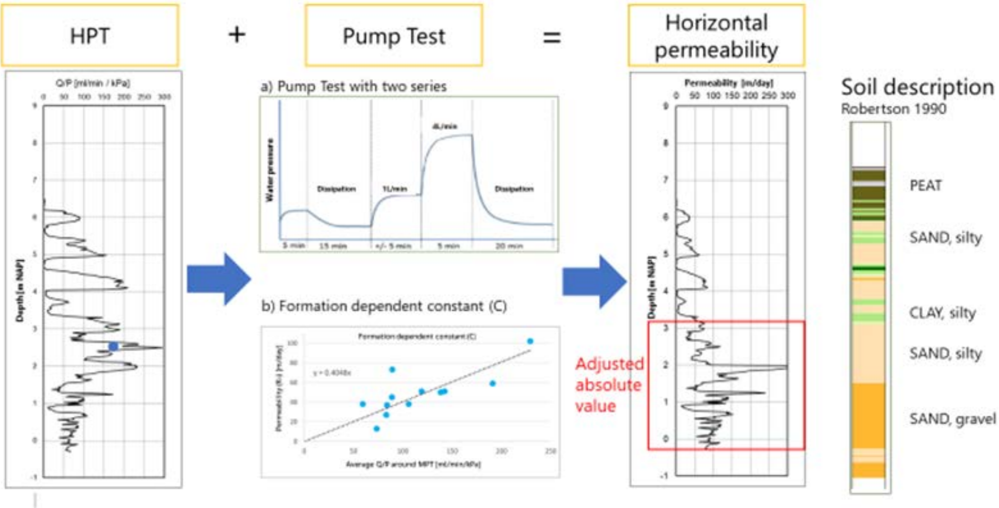

Figure 9. Typical HPT/Pump Test Results

The HPT and pumping test are now widely used in The Netherlands for the improved design of Dyke improvement projects. The better understanding of the variability of permeability beneath the dyke structure allows optimisation of the design typically resulting in reductions in the extent of seepage suppression berms and cut off structures. Such reductions are often in the order of 20% - 30% when compared with designs adopting limited permeability information [16].

7. Continuous Soil Coring

Conventionally, drilled and sampled boreholes utilize disturbed/undisturbed sampling at discrete intervals with the soil conditions in between samples needing to be inferred from the drilling behaviour as recorded on the Driller's Log. Consequently, geotechnical engineers need to interpolate vertically within boreholes as well as laterally between them. Drilling systems are now available such as Atlas Copco's Geobor S and Boart Longyear's Geo Barrel that employ triple tube core barrels to recover large diameter samples of soils whilst advancing the drill string. Drill bits with different fluid discharge configurations and spring loaded retractable cutting shoes protect looser materials from being washed away during drilling. With skilled drillers, high core recovery is obtained and recovered samples easily meet the requirements for visual description and classification testing (Figure 10).

Figure 10. Geobor S Core Sample in Boulder Clay showing cored bedrock beneath clay. Photograph courtesy of Fugro.

In stiffer materials the sample quality can be sufficient for more advanced engineering properties testing [17]. An alternative to these triple tube coring systems is sonic drilling [18] where a single tube barrel is advanced into the subsurface with a combination of rotary and high frequency vibratory action. A support casing is advanced over the core barrel before it is recovered to the surface for extrusion of the recovered material. Whilst both techniques can introduce disturbance to the sample, conventional undisturbed sampling and in-situ testing equipment can be deployed through the drill bit to recover undisturbed samples and perform SPTs.

8. Digital Transformation in Site Characterization

Digitalised workflows offer significant advantages for improving the effectiveness of site characterisation efforts. Use of ruggedised tablet computers with cell phone connections allow field logs of site conditions to be shared in near real time at the end of each working shift. The results of in-situ tests that are logged electronically can also be shared in near real time. This timely information sharing allows the Geotechnical Designer to review site data early in the field programme and modify the scope of the remaining work to ensure that the remaining data are collected optimally meet the objectives of the investigation, effectively eliminating the risk of remobilisations to site to collect data found to be missing during design evaluations. Web-based information sharing portals allow data availability to relevant project stakeholders in a more streamlined way than transmitted data point to point by email [19] and provide a means for better document revision control, more efficient data QA/QC and verification protocols.

Powerful three-dimensional modelling and visualisation software such as Leapfrog by Seequent or ArcGIS by ESRI allows large volumes of historical and recently acquired project site data to be combined and integrated into a high-fidelity representation of the subsurface conditions beneath and surrounding the site. Engineering behavioural properties are easily incorporated into the dataset allowing engineering design profiles to be synthesised anywhere within the data volume. Adding automated routines to interpolate soil conditions and properties at any point below the site allows designs to be computed at every foundation location building a much greater understanding of the project's foundation requirements.

Presenting the data visually in three dimensions (Figure 11) and the ability to easily generate relevant geological cross sections at will (Figure 12) improves the confidence of the understanding of project ground risk by both designers and construction estimators. Increased confidence in subsurface conditions inevitably leads to designs that are cheaper to construct and lower construction bid prices.

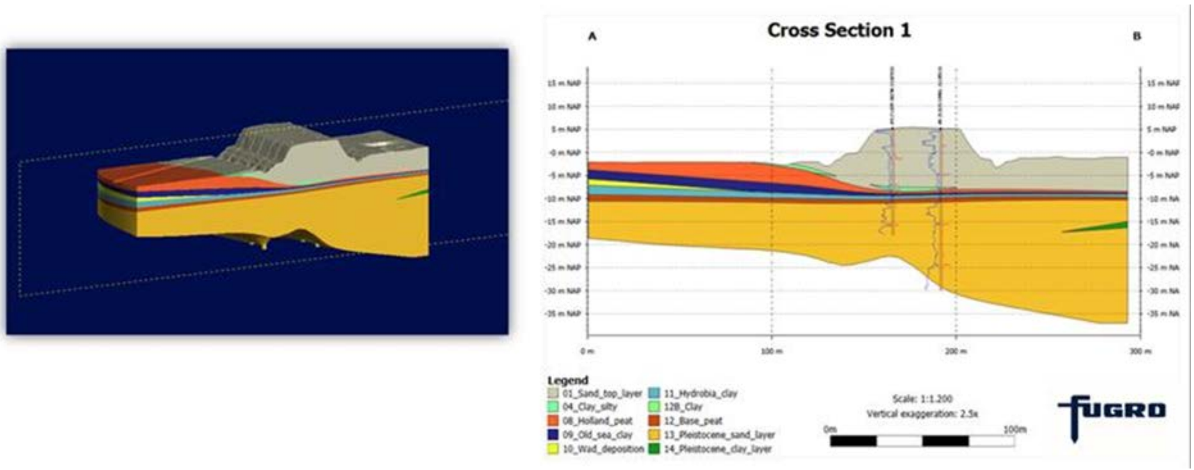

Figure 11. 3D subsurface visualization, courtesy of Fugro

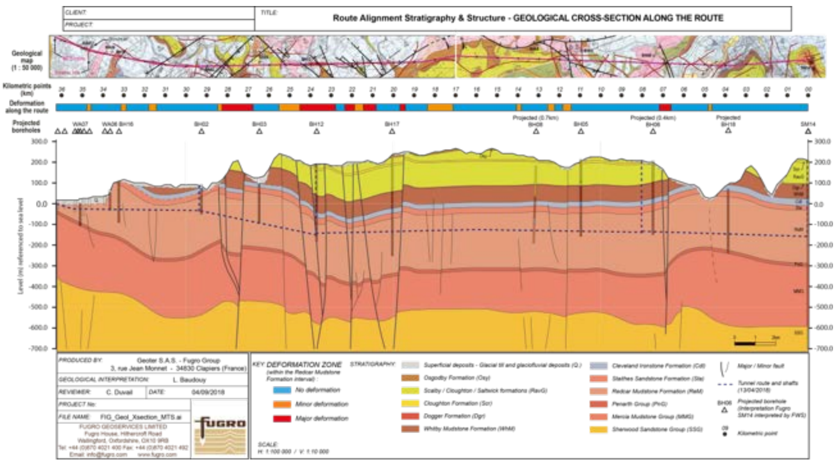

Figure 12. Geological Section, courtesy Fugro.

9. Conclusion

Much of a major civil engineering or building project's risk lies within the ground and subsurface conditions unforeseen at the time of project design can and often lead to significant cost increases and delays to completion. Adopting an approach of integrating advanced remote sensing techniques using satellite data and recently developed geophysical survey techniques will often provide valuable insights into the structure and condition of the subsurface. Such a phased approach allows follow-on intrusive investigations to be better planned in terms of spatial distribution and scope to ensure that all geological profiles significant to the project's design and construction can be properly investigated and characterized. Supported by increasingly digital workflows, a well scoped site characterization program that minimizes subsurface uncertainty should lead to the design of more economic construction; reduced construction bid premiums for constructors assuming the management of ground risk; reduced claims for unforeseen ground conditions that lead to cost increases and delay and minimized professional risk exposure for designers.

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