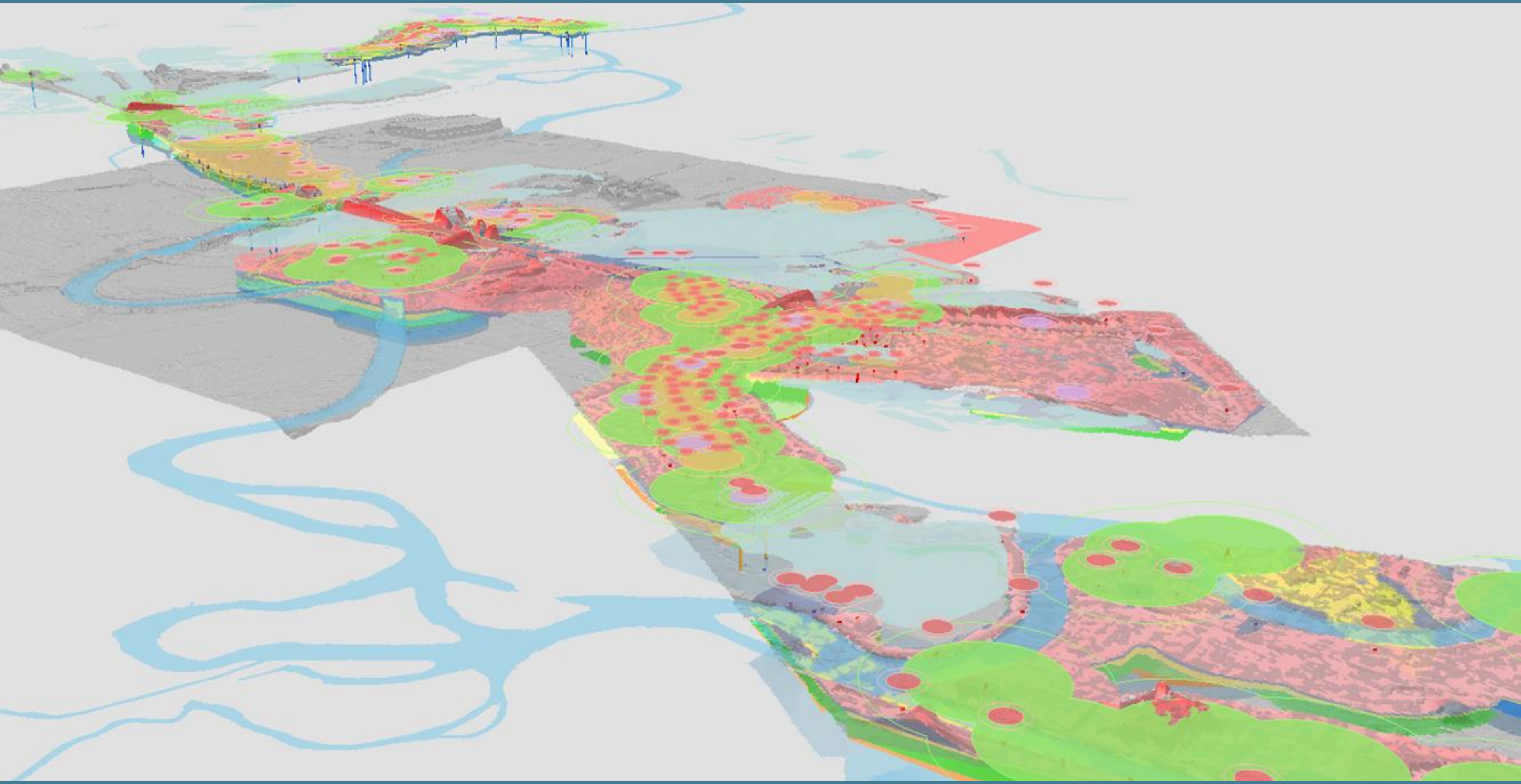
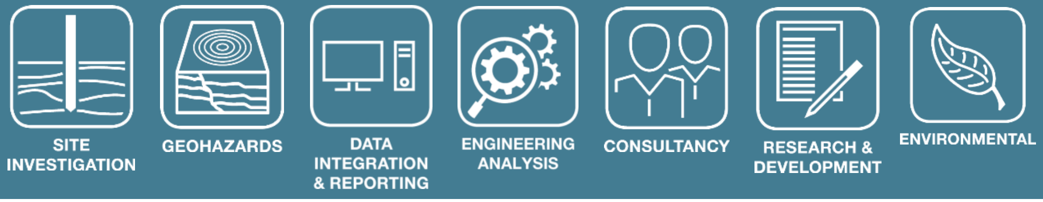
Appropriate Site Characterisation – An Integrated Approach





Why do we procure Ground Investigations?

Managing Geotechnical Uncertainty

What is an engineering ground model and what is it used for?

Types of engineering ground model

Approaches to ground model development

Dynamic Investigations: The evolving ground model

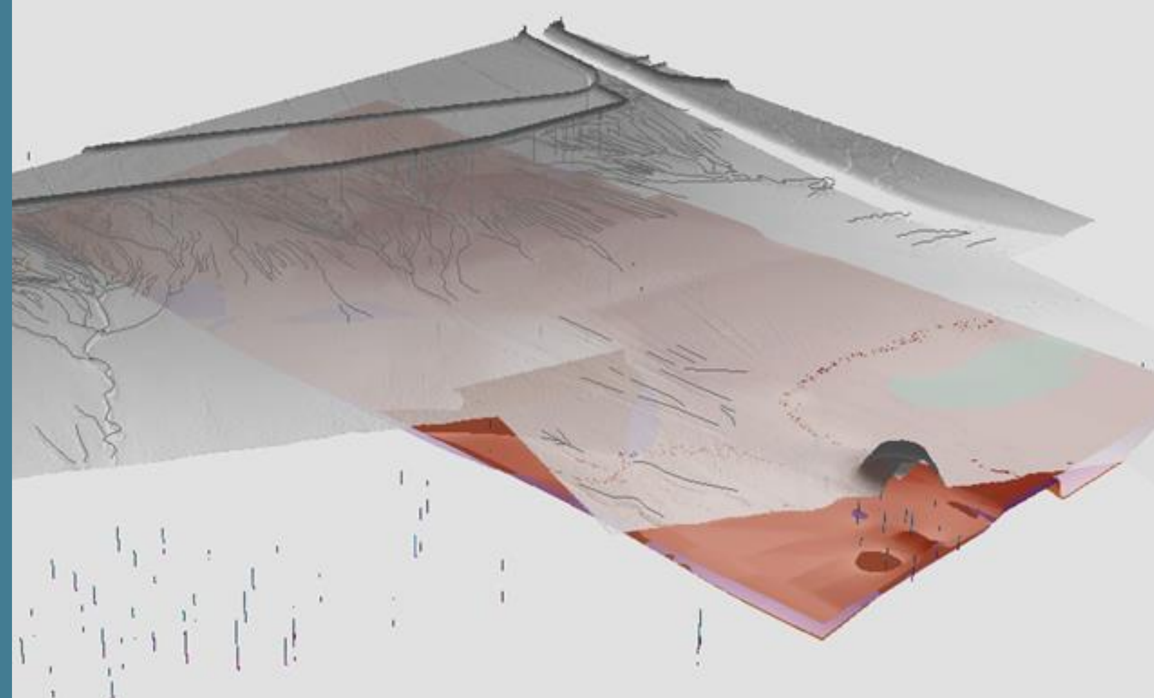
Types of data in the ground model

Issues with data integration and good practice

Uncertainty in the model

Utilisation of the model: Analysis & decision making

Case Studies



Why do we procure Ground Investigations?

Why do we procure Ground Investigations?

- We've always done some ground investigation….
- The guidance/standards say we have to….
- Planning told me to….
- It's good practice….
- I'm worried about the ground conditions at my site….
- I really want to minimise spiraling construction costs….
- I really want to minimise construction programme over-runs…..

How do we procure?

- What's the bare minimum I have to do?
- Cheapest possible bid….GI is just another commodity right?
- Quickest possible delivery….I've forgotten about the ground investigation and construction starts next week…..
- Doesn't matter….. the construction contractor will price for ground risk anyway
- With thought, patience and recognition that we need to fully understand our ground risk…..
- I realise that no two GI's are the same…..
- This isn't going to be cheap but it's worth it….

What is the biggest cause of construction cost and time overruns?

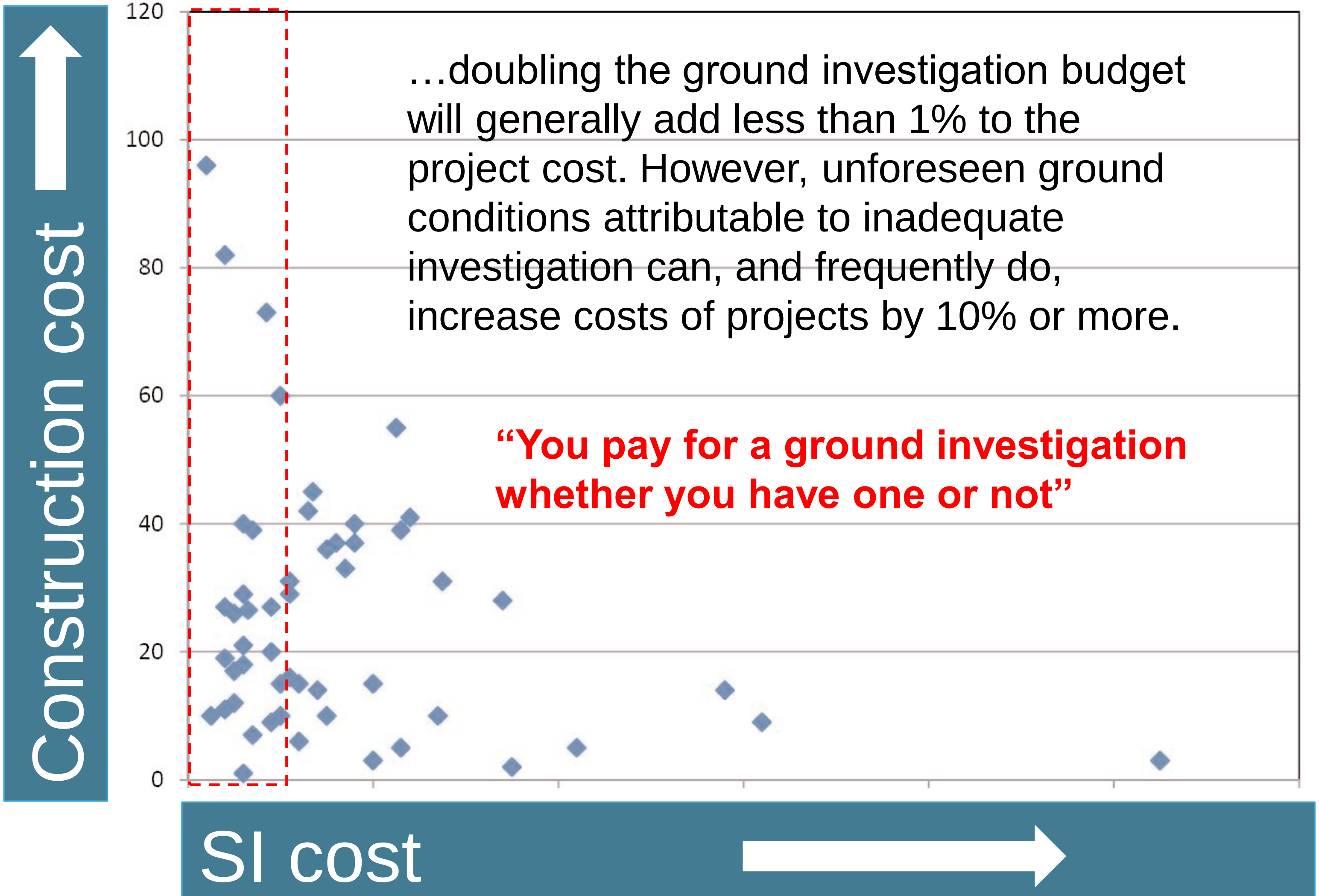
Back in 1998…

….Department of the Environment, Transport and the Regions (DETR) annual report, highlighted that the seven largest road projects were some £516 million over budget, due mainly to unforeseen ground conditions [1]. This equated to an over-spend, which accounted for a massive **63% increase** in projected expenditure [2].

1. McLellan, A., Major Roads Projects Clock Up £516m Overspend. New Civil Engineer Magazine (1998), 14October 2009, http://www.nce.co.uk/major-roads-projects-clock-up-516m-overspend/842575.article

2. Jones, M., Difficult ground: the biggest excuse in the book. large cost overruns due to insufficient site investigation still dog the construction industry. New Civil Engineer Magazine (1998), 31 October 2009,http://www.nce.co.uk/difficult-ground-the-biggest-excuse-in-the-book-large-cost-overruns-due-to-insufficient-site-investigation-still-dog-the-construction-industry-matthew-jones-asks-why/842681.article

Impact of site investigation on overrun



…doubling the ground investigation budget will generally add less than 1% to the project cost. However, unforeseen ground conditions attributable to inadequate investigation can, and frequently do, increase costs of projects by 10% or more.

“You pay for a ground investigation whether you have one or not”

Impact of Site Investigation on highway contract cost over-runs in the UK from TRL Project Report 60

Uncertainty in Geotechnical Engineering

Three broad sources:

Site Variability and Conformance Errors

Phased integrated investigations incorporating:

- Desk Study/Remote Sensing
- Geophysics – overall geological structure and targeting of intrusive work
- In-Situ Probing – continuous vertical profiling and targeting sampling
- Borehole Drilling and Sampling – improved technique, better lab testing

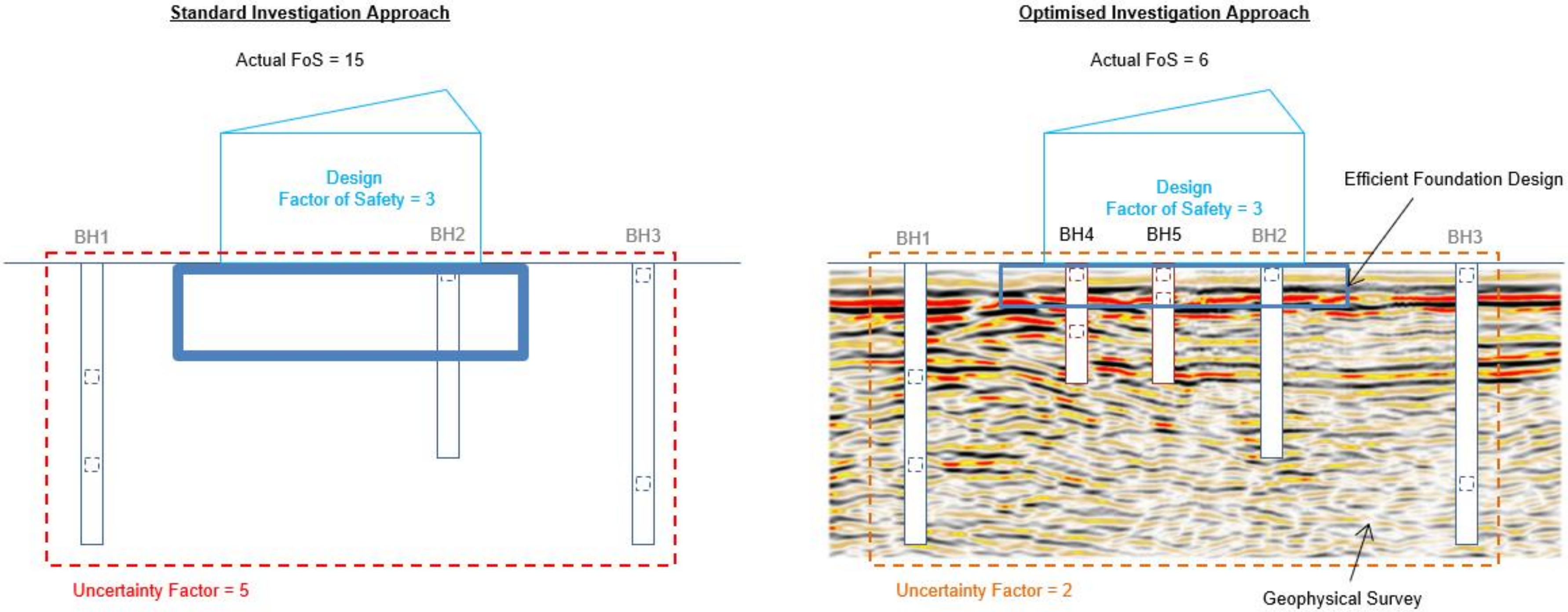
Design Method Applicability

- Code values, resistance factors/FoS, coefficients – are we over engineering (realistically are we designing to FoS of 15? When in reality this is a FoS of 3 and uncertainty factor (UF) of 5 due to conservative selection of parameters? We don't want to reduce FoS below 3 but how do we reduce the UF? – see box above)
- Site specific verification, calibration and optimisation – benefits for the contractor as well as the detailed designer
- Full or Semi Full Scale Testing – piles, grouting, other ground improvement,

Construction Quality

- Experienced supervision – including geotechnical engineers?
- Effective foundation acceptance criteria
- QC testing

"*much of a civil engineering project's risk lies in the ground*"



Is GI a commodity?

What about what we do with the GI data?

Effective Management of Project Ground Risk

Effective and successful management of ground risk requires development of a high fidelity representation of ground conditions beneath and surrounding the site – the Geotechnical and Geological Model or 'Ground Model'.

Benefits of the integrated approach to GI (geophysics, in-situ testing and drilling and sampling) and staged site characterisation to develop this model:

- A more cost and time effective site characterisation study;
- More cost efficient geotechnical and foundation design due to reduced unnecessary over-engineering;
- Ability to transfer ground risk management to the Constructor without being charged an exorbitant premium for the assumption of this risk in the Constructor's bid price; and
- Fewer differing site conditions claims leading to reduction and possible elimination of such claims that invariably lead to project cost and time overruns.

All projects end up paying for a good site characterisation study regardless of whether one is performed

What is a Engineering Geology Ground Model?

See Fookes (1997) (quoting Glossop's 1968 Rankin Lecture) definition:

'geological model'

A representation of the geology of a particular location. The form of the model can vary widely and include written descriptions, two-dimensional sections or plans, block diagrams, or be slanted towards some particular aspect such as groundwater or geomorphological processes, rock structure and so on.

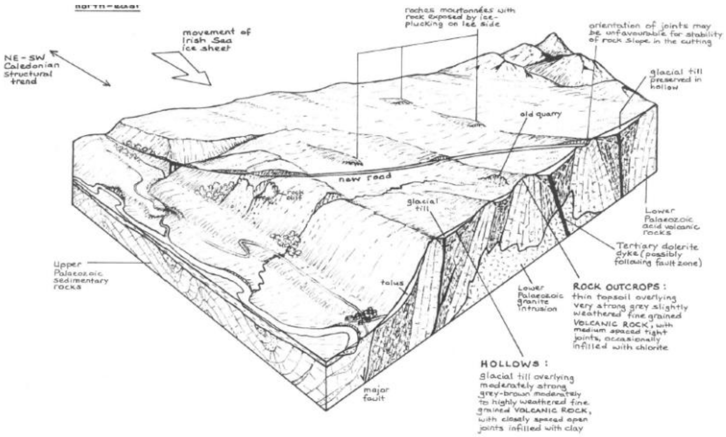


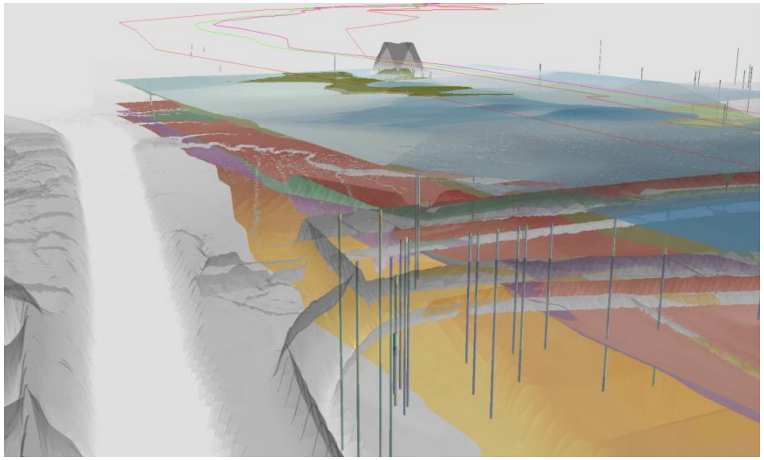
Fig. 14. Conceptual route of a new road in Wales illustrating the relationship between landforms and underlying geology.

Fookes (1997)

Parry et al (2014): definition of different types of model:

- **The Conceptual Ground Model**
- **The Observational Ground Model**
- **The Analytical Ground Model**…

  This model is used to interpret how the ground is likely to behave when it is impacted by the engineered project during the construction process.



Prior to breaking ground with intrusive investigation or planning geophysics:

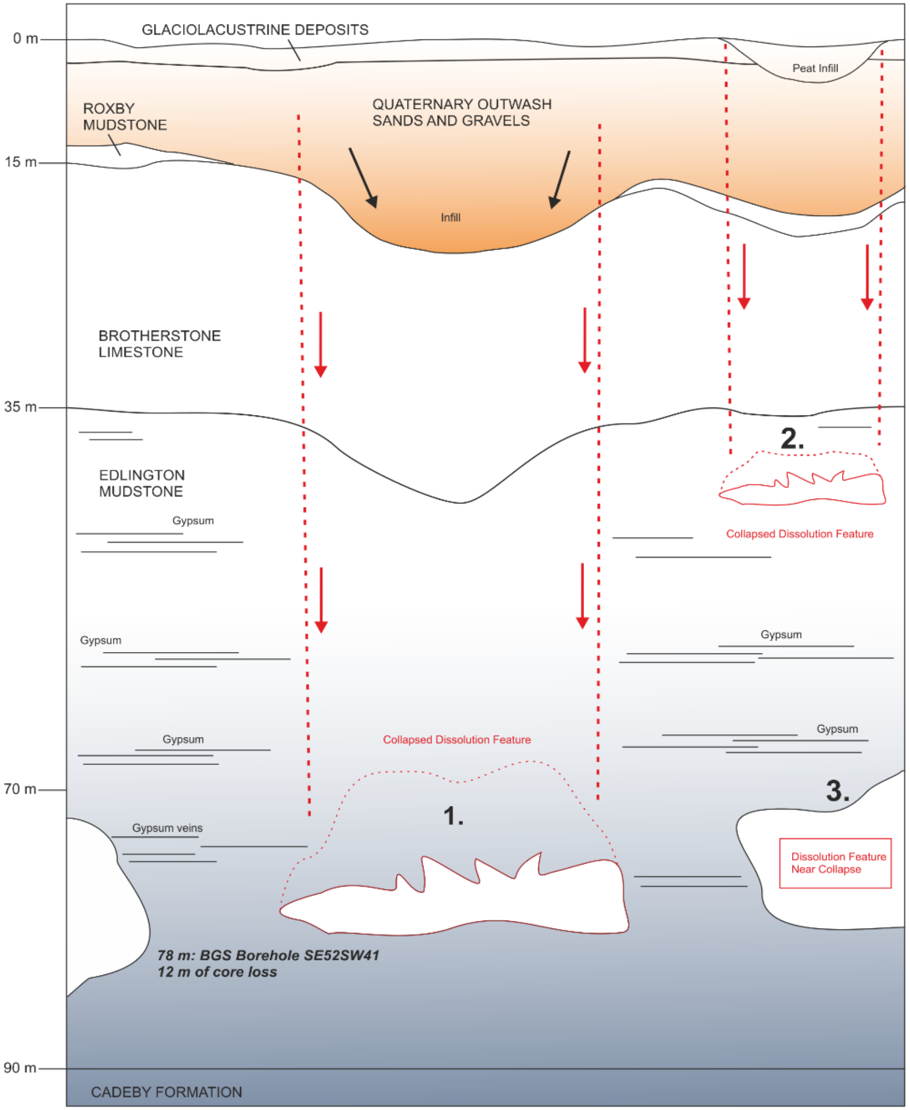
Conceptual models developed from:

- Review of available geological maps/memoirs/academic publications
- Historical site investigation data
- Site walk over and logging of local exposures.

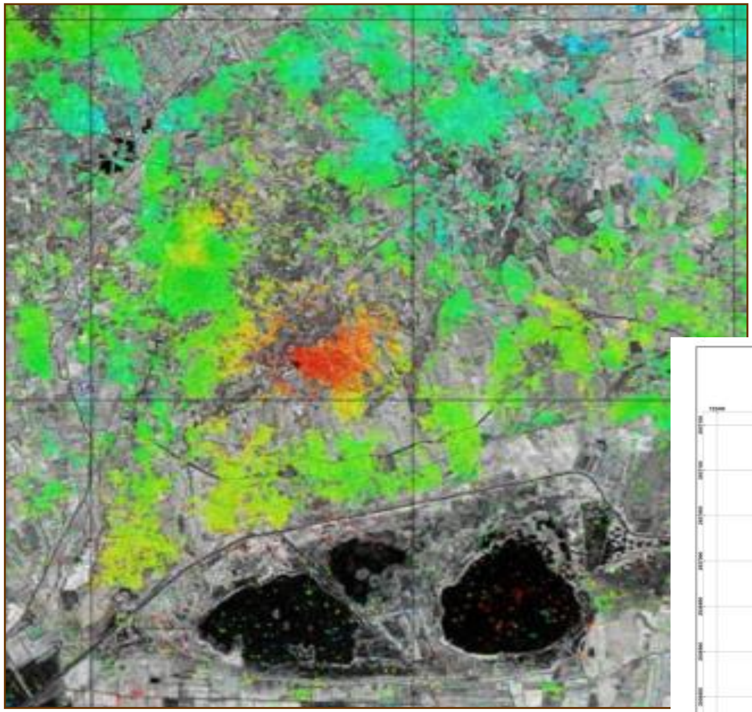
Applications:

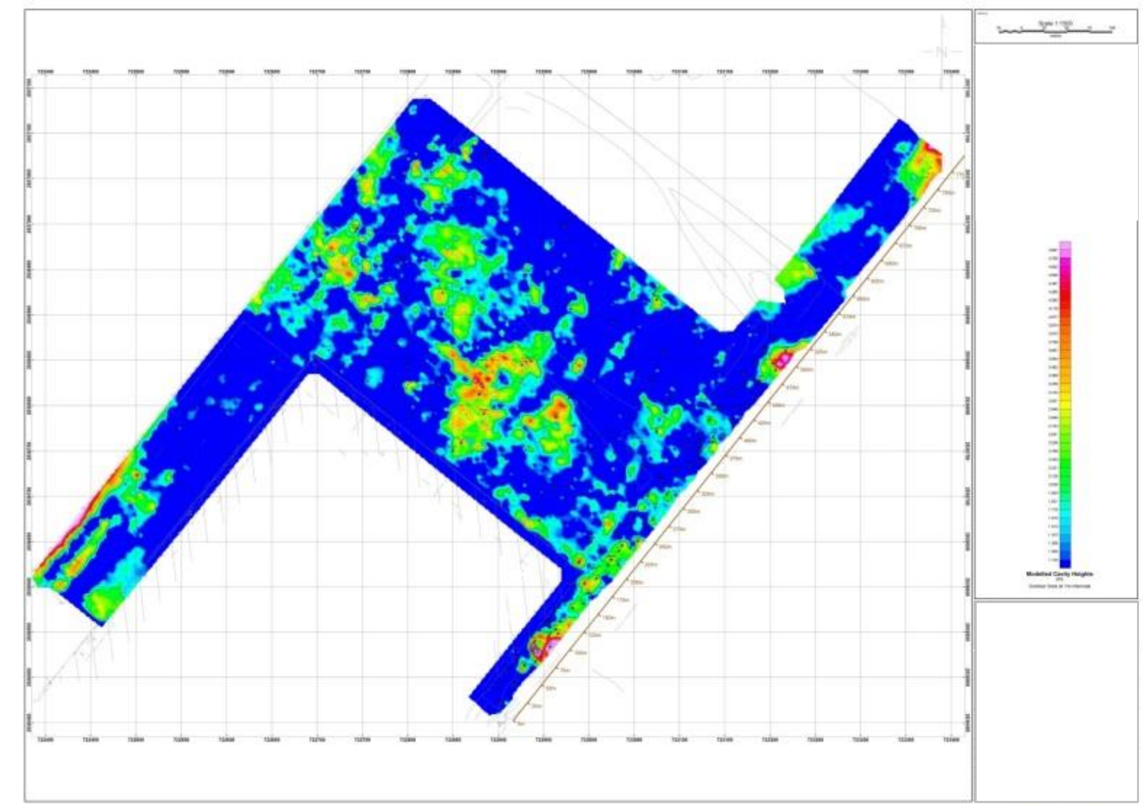
- Qualitative risk assessment for preliminary appraisals of project or site viability
- Support contaminated land desk studies
- **Plan intrusive investigations**
- Visualise likely geohazards and explain likely extent/depth/significance to all levels of stakeholder.

Conceptual Ground Model



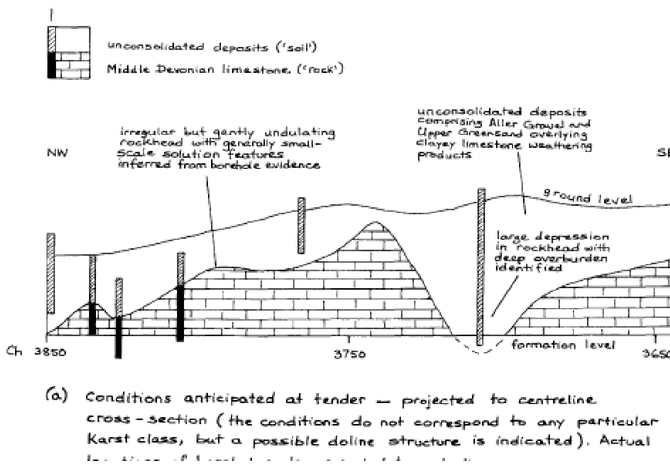
Screening Ground Models: Screening Geophysics & Remotely Sensed Data



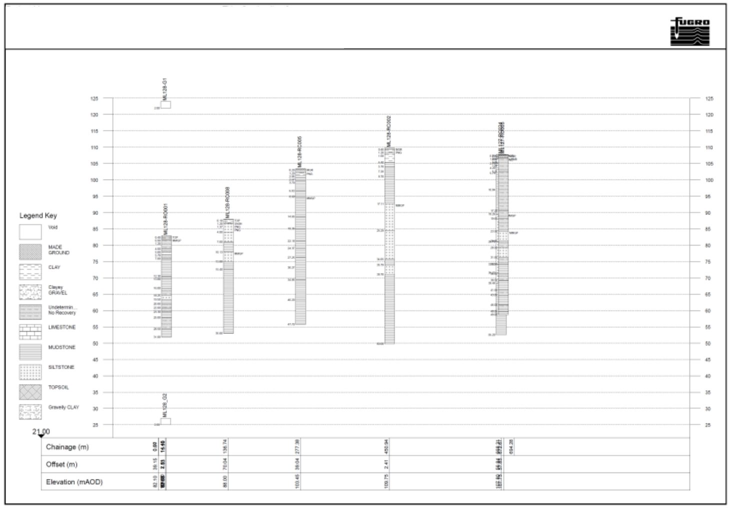


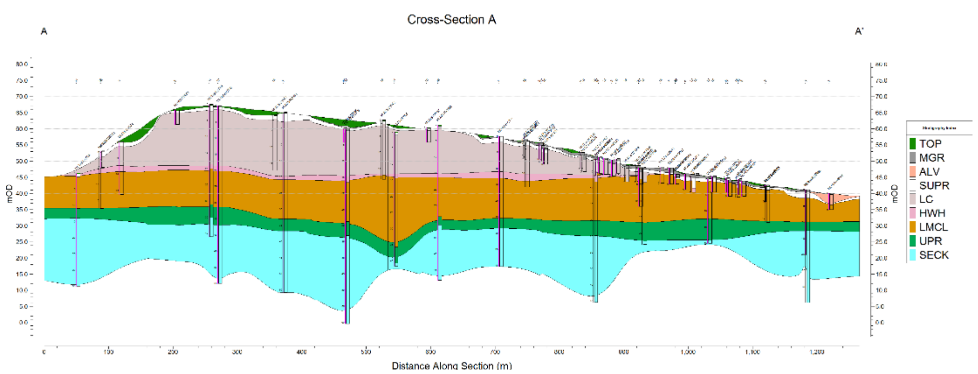
Observational Ground Model

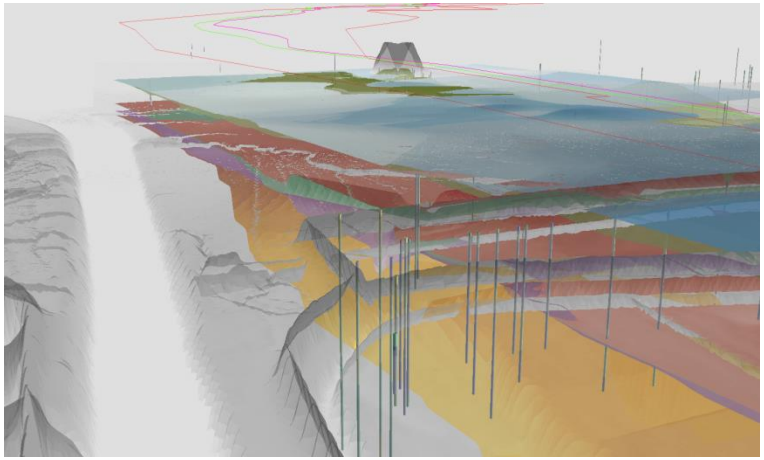
Modelling approaches using extrapolation between exploratory hole locations and geophysics



- From Fookes (1997)



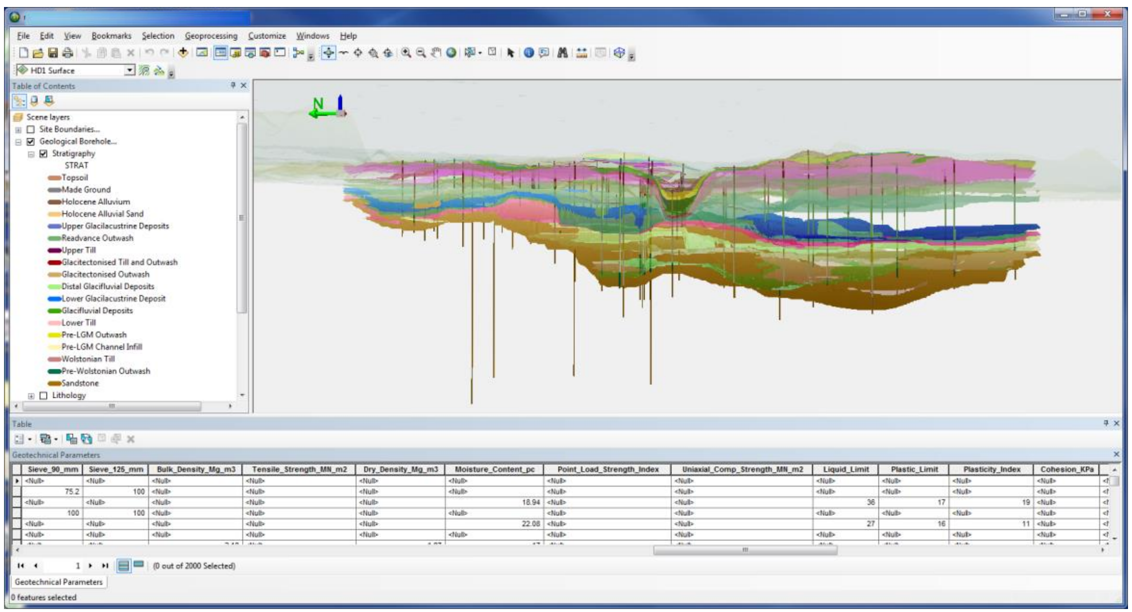




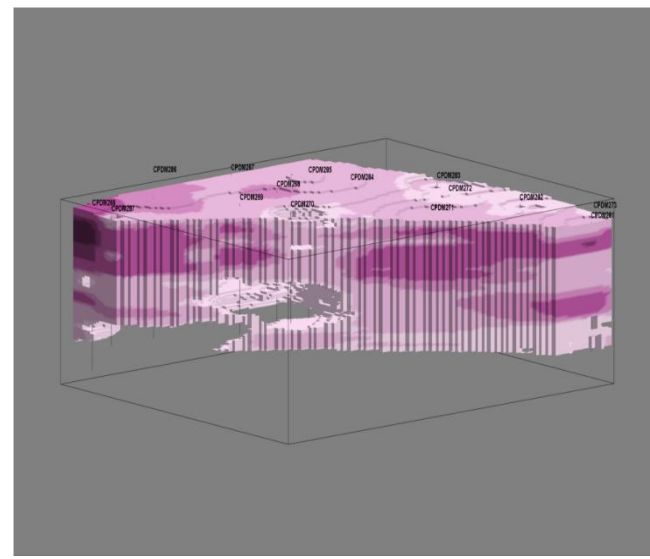
A Fugro 3D GIS hosted ground model based on exploratory hole and surface geophysics data

Geotechnical/chemical parameters can be stored, displayed and analysed within the GIS and exported along with geological surfaces for foundation design.

Model surfaces/parameters can also be used for engineering analysis (e.g. slope stability) and decision making, with the analysis results displayed in the model



Geological ground model with geotechnical parameters in attribute table



Contamination model

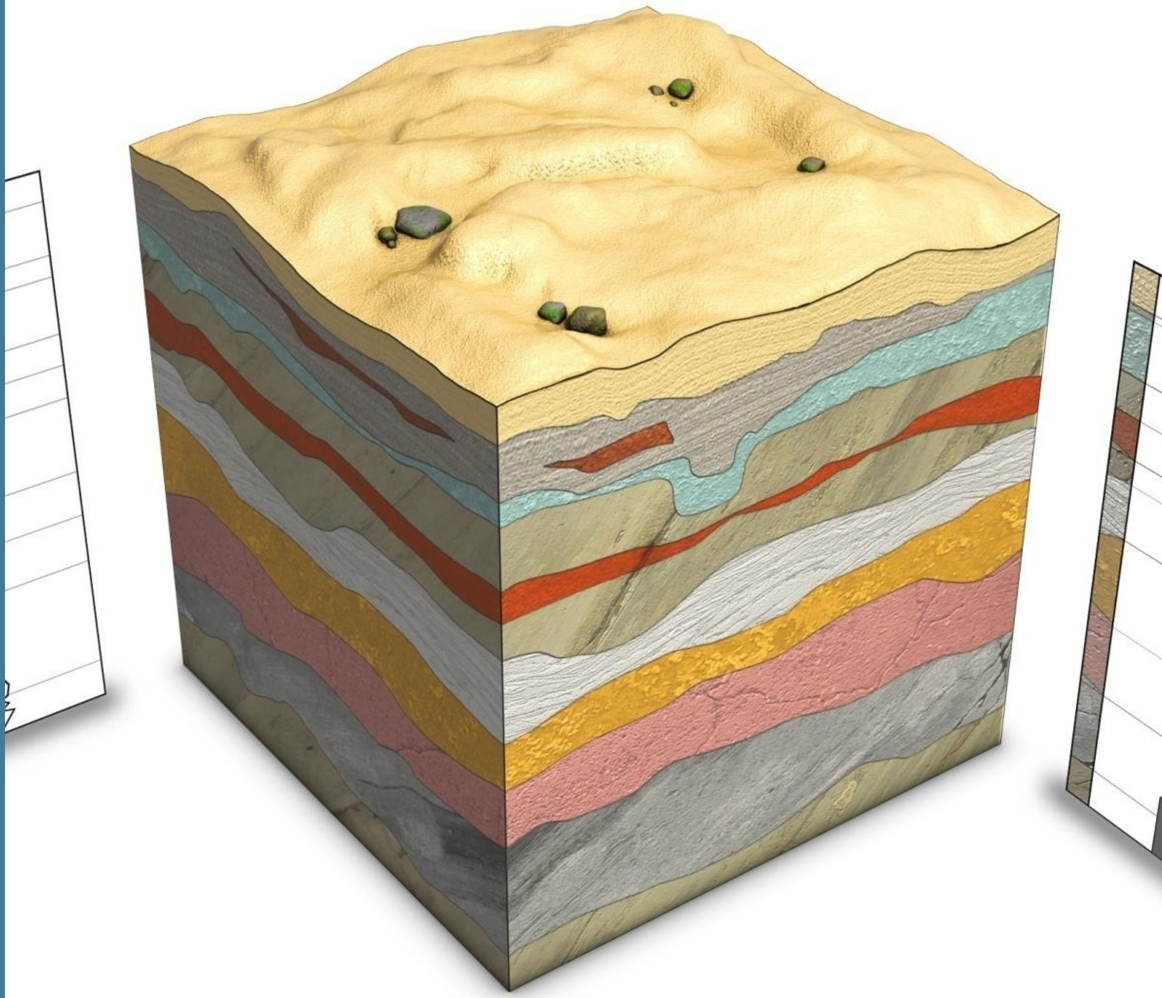
Approaches to building a Integrated Ground Model:

Scope

Intrusive: Lithological/ Stratigraphic

Importance of Geophysics: EM/ERT/SRT/MASW/ Reflection

Integration and presentation



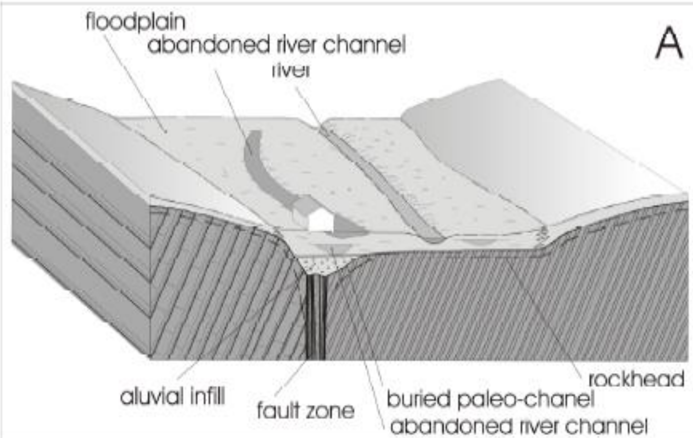
Scope of the GI and Resulting Ground Model

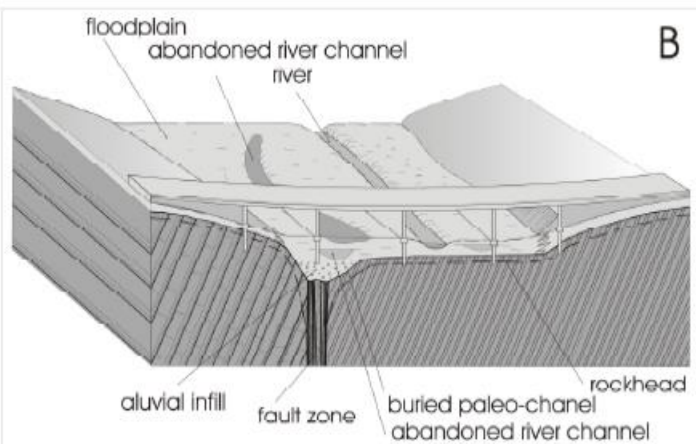
Nature of development/engineering task should determine:

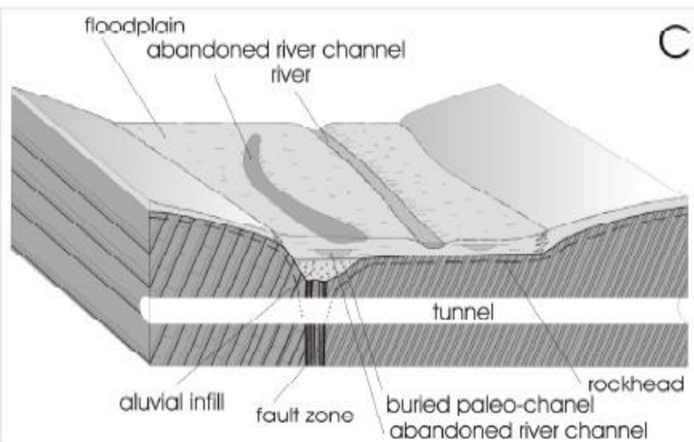
- Model extent
- Model depth
- Model resolution
- Data source
- Parameters displayed in Analytical Model

But this should be considered at conceptual stage and throughout the observational and analytical model development by:

- Complexity of geological units
- Complexity of geological structures
- Internal heterogeneity
- Presence of geohazards
- Presence of geology conducive to geohazards







Reproduced from Parry et al. (2014)

Building a Stratigraphic Framework

Defined by desk study but flexible and needs to evolve with data collection and interpretation

Drilling Method	Location Name	Depth to Top (m)	Depth to Base (m)	Thickness (m)	Lithological Descriptor	Lithology (2nd Order)	Depth to Top (m)	Depth to Base (m)	Comment	No.	Stratigraphic Interpretation
CPT	MIP-E-4	6.60	7.10	0.5	SANDS - clean sand to silty sand	SILTY SAND	6.60	7.10		7	GLACIOFLUVIAL SAND LOWER
CPT	MIP-E-4	7.10	7.90	0.8	SANDS - clean sand to silty sand	SILTY SAND	7.10	7.90		7	GLACIOFLUVIAL SAND LOWER
CPT	MIP-E-4	7.90	8.00	0.1	silt mixtures - clayey SILT to silty CLAY	CLAYEY SILT	7.90	8.00		8	GLACIOFLUVIAL CLAY LOWER
CPT	MIP-E-4	8.00	8.41	0.41	SAND mixtures - silty sand to sandy silt	SILTY SAND	8.00	8.41		9	GLACIOFLUVIAL GRAVEL
Cable Percussion	MW112A	0.3	0.45	0.15	MADE GROUND. Light brown fine to coarse gravel of limestone.	GRAVEL	0.3	0.45		1	MADE GROUND
Cable Percussion	MW112A	0.45	2	1.55	Brown slightly gravelly coarse grained SAND. Gravel is angular to sub angular, fine to medium of limestone and occasional pieces of coal. Cresol odour. Sample recovered but liner got stuck in sample tube so core not recovered intact.	SAND	0.45	2		3	BREIGHTON SANDS
	MW112A	2	2	0		GRAVELLY SAND	2	2	ZERO THICKNESS	3	BREIGHTON SANDS
Cable Percussion	MW112A	2	3.6	1.6	Firm red brown to brown very closely fissured sandy CLAY. Occasionally mottled black with cresol odour.	SANDY CLAY	2	3.6		4	GLACIOLACUSTRINE
Cable Percussion	MW112A	3.6	4.2	0.6	Black slightly gravelly SAND. Gravel is angular to sub angular, fine of mixed lithology. Very strong cresol odour. At 4.2mbgl gas generated - can be heard bubbling through groundwater. Gas sample taken and borehole backfilled with bentonite.	SAND	3.6	4.2		5	GLACIOFLUVIAL SAND UPPER
	MW112B	0	0	0		TOPSOIL	0	0	ZERO THICKNESS	1	TOPSOIL
Rotary	MW112B	0	0.15	0.15	MADE GROUND: Concrete.	MADE GROUND	0	0.15		1	MADE GROUND
Rotary	MW112B	0.15	0.4	0.25	MADE GROUND: Light to dark brown sandy angular to subangular, fine to coarse GRAVEL of sandstone and limestone. Sand is fine to medium of sandstone and limestone.	SANDY GRAVEL	0.15	0.4		1	MADE GROUND
Rotary	MW112B	0.4	2	1.6	MADE GROUND: Brown slightly clayey, gravelly fine to coarse SAND. Gravel is angular to subangular, fine to medium of sandstone and limestone with occasional fragments of coal. Faint cresol odour.	GRAVELLY SAND	0.4	2		1	MADE GROUND
	MW112B	2	2	0		SAND	2	2	ZERO THICKNESS	3	BREIGHTON SANDS
	MW112B	2	2	0		GRAVELLY SAND	2	2	ZERO THICKNESS	3	BREIGHTON SANDS
Rotary	MW112B	2	3.6	1.6	Firm red brown to brown very closely fissured sandy CLAY. Occasionally mottled black with cresol odour.	SANDY CLAY	2	3.6		4	GLACIOLACUSTRINE
Rotary	MW112B	3.6	6	2.4	Black slightly gravelly fine to coarse SAND. Gravel is angular to subangular, fine of mixed lithologies. Strong cresol odour.	SAND	3.6	6		5	GLACIOFLUVIAL SAND UPPER
	MW113	0	0	0		TOPSOIL	0	0	ZERO THICKNESS	1	TOPSOIL
Rotary	MW113	0	0.56	0.56	MADE GROUND. Rough grass and vegetation over brown very sandy gravelly CLAY. Sand is fine to coarse. Gravel is angular to sub angular, fine to coarse of sandstone with occasional fragments of brick and frequent rootlets. At 0.4mbgl material becomes dark brown to black.	SANDY GRAVELLY CLAY	0	0.56		1	MADE GROUND
Rotary	MW113	0.56	0.78	0.22	MADE GROUND. Light brown clayey slightly gravelly fine to medium SAND. Gravel is angular to sub angular, fine to medium of sandstone.	SAND	0.56	0.78		1	MADE GROUND
Rotary	MW113	0.78	1.2	0.42	MADE GROUND. Grey black slightly clayey slightly gravelly fine to coarse SAND of sandstone and black coal dust. Gravel is angular to sub angular, fine of sandstone and coal dust. Perched water encountered at 1.1mbgl.	SAND	0.78	1.2		1	MADE GROUND
Rotary	MW113	1.2	1.8	0.6	No recovery, possible obstruction.	CORE LOSS	1.2	1.8		1	MADE GROUND
Rotary	MW113	1.8	2.2	0.4	Mottled black dark grey slightly gravelly fine to coarse SAND. Gravel is sub angular, fine of sandstone and stones of mixed lithologies. Occasional fine rootlets. Faint to moderate cresol odour.	SAND	1.8	2.2		2	ALLUVIUM
	MW113	2.2	2.2	0		GRAVELLY SAND	2.2	2.2	ZERO THICKNESS	3	BREIGHTON SANDS
	SE52SW11	21.34	22.96	1.62	Red marl with bands of grey marl	LIMESTONE	21.34	22.96		11	BROTHERTON LIMESTONE

Formation Tops - Grid Surface Models

Extent: determined by end use

- Geotechnical design
- Hydrogeology (ConnectFlow)

Process: Extrapolation of upper and lower bounding surfaces of units based on exploratory hole locations supported by geophysics where available.

Extrapolation Algorithms:

- Inverse Distance Weighting (IDW)
- Kriging; managing linear data clustering

- Limited functionality in ArcGIS
- Specialist software to apply geological principals to extrapolations; channels/faults/on-lap

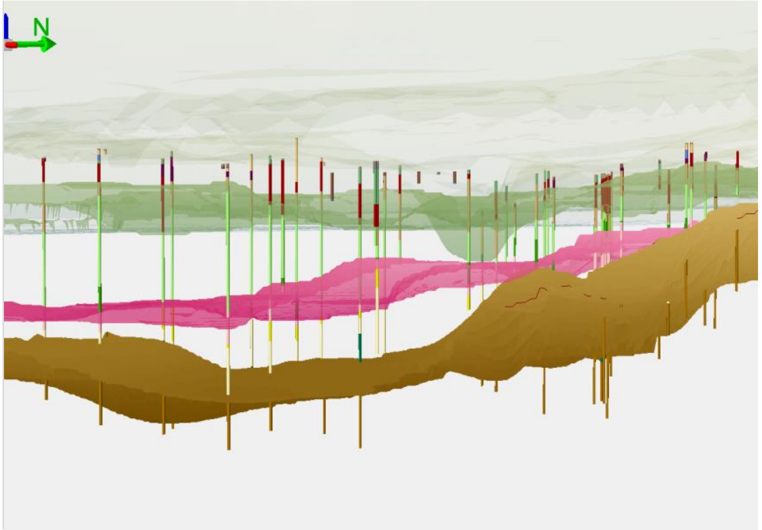
Produces a raster grid that can be visualised in GIS as a surface.

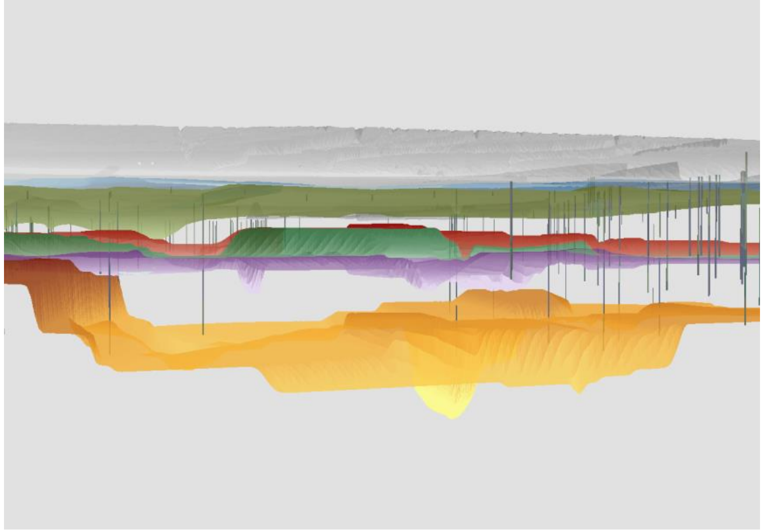
Consider spacing of observation points to delineate features of interest

Can incorporate geophysics producing an integrated model.

Requires:

- Interpretation of geologies from CPT/Boreholes/Geophysics
- Stratigraphic ordering
- Multiple layers to model interbeds/erosional features/channel infill etc…easy to get this wrong





Voxel Models

Non-interpretative calculation into solid 3D voxel based model of parameters derived from ground investigation including:

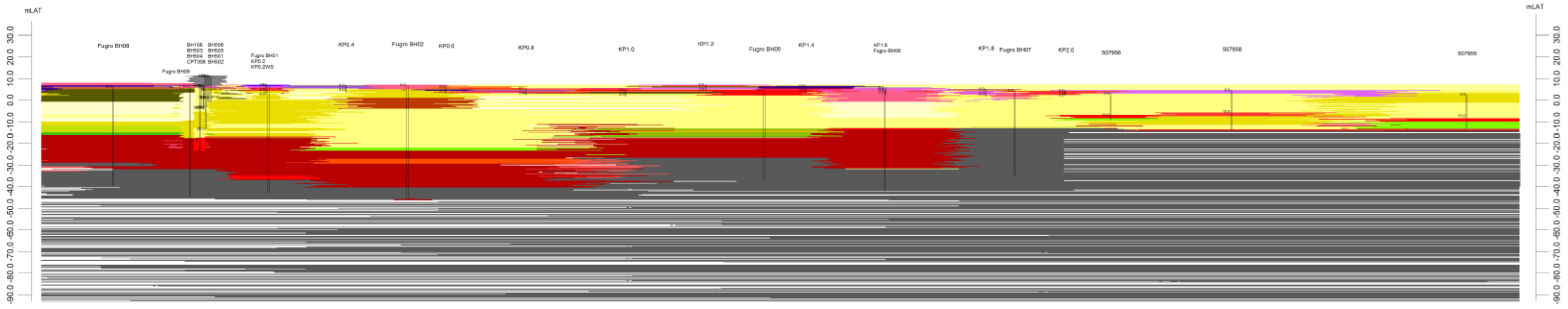
- Soil descriptions: consider complexity of variables
- Particle size descriptions
- Some geotechnical/chemical parameters.
- Chemical Visualisations

Algorithms:

- Closest Point
- Lateral Blending: extrudes with randomisation between 1/3 to 2/3 between control points
- Lateral Extrusion: extrudes to midpoint
- Highest probability

Used for:

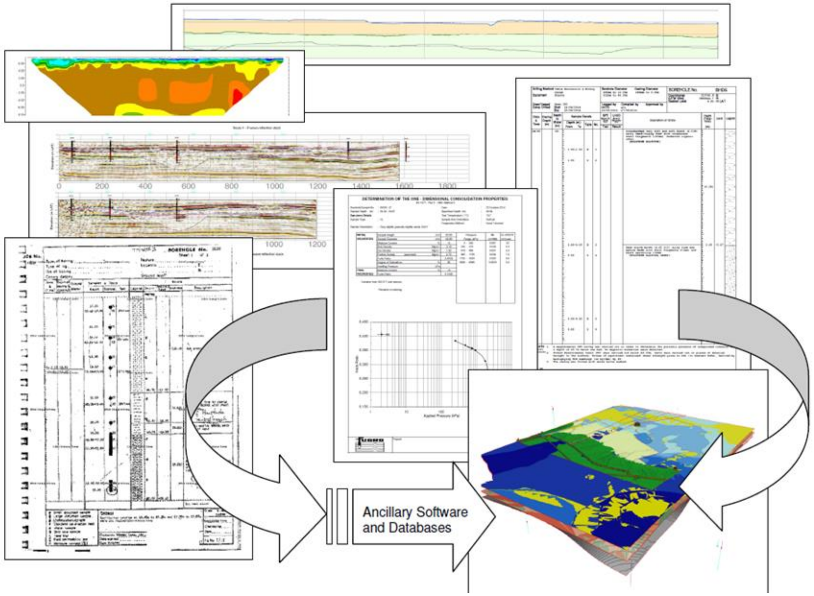
- QC of strata unit interpretations; great for extrapolation from multiple points (CPT)
- Randomisation in extrapolation beyond comfortable bounds for multiple model runs as part of probabilistic assessments
- Randomisation of hydrogeological variables for modelling internal heterogeneity in geological units.



Building Integrated Ground Models

Only when datasets are fully integrated into a seamless model is real value gained - levels of uncertainty in ground conditions, and hence project risk, significantly reduced.

- Boreholes
- CPT
- Trial Pits
- Exposures
- Geophysics: ERT, Seismic Refraction/Reflection, 2D/3D
- Down-hole



- **Proprietary Approaches:** A range of specialist software used to integrate geophysical and intrusive site investigation datasets into integrated ground models. Approaches and experience are important not software

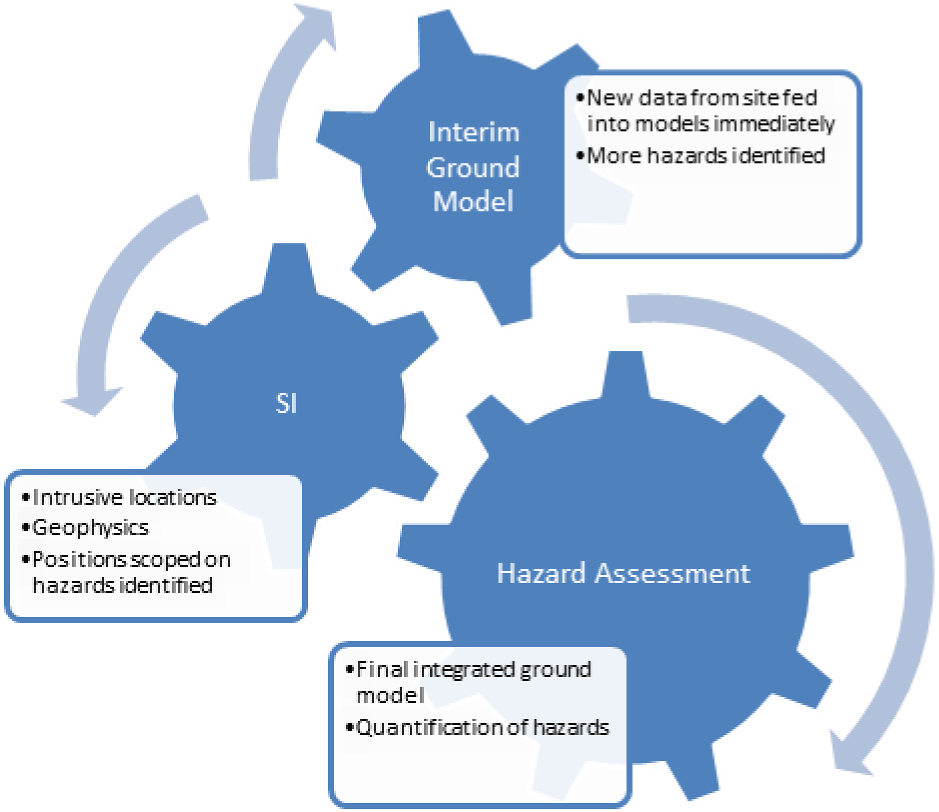
- **Historical data:** Opportunity to integrate historical datasets (geophysical, boreholes, interpreted sections) held by clients/third parties; data can be assessed and incorporated to add value

- **Analytical Models:** With the addition of geotechnical or chemical measurements models may include spatial analysis to show trends and aid decision making and design

- **Specialist Knowledge:**Models incorporate the judgement of geologists and geophysists and are typically delivered in GIS format with selected elements also exported for design

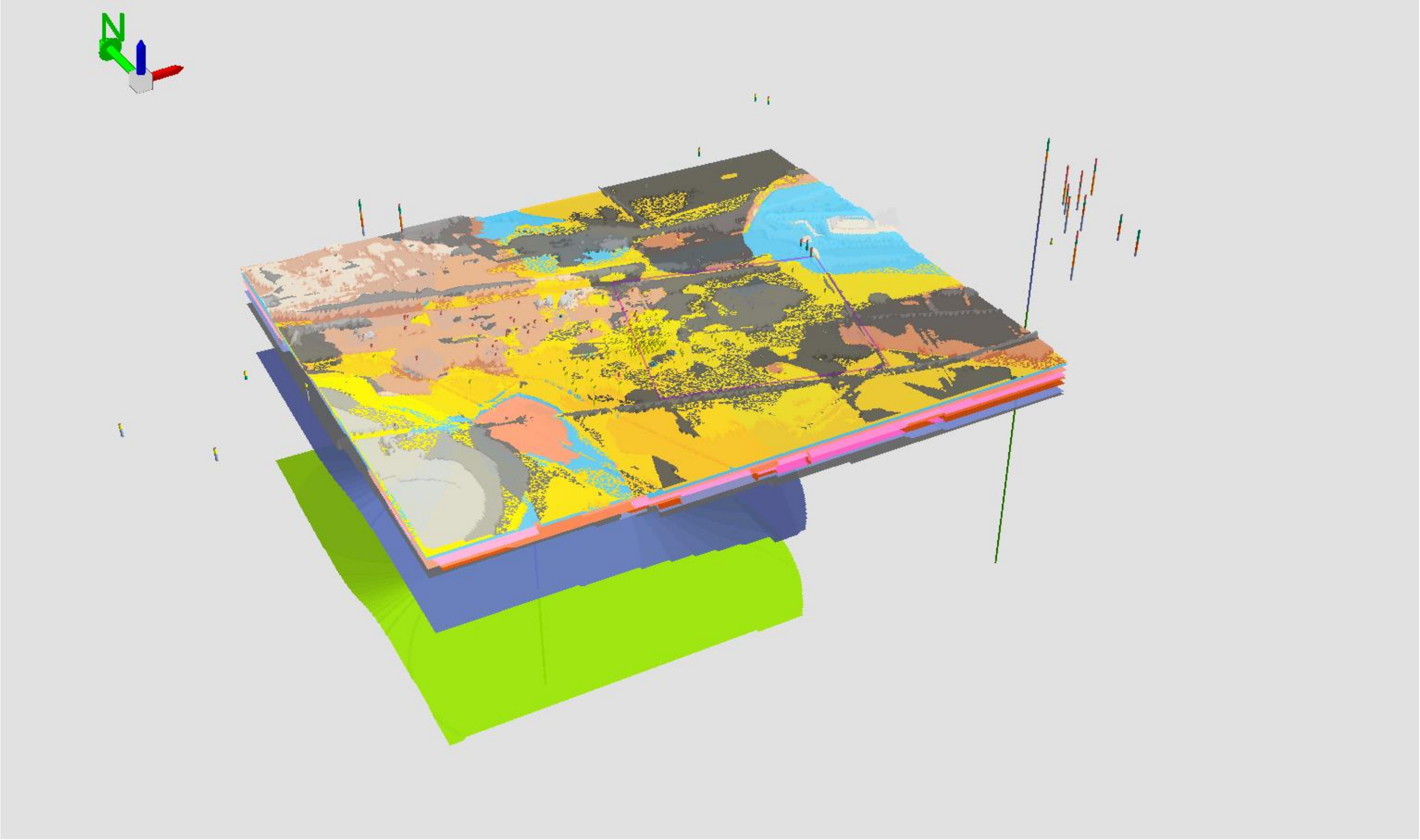
- **Specialist data:** e.g. geology models add value to UXO magnetometer survey as object penetration/age can be assessed.

Dynamic Site Characterisation and the Evolving ground Model



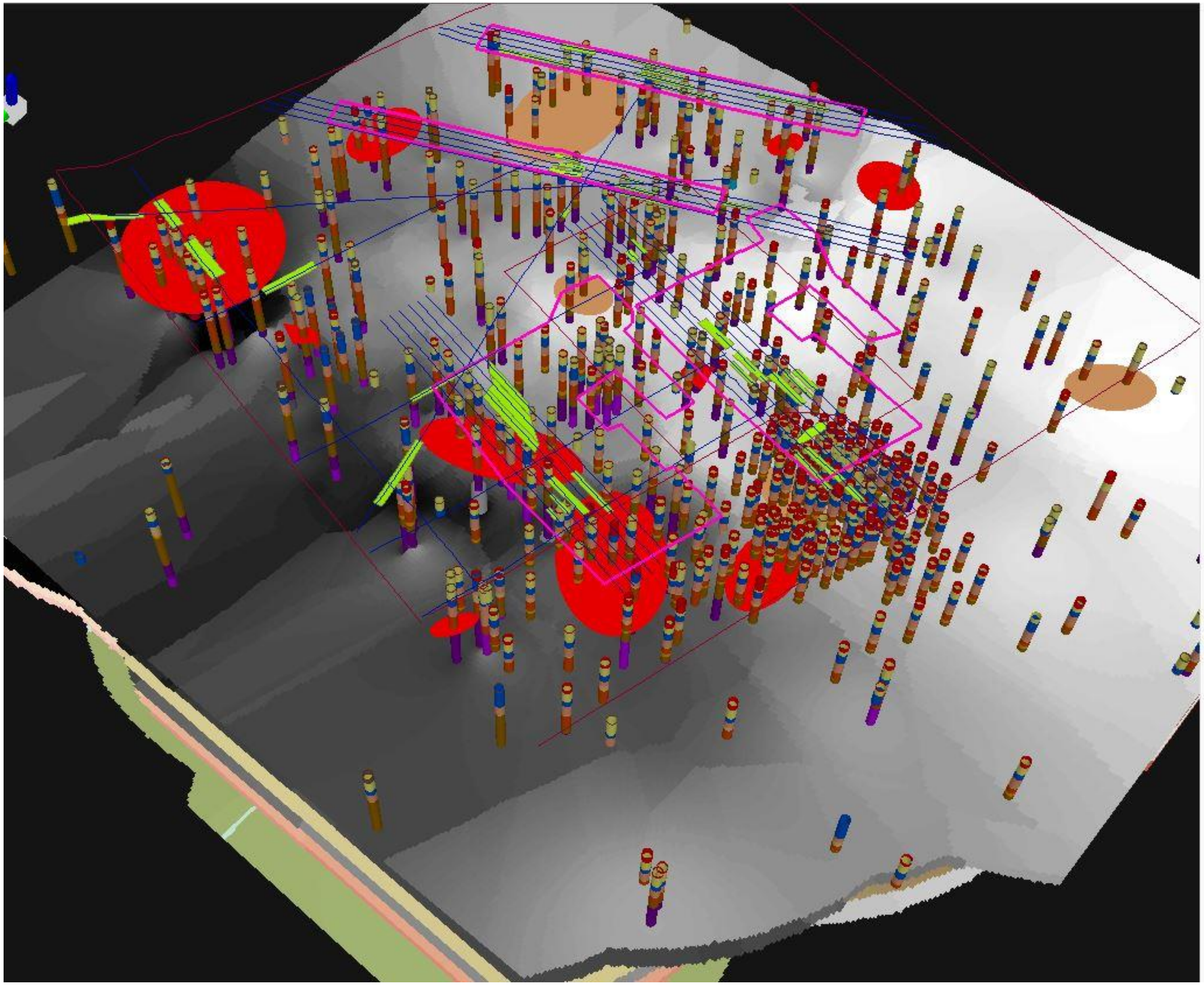
Case studies to follow

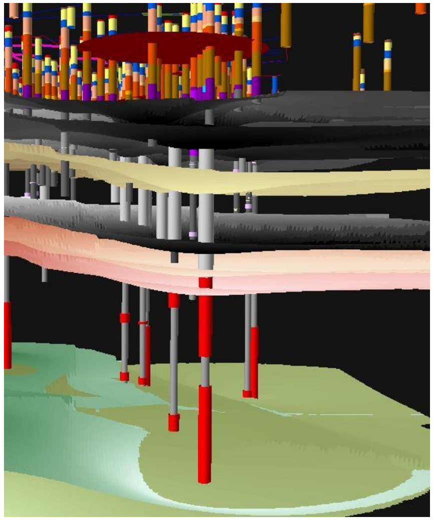
Early Stage Observational Models: Historical Data/Screening Geophysics

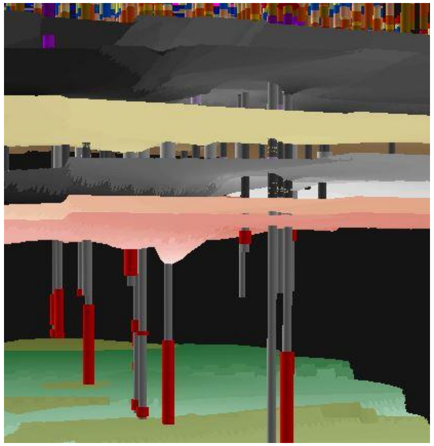


- Use for assessing suitability of detailed geophysics approaches
- Design initial spread of intrusive investigation
- Model updated as investigation stages progress in real time

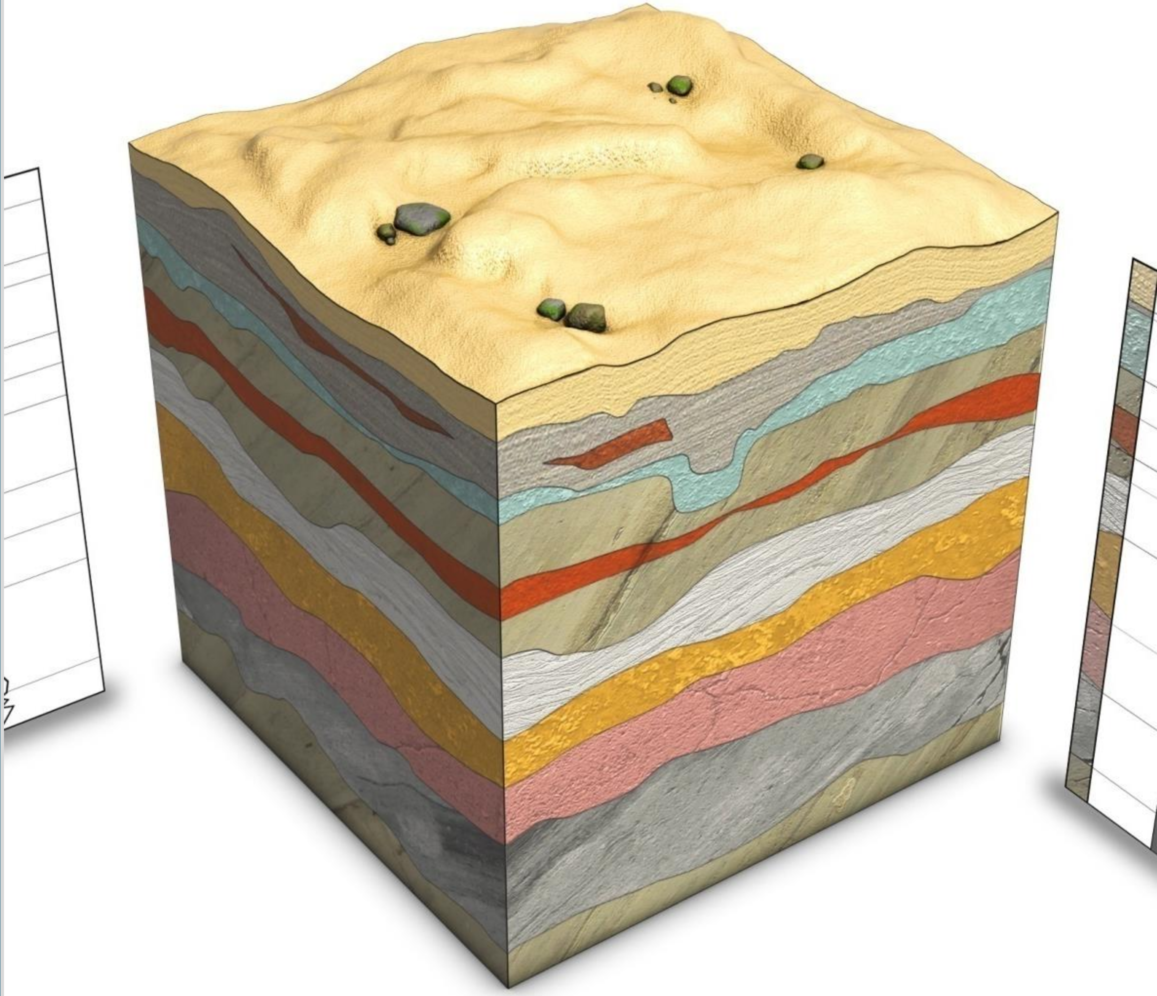
Dynamic SI: Integrated Geophysics and Targeted Boreholes







What data/information can be brought into the Integrated Ground Model?

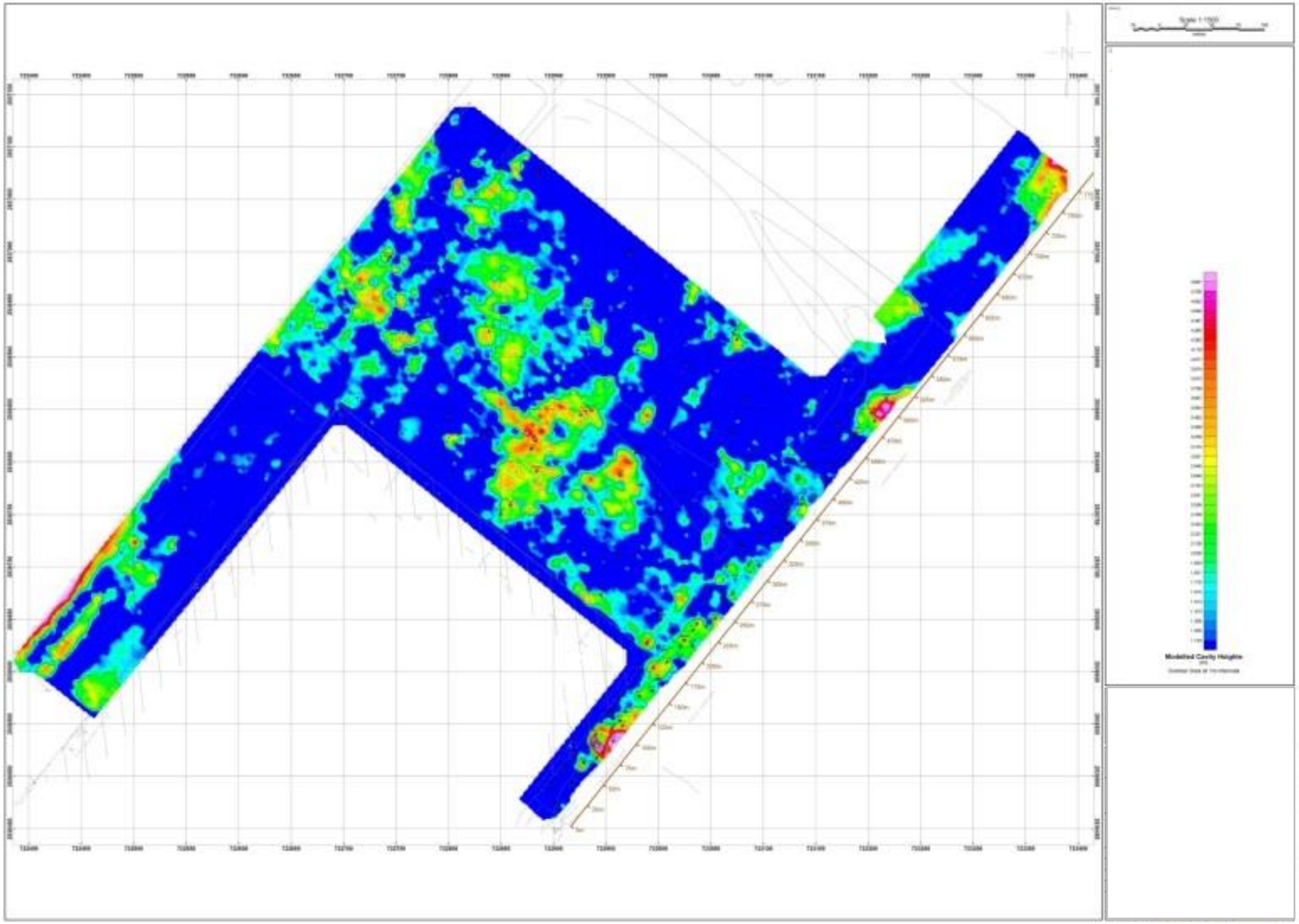


Surface Geophysics – depth dependencies on land

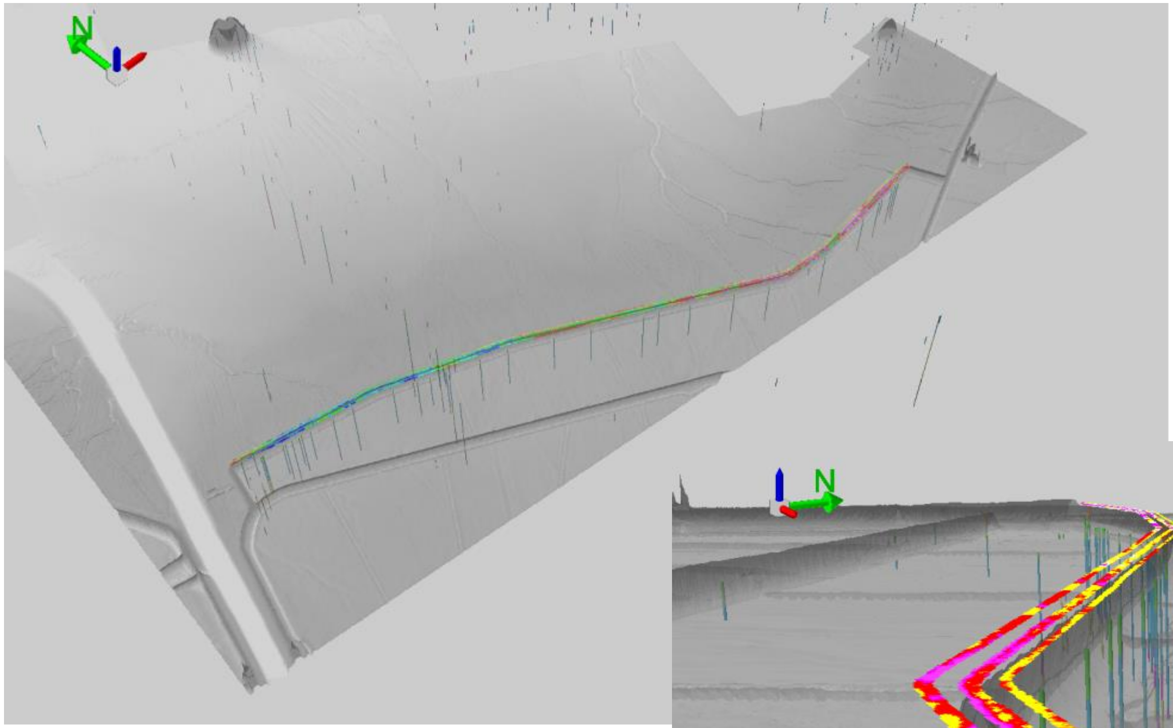
Depth	Methods	Applications
10 m	Ground Penetrating Radar Electromagnetics Magnetics	Buried obstructions Services Near surface conditions and geohazards
30 m 50 m 100 m	Surface wave seismic Microgravity Magnetics Electrical resistivity tomography Seismic refraction	Stratigraphy Structure Stiffness / elastic properties Cavities & voids Geohazards
1.5 km	Seismic reflection*	Deep structure and stratigraphy

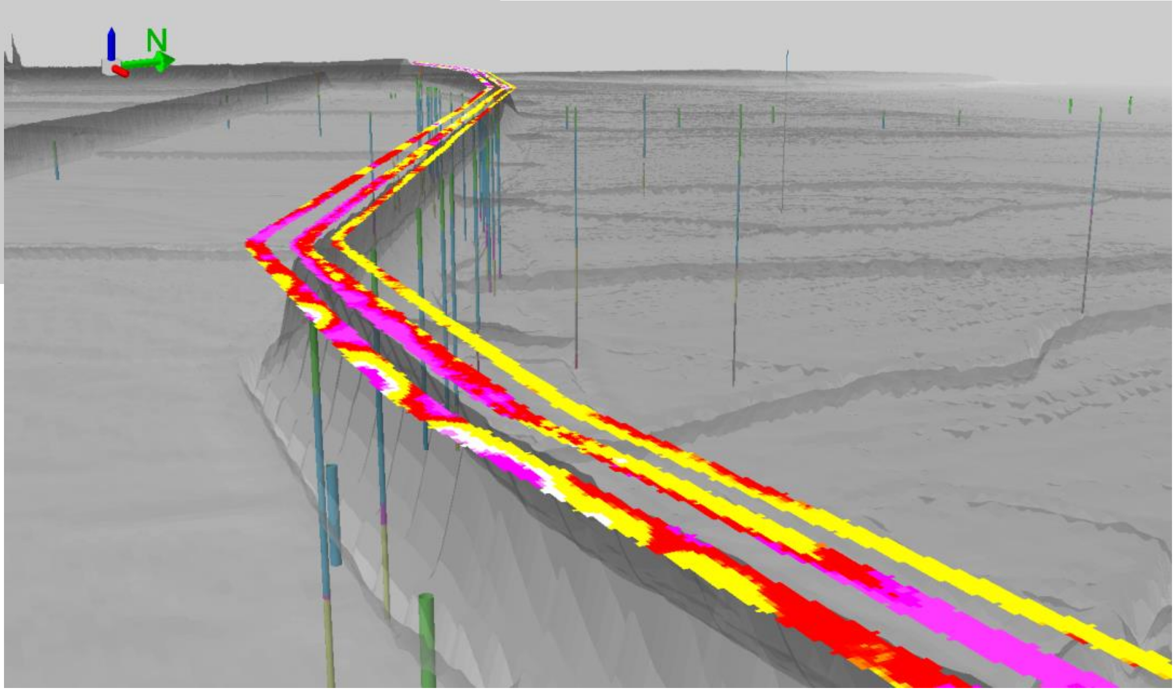
*shallow limitations

Shallow Risks (Microgravity Solution)

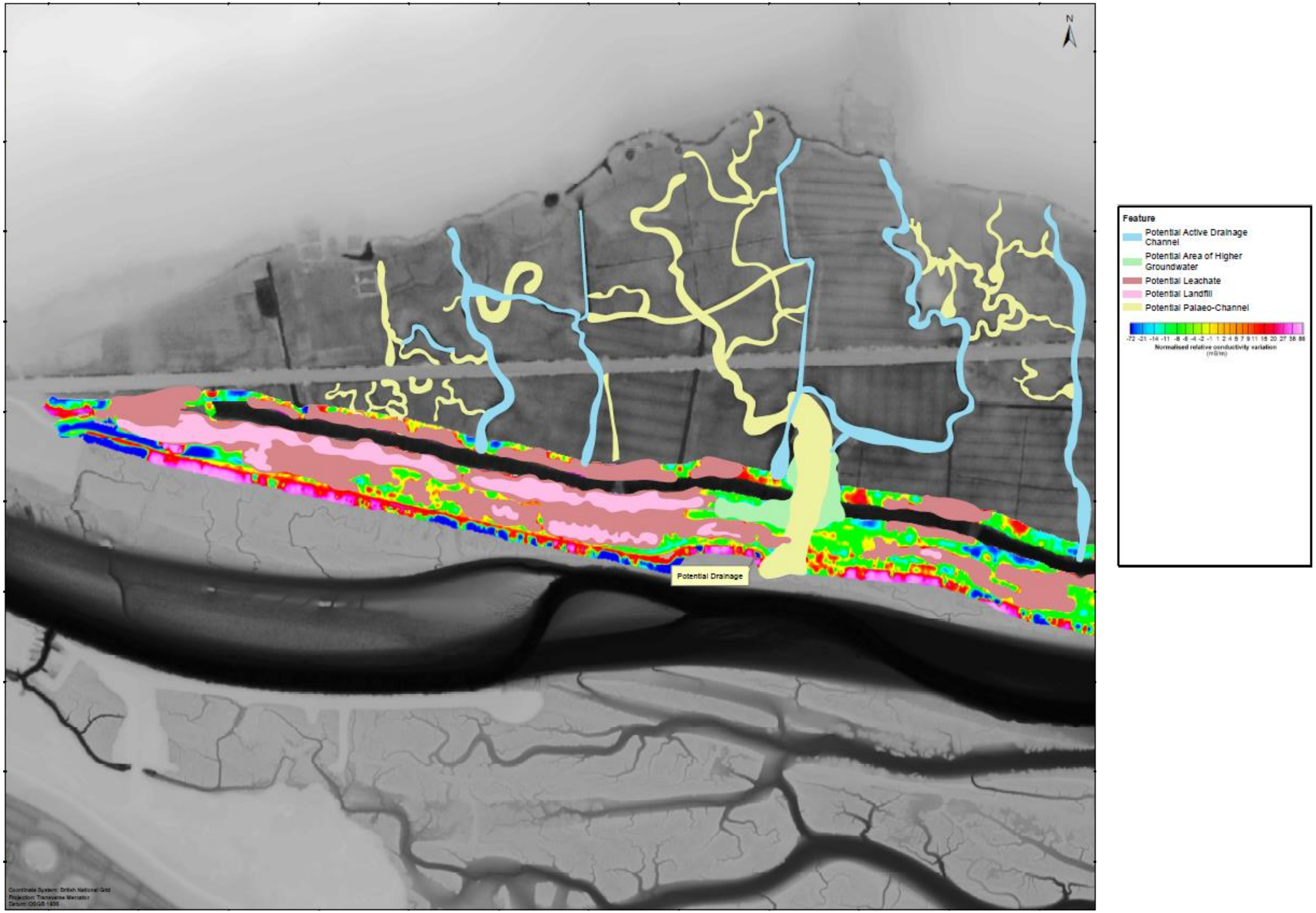


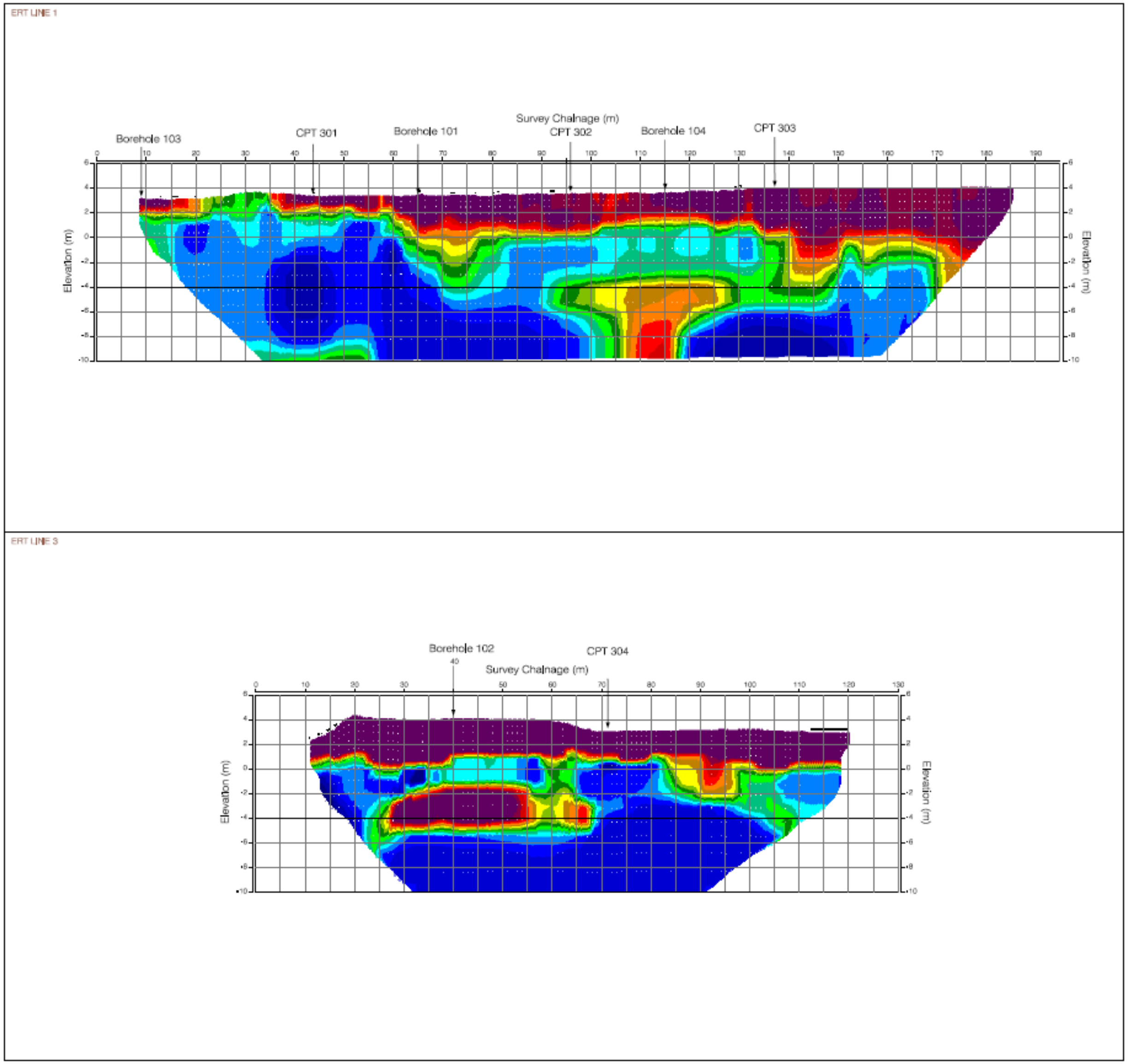
EM31/38



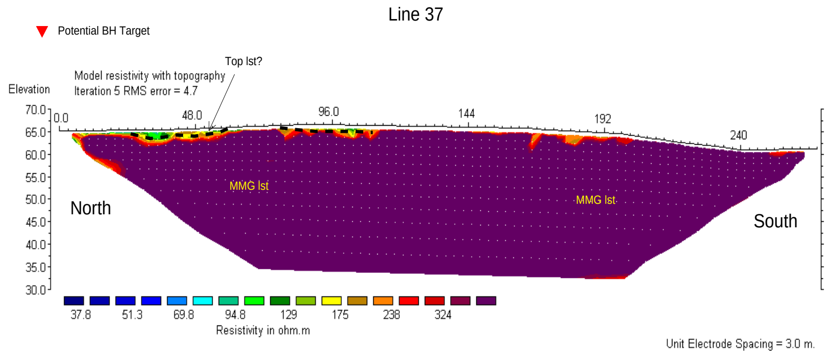


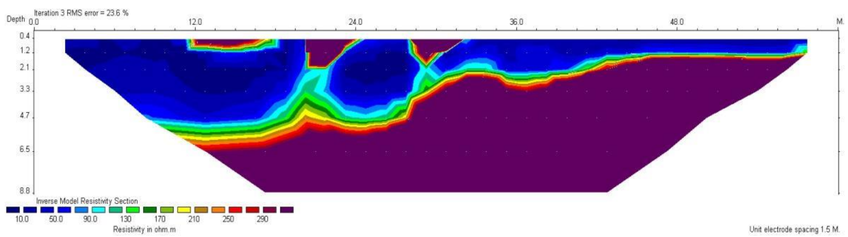
EM31/38

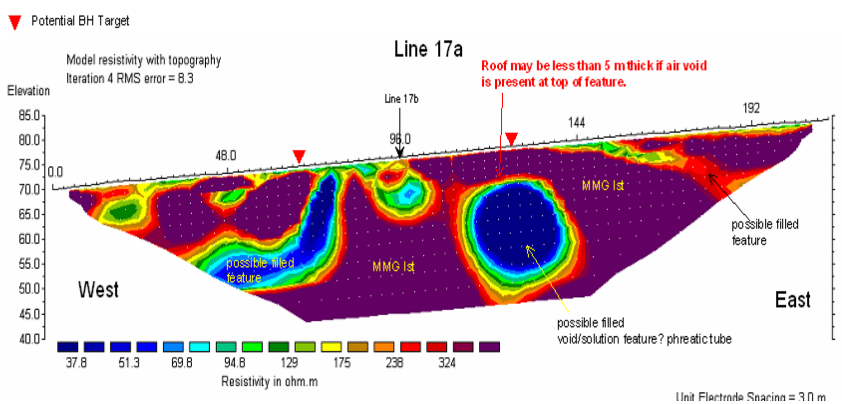

N
Potential Drainage
Coordinate System: British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936
Feature
Potential Active Drainage Channel
Potential Area of Higher Groundwater
Potential Leachate
Potential Landfill
Potential Palaeo-Channel
Normalised relative conductivity variation (mS/m)


ERT LINE 1
Survey Chainage (m)
Borehole 103
CPT 301
Borehole 101
CPT 302
Borehole 104
CPT 303
Elevation (m)
ERT LINE 3
Borehole 102
CPT 304
Survey Chainage (m)
Elevation (m)

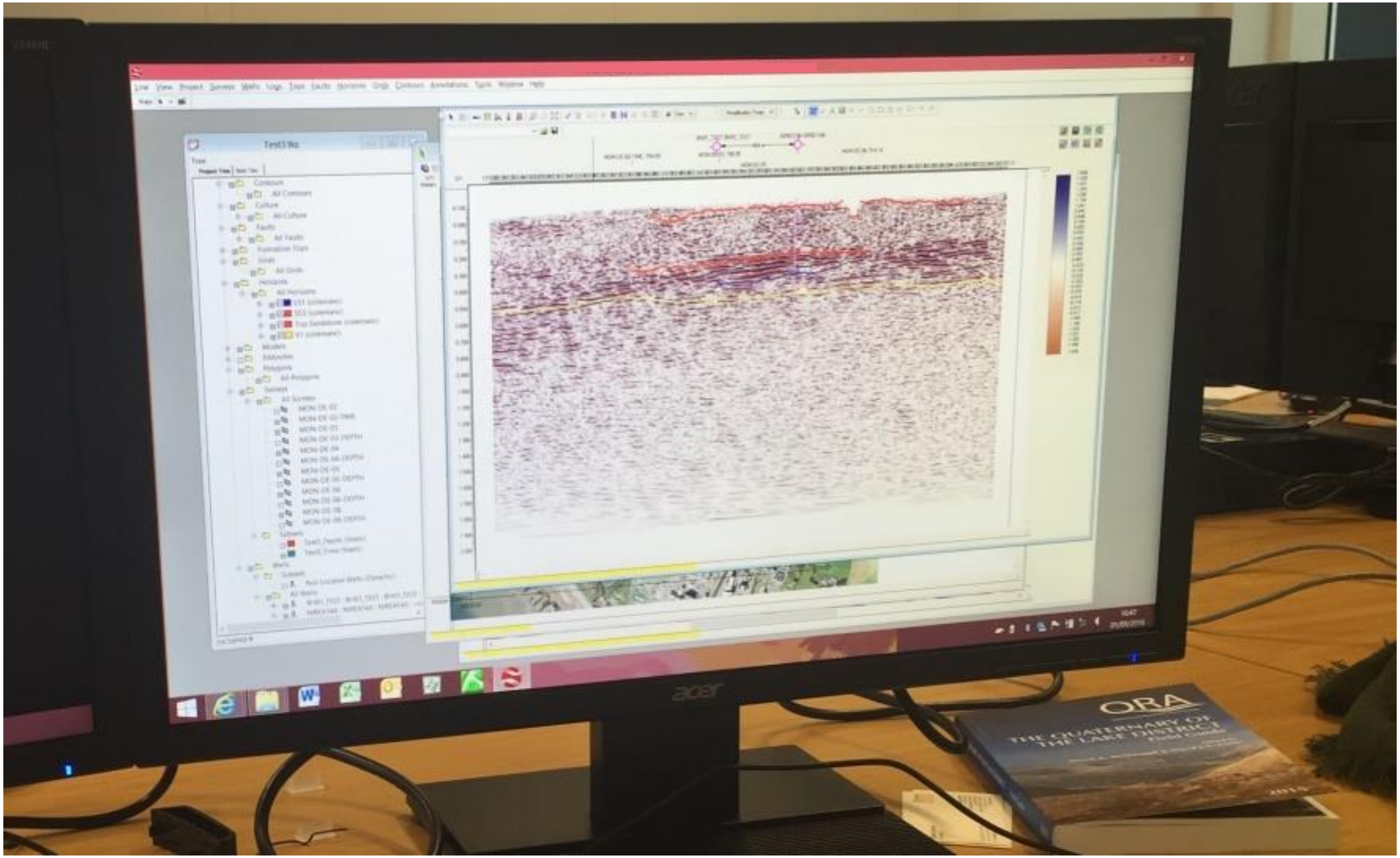
ERT and Karstic Features



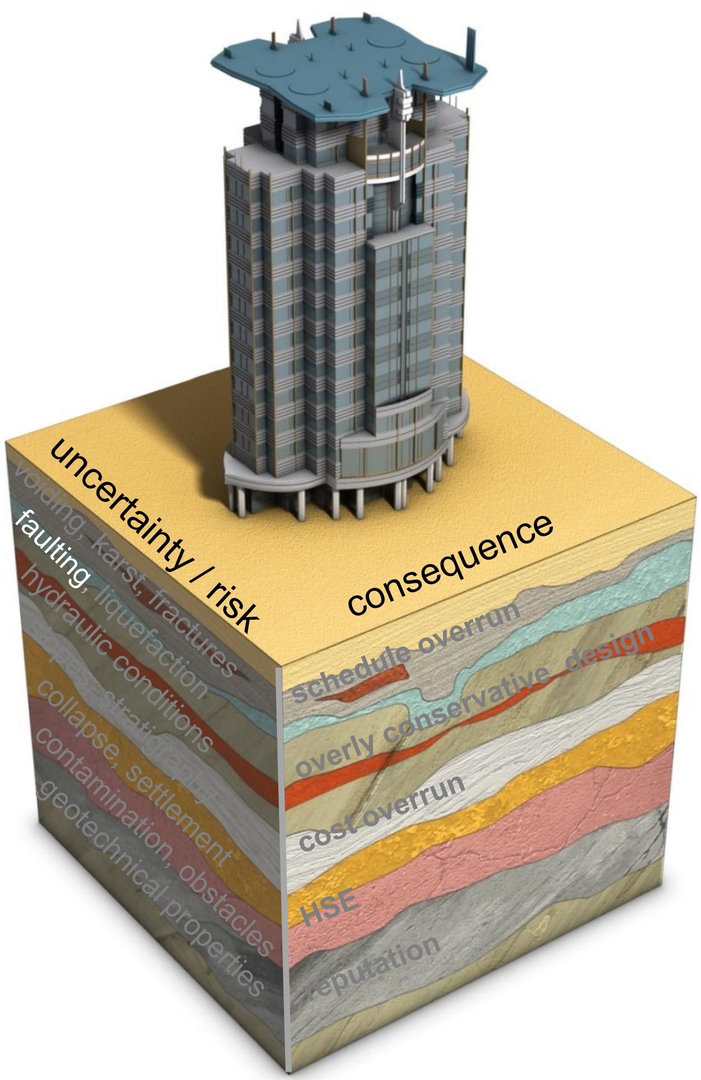


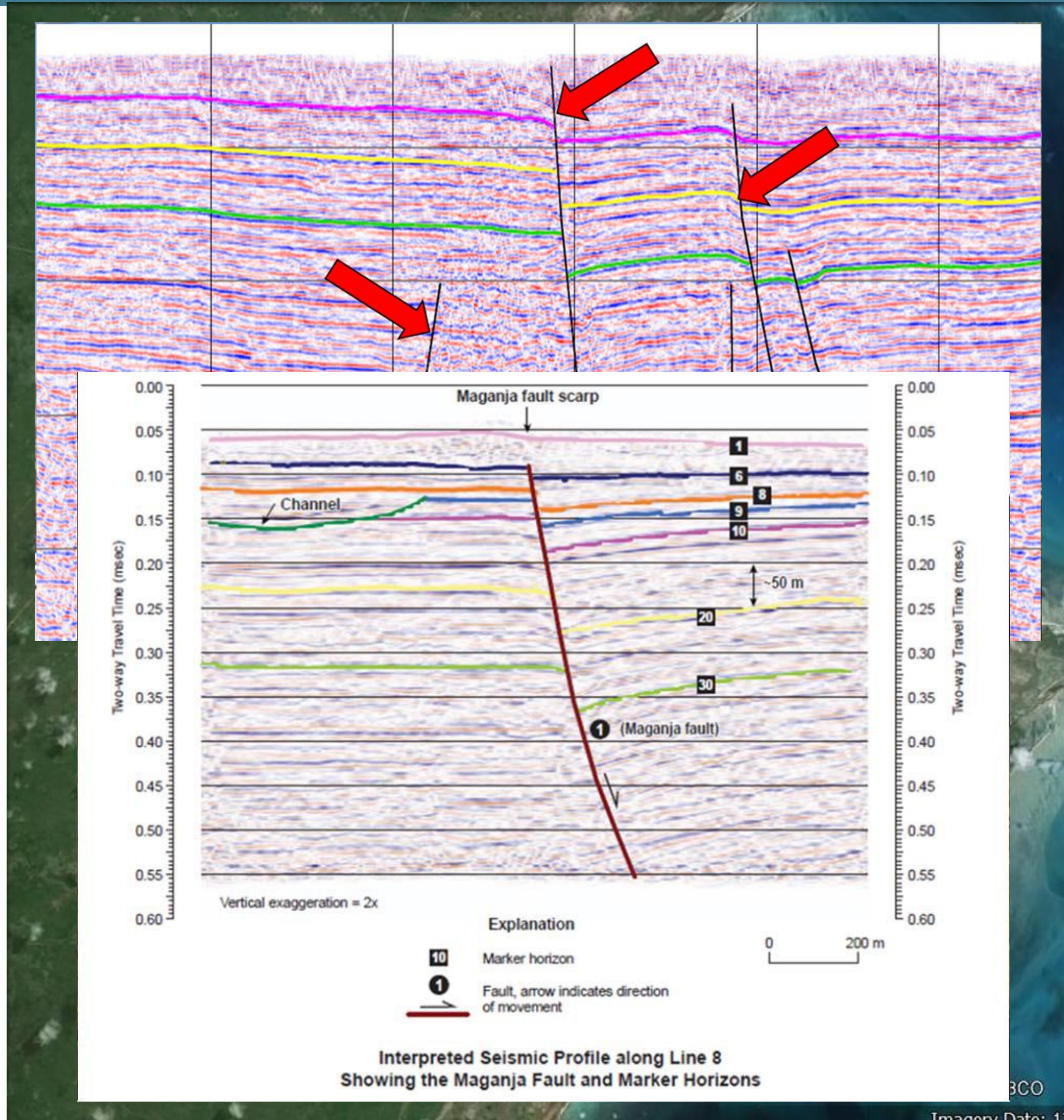


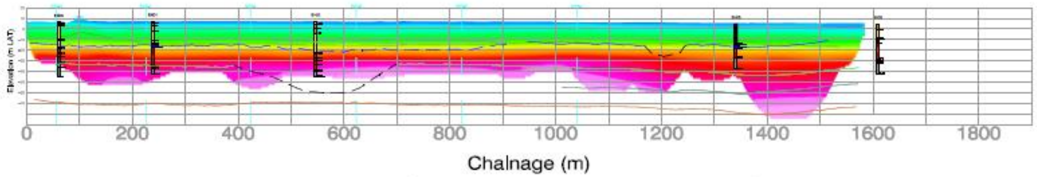
Geophysics: Ground Models from Geophysics



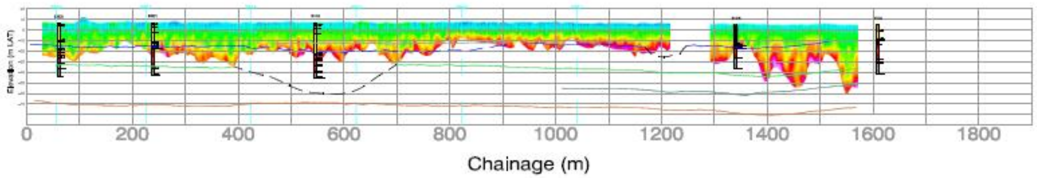
Reflection Geophysics - Capable Faulting



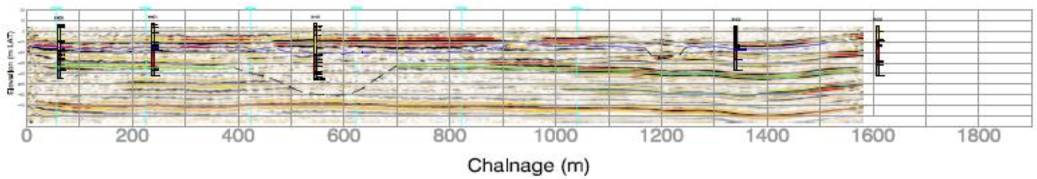




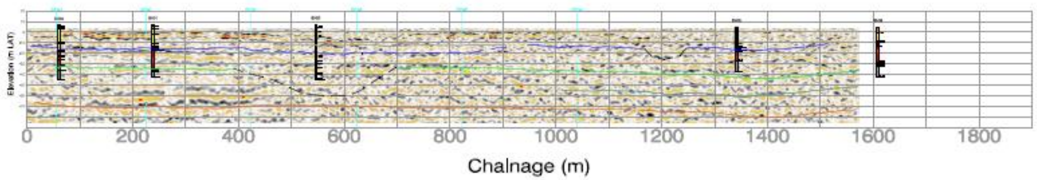
Route 1 - S-wave velocity from SRT



Route 1 - S-wave velocity from MASW

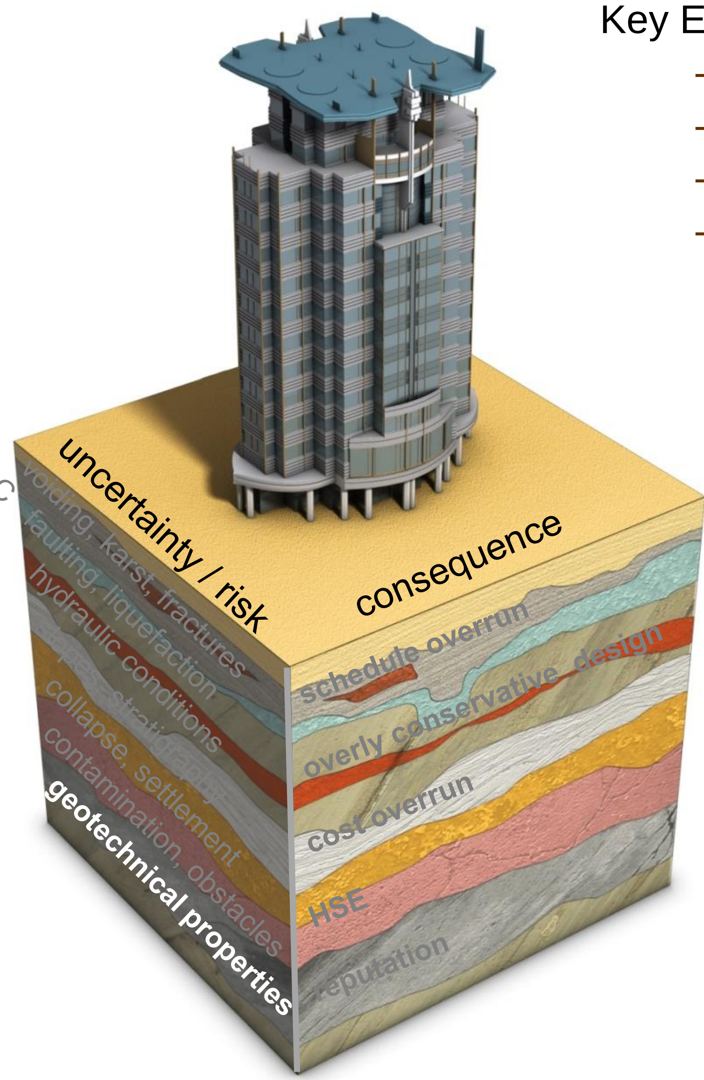


Route 1 - P-wave reflection stack



Route 1 - S-wave reflection stack

Site Screening: Geophysics – (Stiffness, Vs, Gmax)



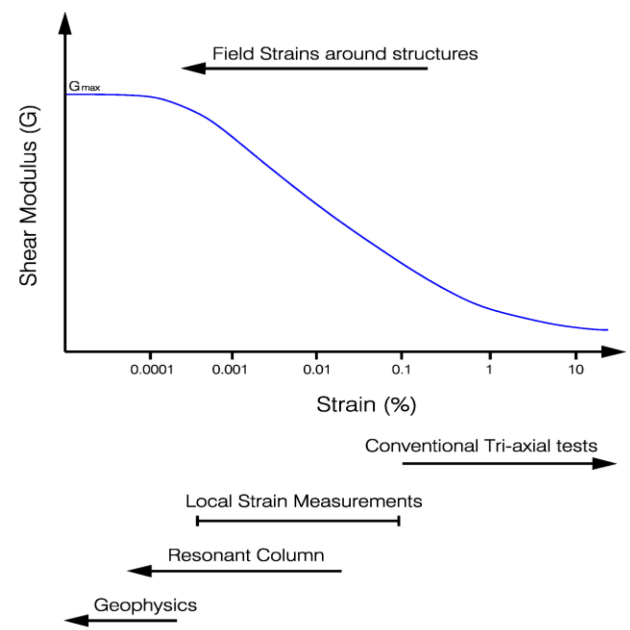
Key Elastic Properties:

- Poisson's Ratio – change in transverse strain with applied axial str
- Shear Modulus – shear strain with applied shearing force
- Bulk Modulus – change in volume with applied pressure
- Young's Modulus – change in length with applied tension

Poisson's Ratio is determined by measuring P- and S-wave seismic velocity.

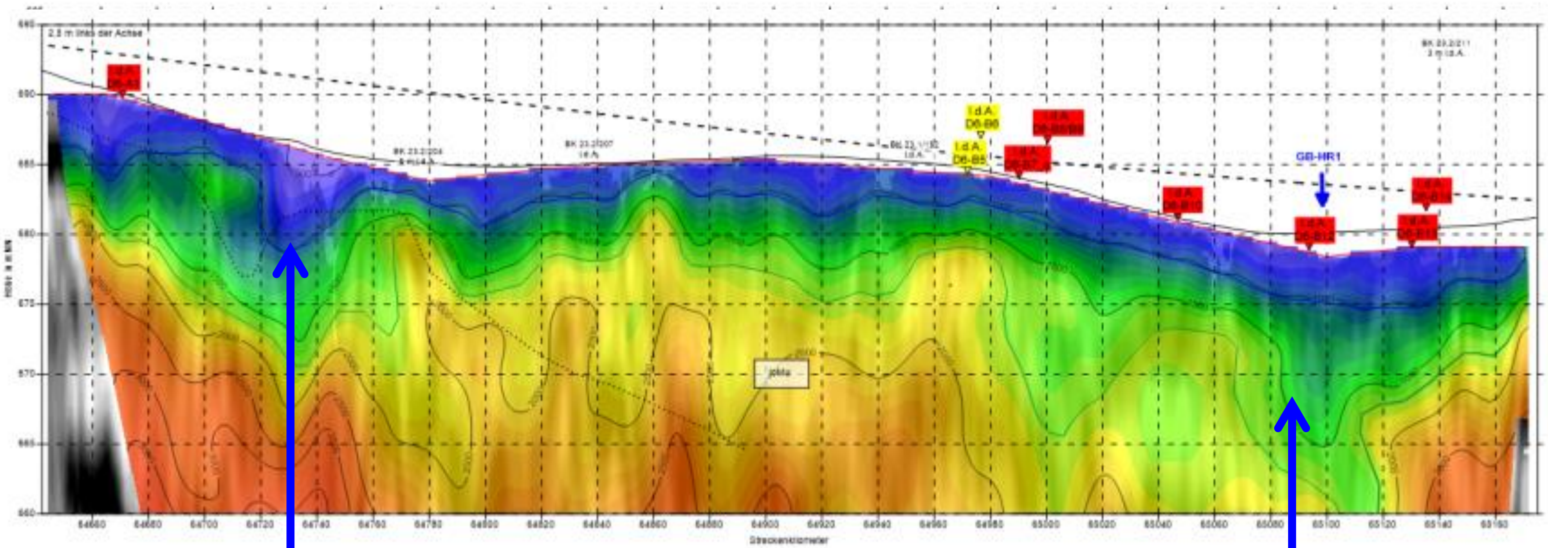
Modulus determination combines P- and S-wave seismic velocity and density.

Geophysical methods are particularly effective for determination of stiffness at very low strain.



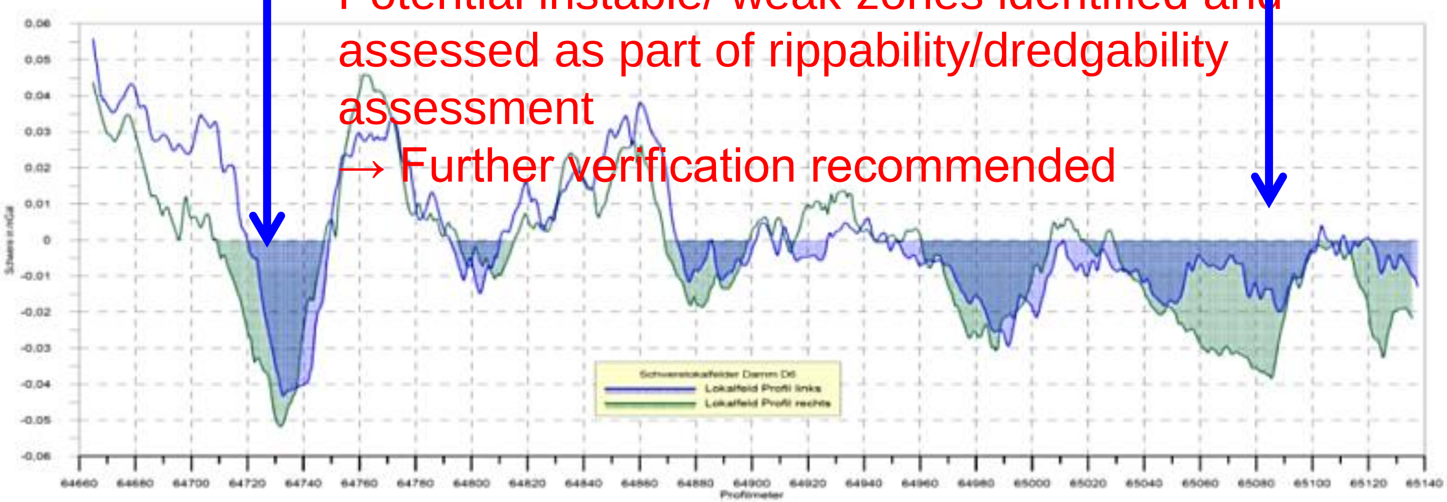
Shallow Risks and Stiffness (Seismic Refraction Solution)

Joint application and interpretation of reflection seismic and refraction (MASW)



Potential instable/ weak zones identified and assessed as part of rippability/dredgability assessment

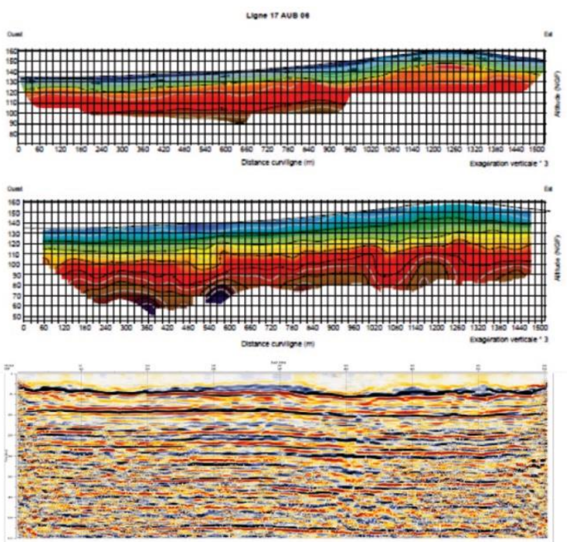
→ Further verification recommended

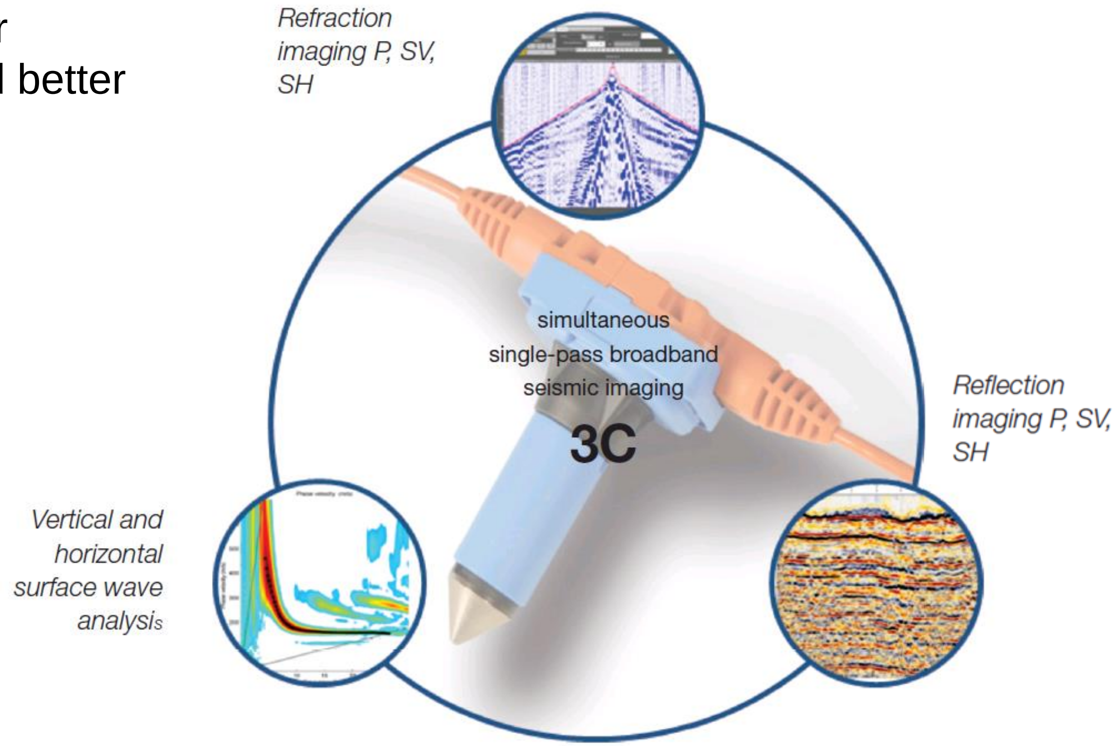


Fugro Innovations: Multi component 3C seismic surveying

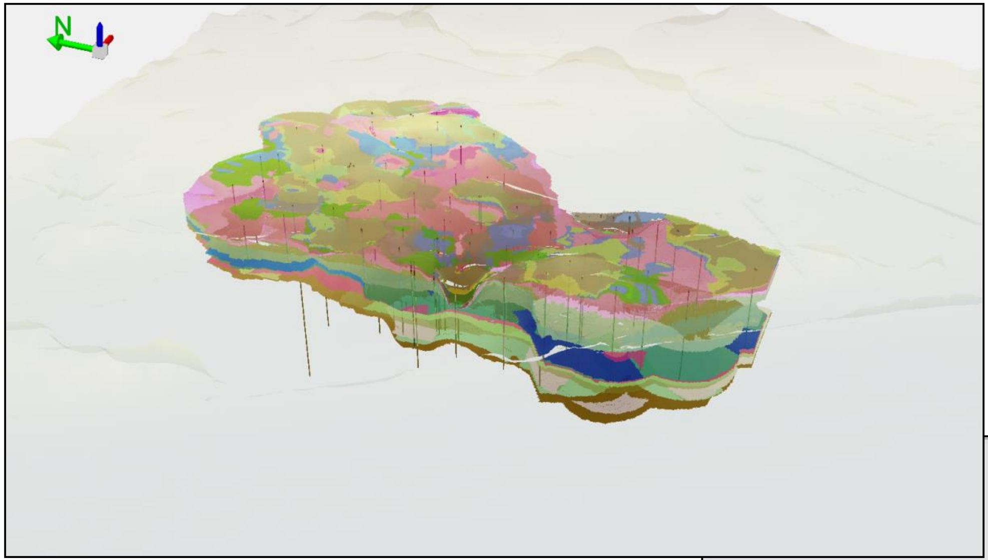
Fugro’s 3C system is based on multicomponent MEMS receiver technology, giving:

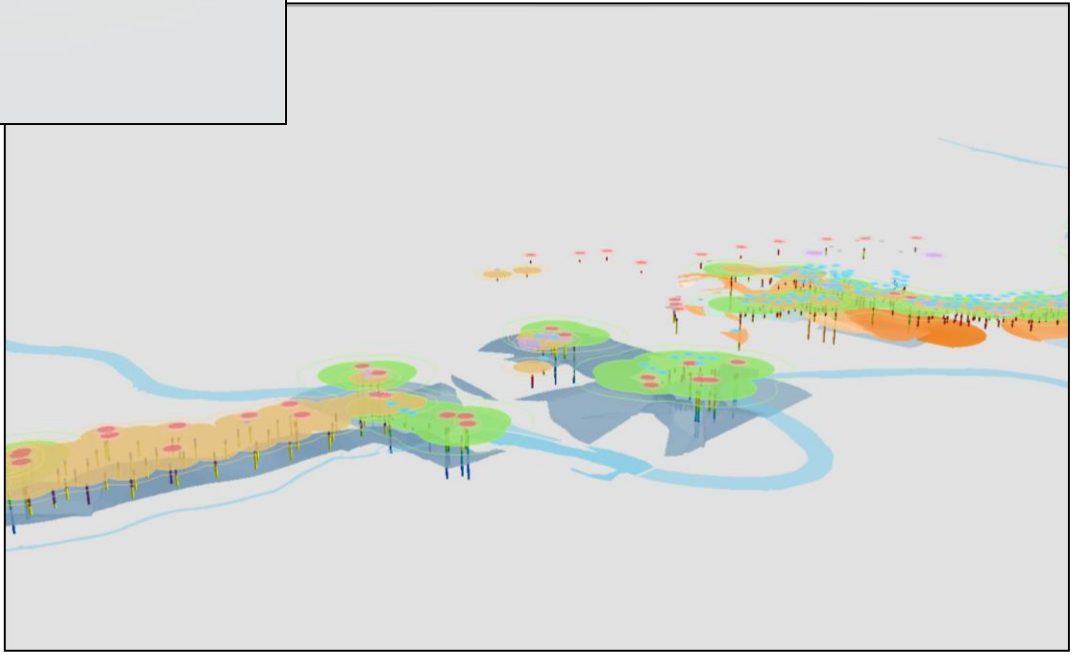
- Combined stratigraphic and structural imaging and screening of geotechnical properties in a single-pass: Seismic reflection imaging of deeper geologies and faulting, refraction imaging of shallow hazards, stiffness profiling
- >30% reduction in field schedules and lower data acquisition cost
- Fully scalable to shallow or deep applications (greater depth than traditional)
- Higher data volumes compared to traditional approaches – higher interpretational confidence and better Ground Model deliverables





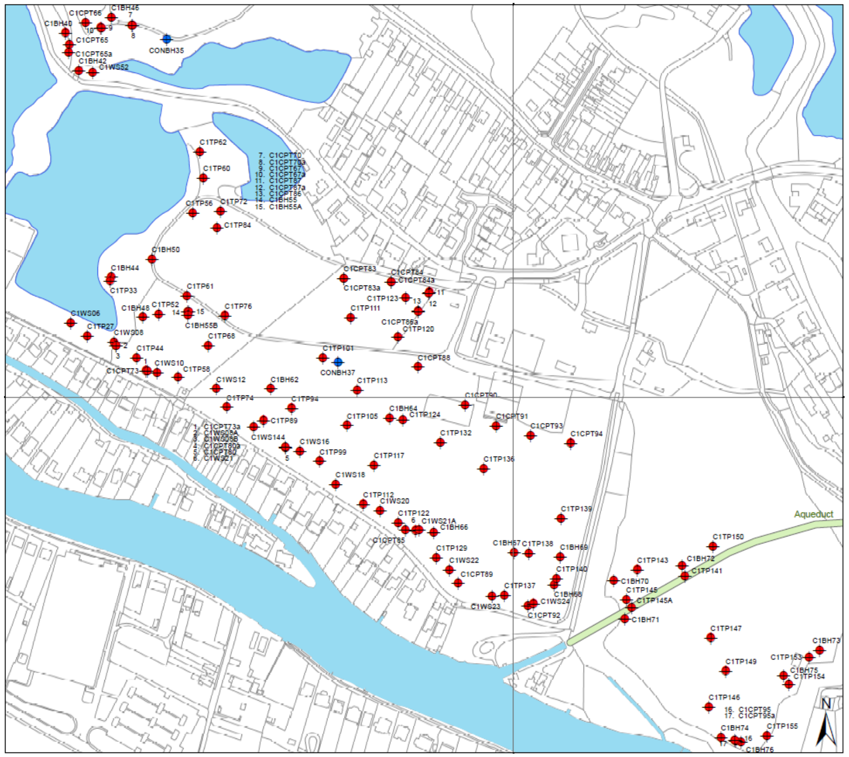
Intrusive Investigation Based Models



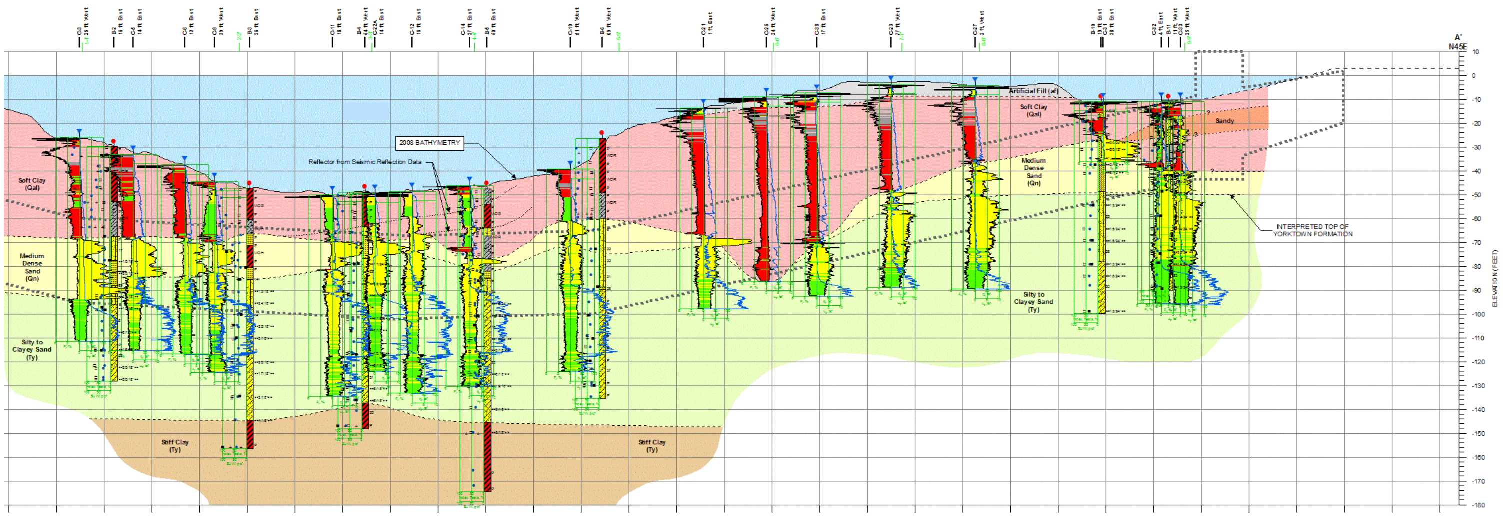


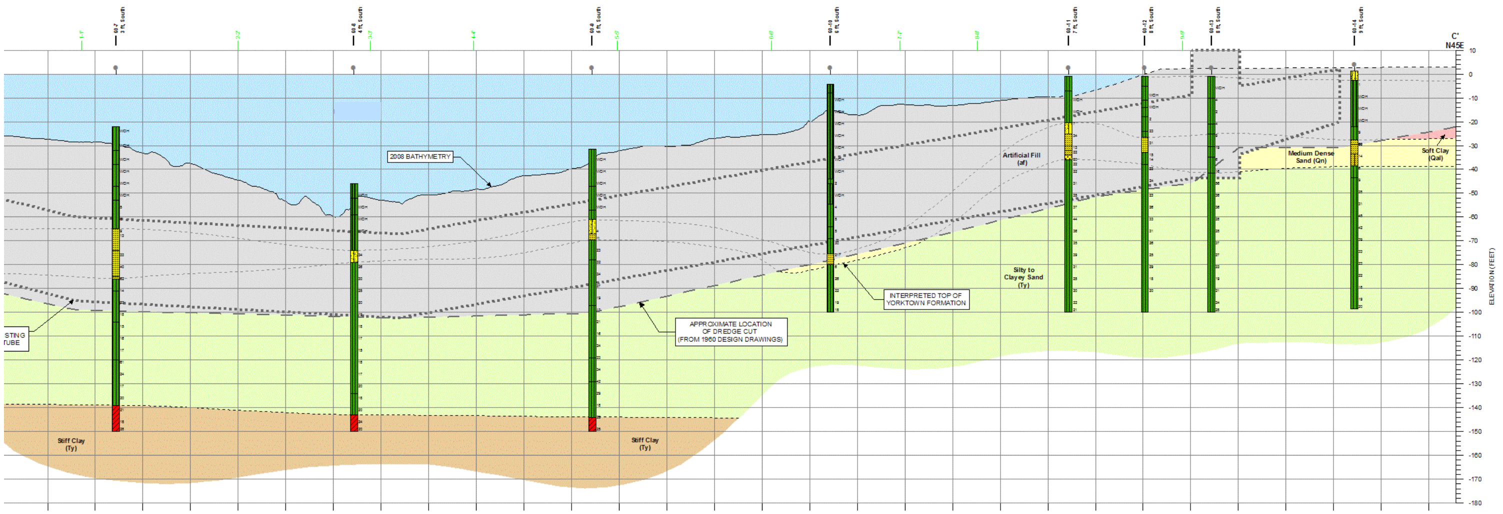
Targeted Investigations Vs. Grid Based:

How will you manage continuous vs. spot sampled data in the model?...introduction of bias due to weighting exponents…bias can be isotropic and anisotropic

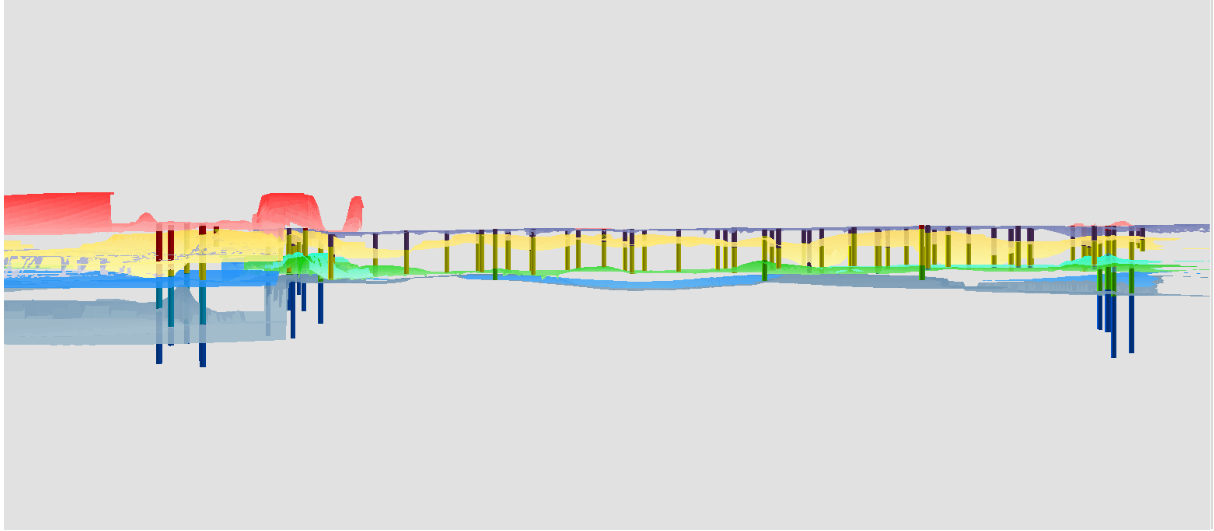


Case Study - Midtown Tunnel, Virginia: Reliance on Boreholes



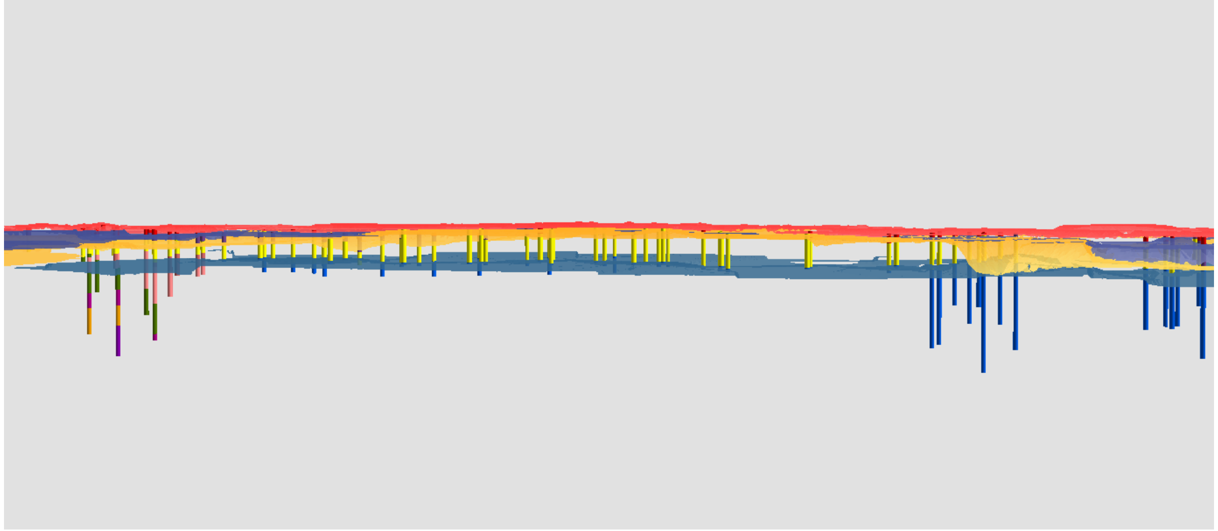


CPT and the Ground Model



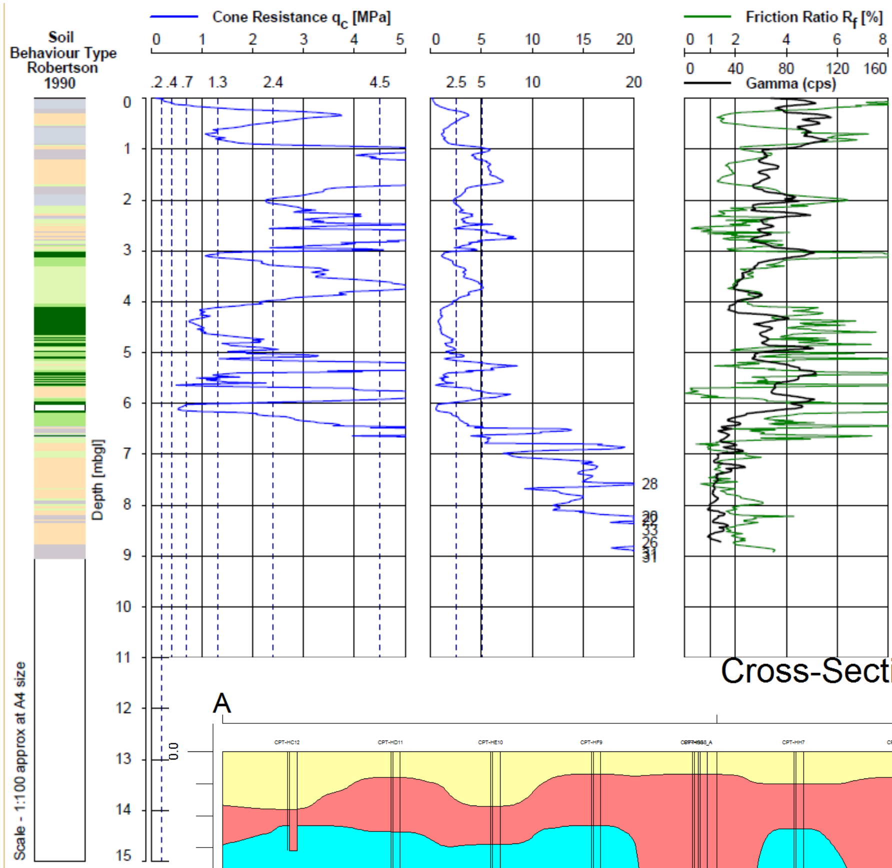
Clustered CPT producing high detail areas in a model; all refusing at the same geological boundary and delineating it

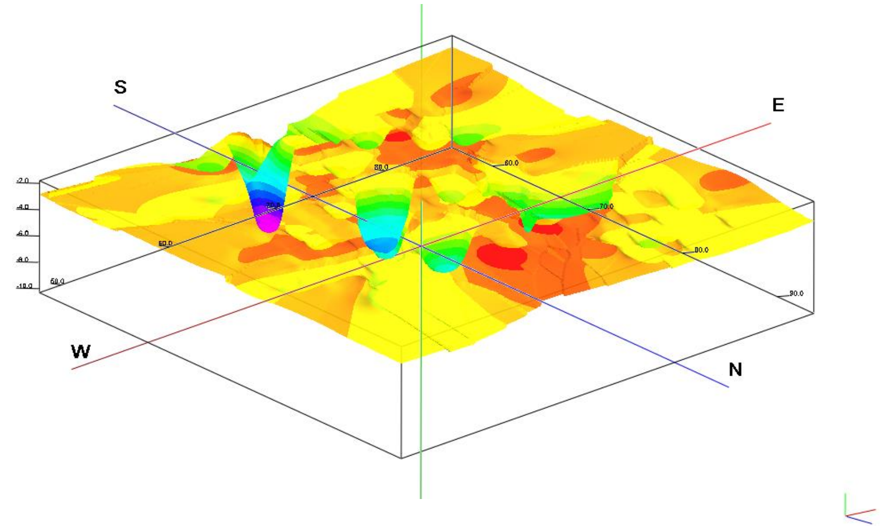
Better depth penetration than trial pits

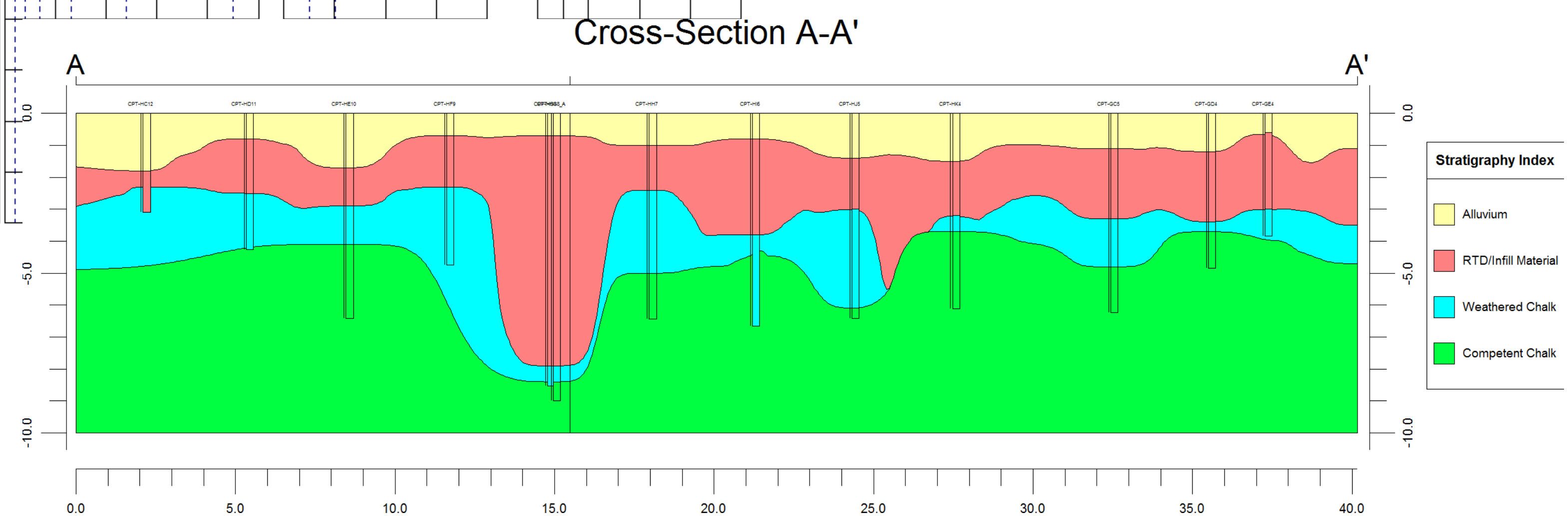


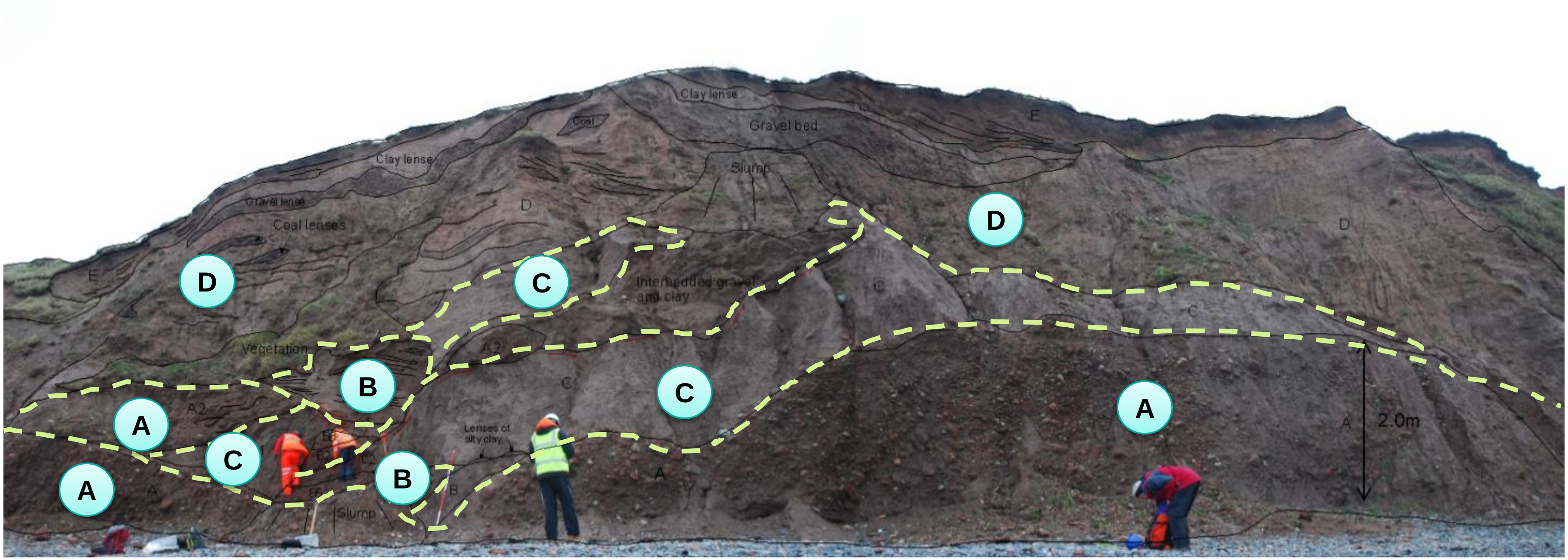
All CPT's penetrated to depth of key geology; London Clay/Lambeth Group

Specialist data collection: Gamma Cone

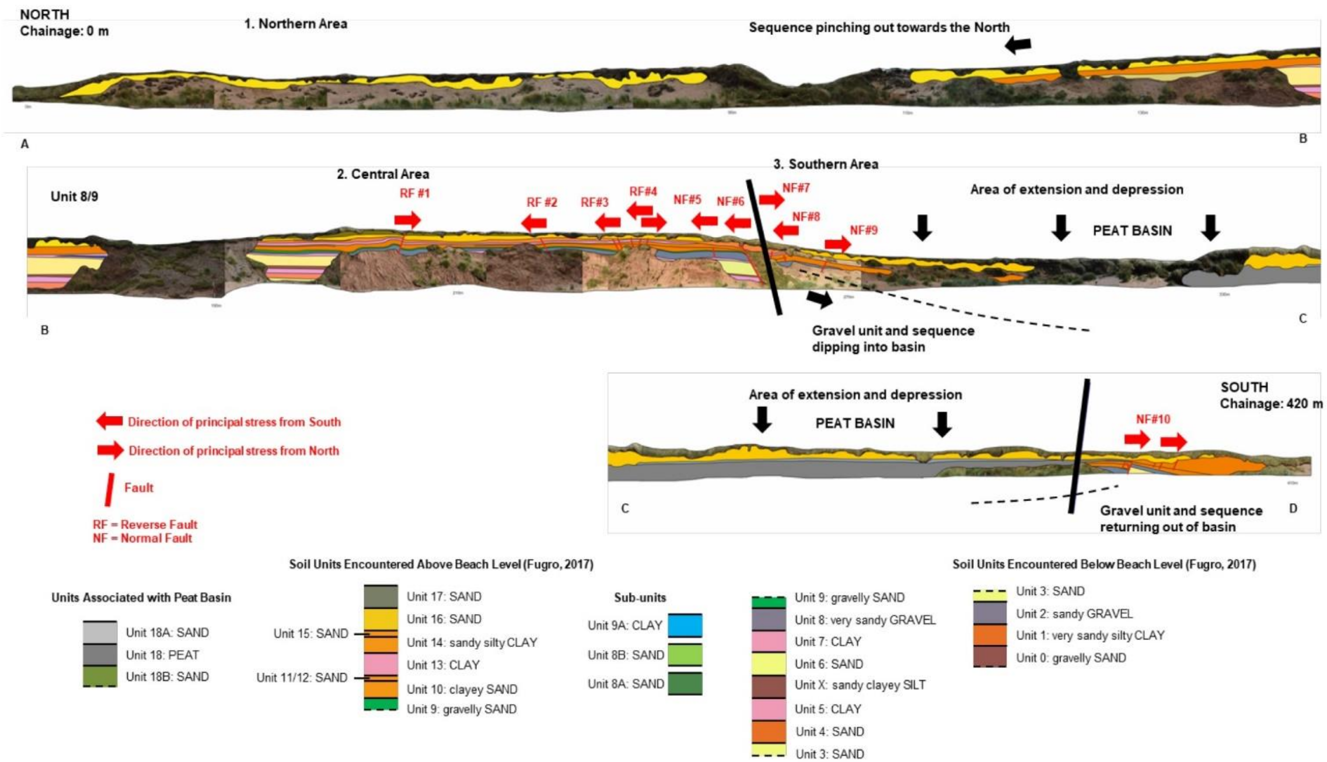


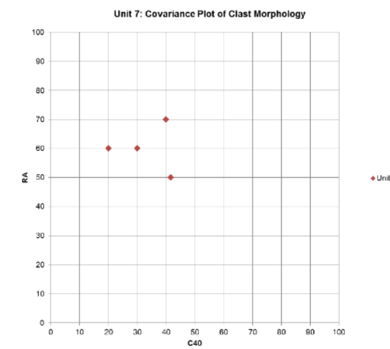


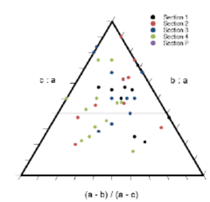


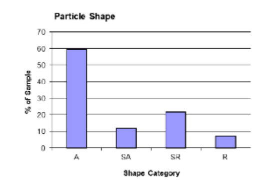

D
C
D
B
C
A
A
C
A
B
Clay lense
Gravel bed
Slump
Clay lense
Gravel lense
Coal lenses
Coal
Interbedded gravel and clay
Vegetation
Lenses of silty clay
Slump
2.0m

- Understanding depositional events and processes to support the ground model is very beneficial
- Use to develop a workable stratigraphic framework that can be extrapolated sensibly beyond observational data
- Use of specialists in relevant terrain types essential



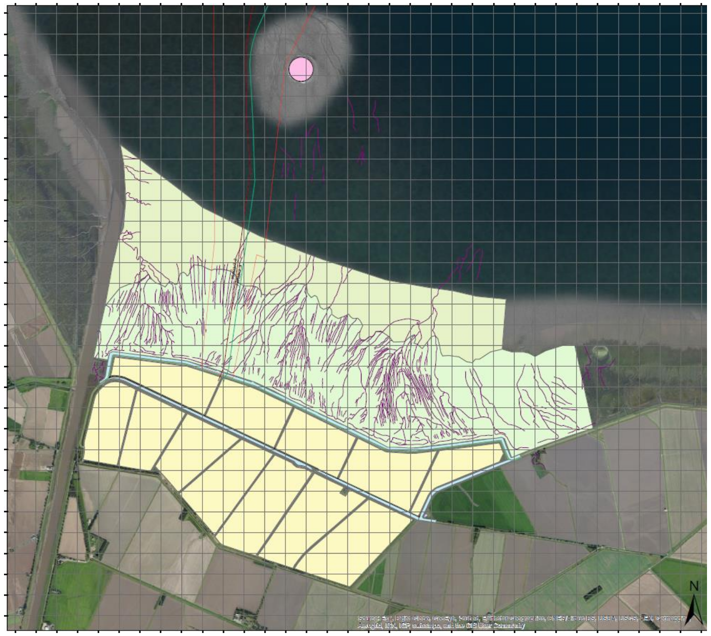




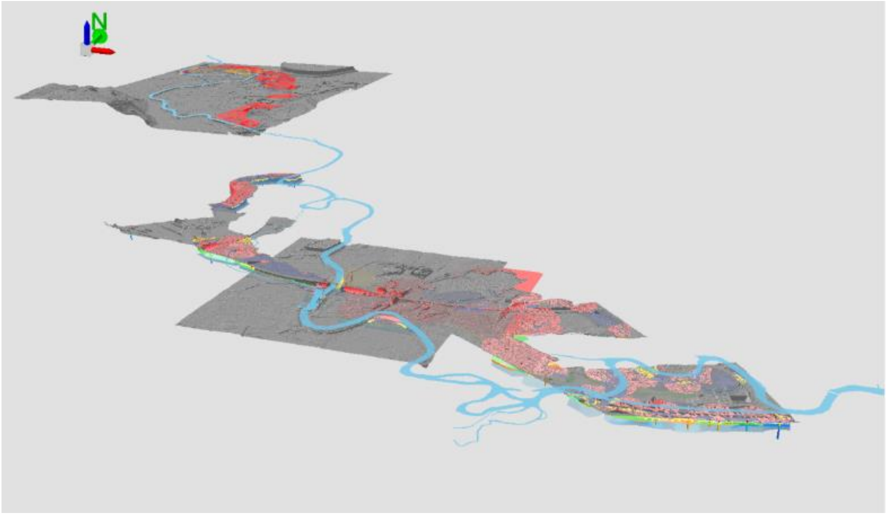


Geomorphology in the Ground Model

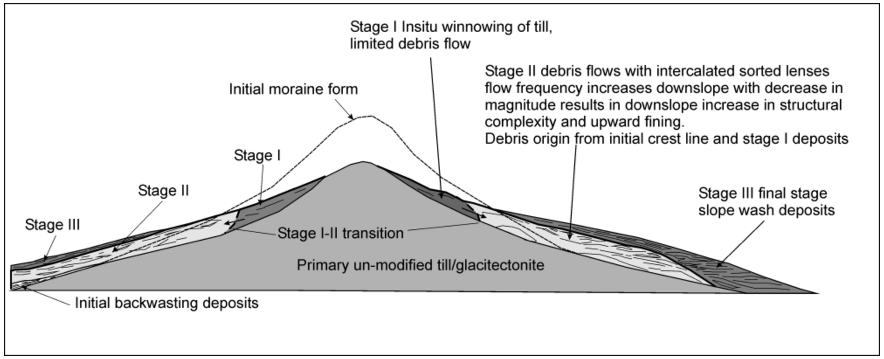
Mapping and visualising Geomorphology

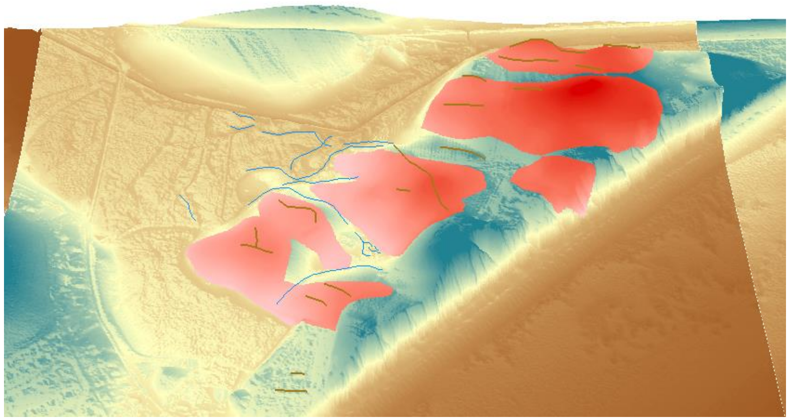


LiDAR surfaces constraining the upper surface of the model

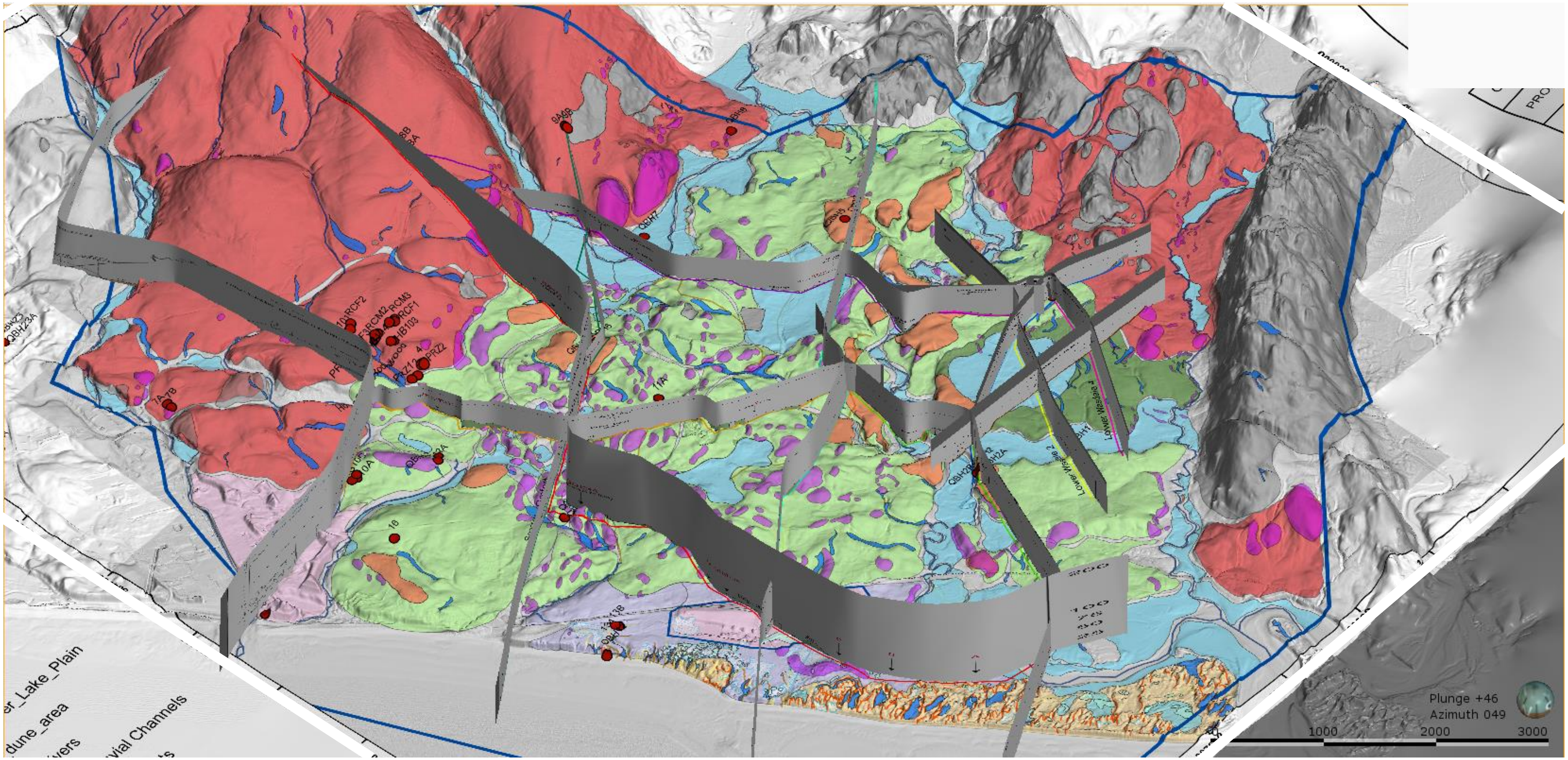


Mapped Geomorphology used to extrapolate geologies based on sediment-landform and process-form relationships





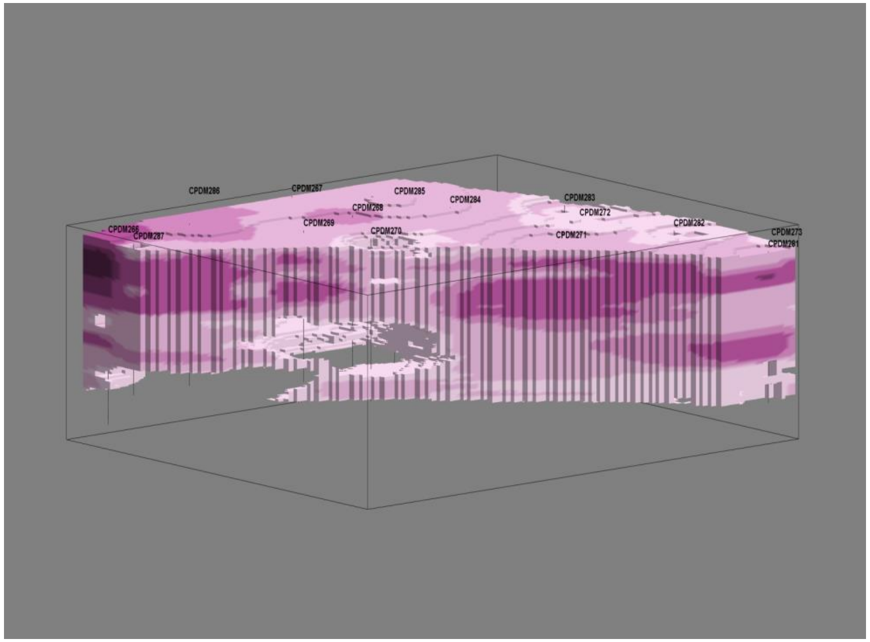
Geomorphology and Geological Judgement

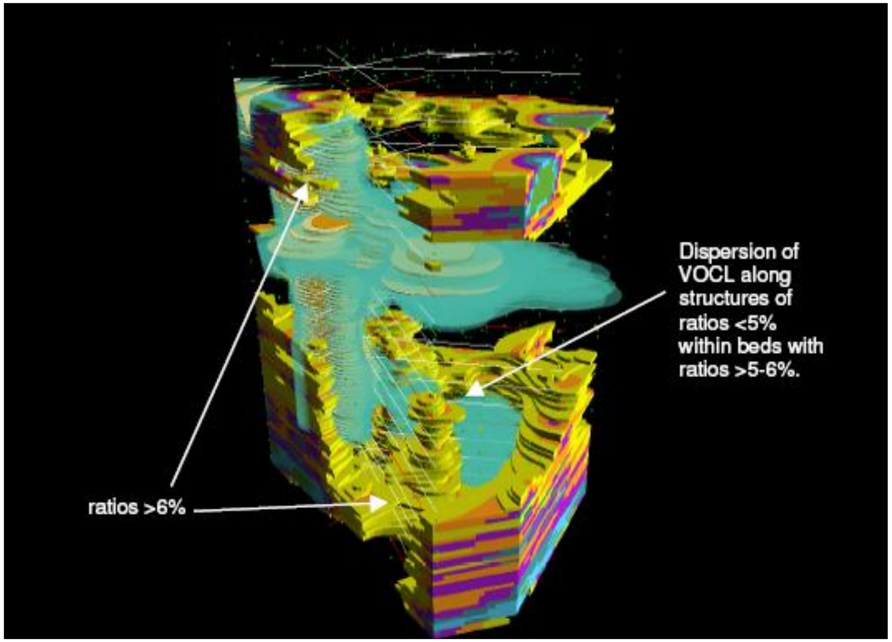


Contamination Assessment

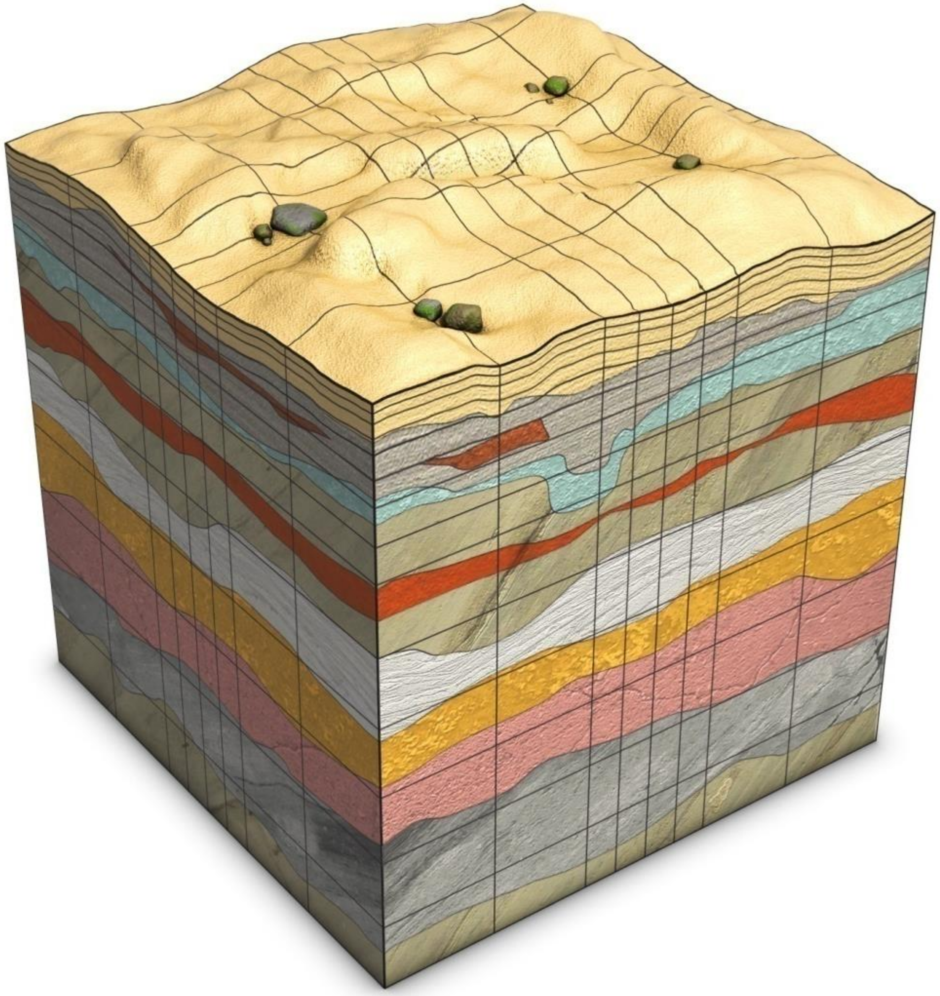
- Normally voxel based extrapolation
- Parameter visualisation
- Digital data straight into model
- Visualise contamination extents within geology types
- Plan for better remediation
- 4D models for remediation validation and pollutant migration

- Due to high frequency of data capture environmental CPT lends itself to building these types of models

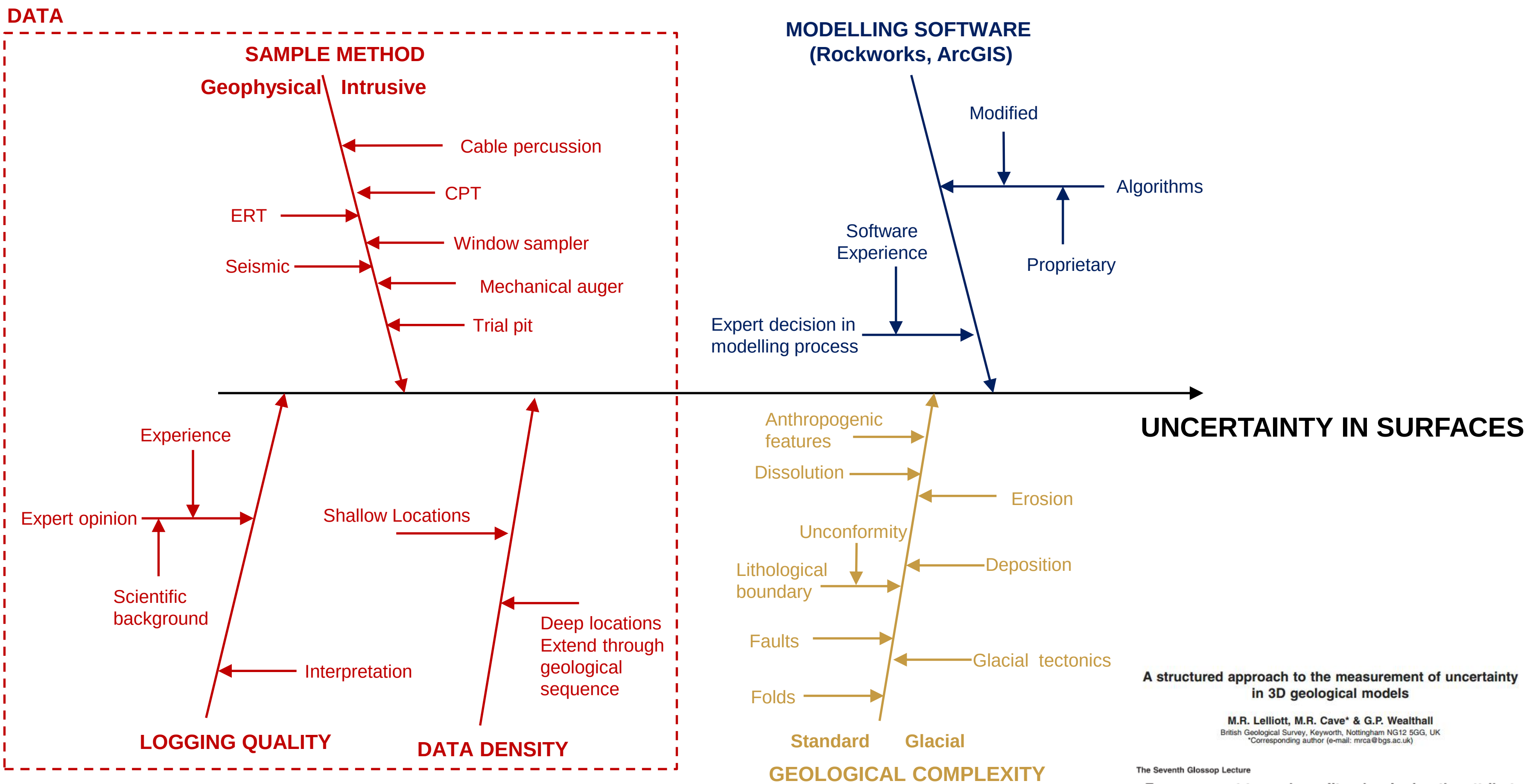




Communicating Uncertainty



Uncertainty in Ground Model Surfaces



A structured approach to the measurement of uncertainty in 3D geological models

M.R. Lelliott, M.R. Cave* & G.P. Wealthall
British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
*Corresponding author (e-mail: mrca@bgs.ac.uk)

The Seventh Glossop Lecture

From concept towards reality: developing the attributed 3D geological model of the shallow subsurface

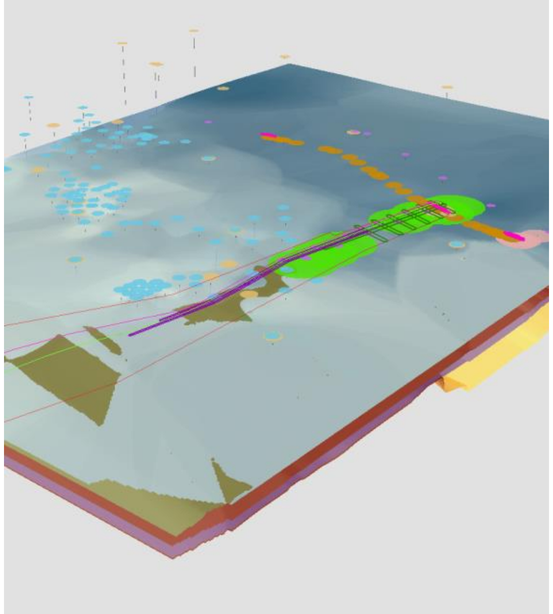
M.G. Culshaw
British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, UK

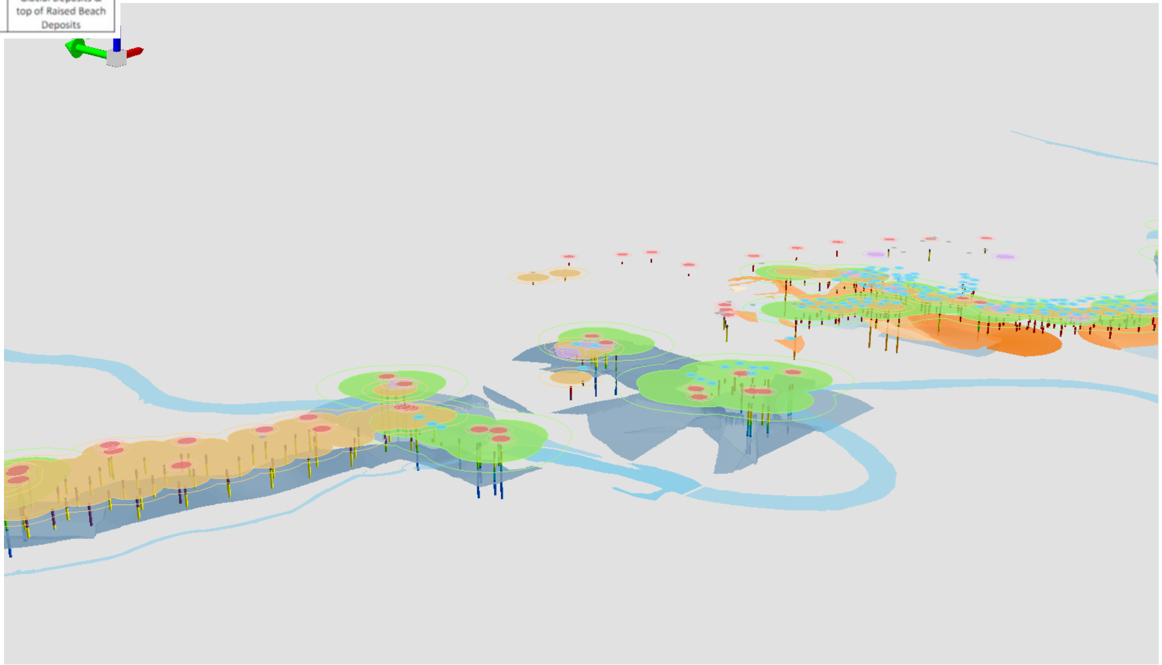
Building Ground Models: Data Quality and Uncertainty

Data Quality Assessment used in Ground Models

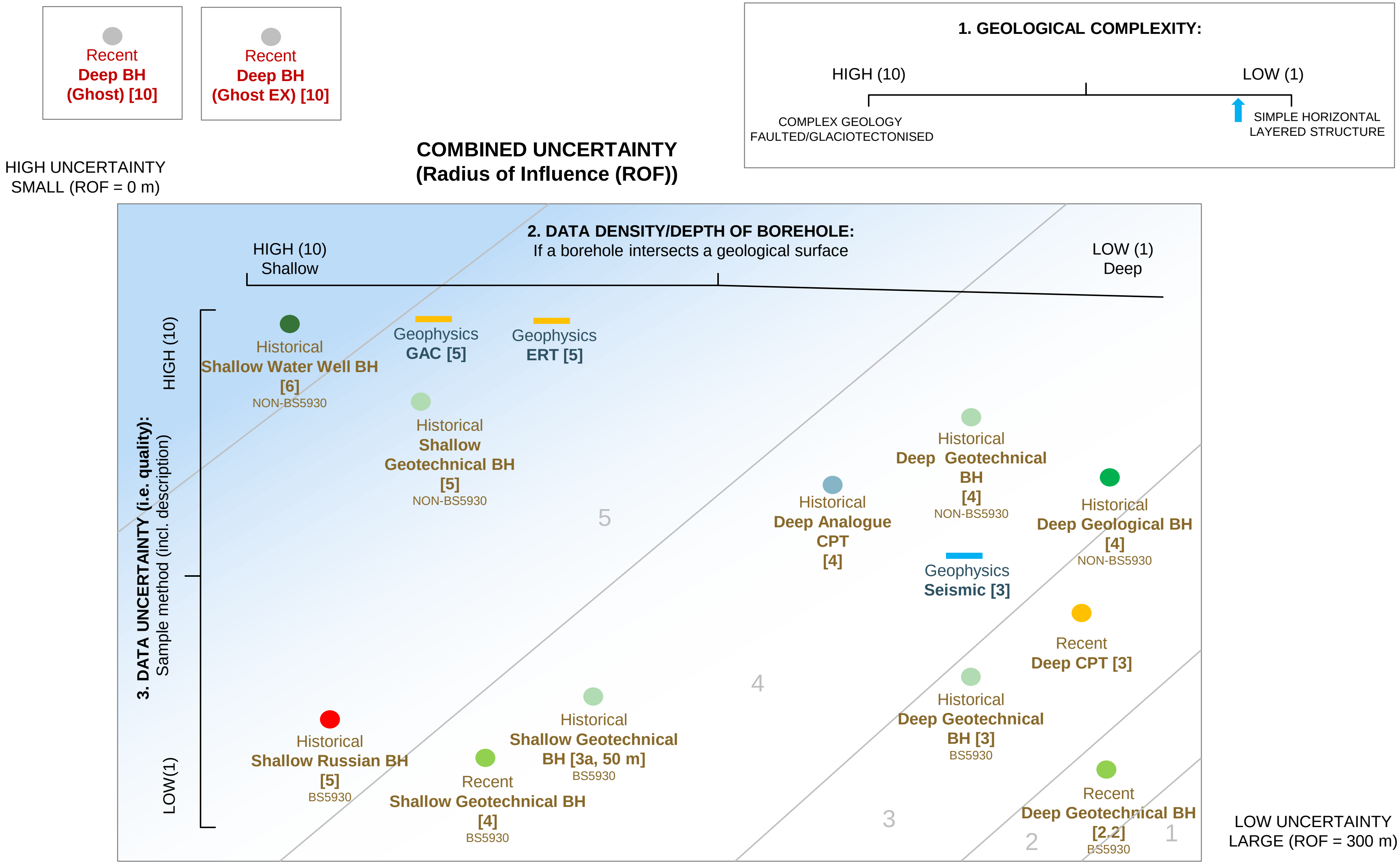
Borehole No.	ETRS89 UTM 31N Co-ordinates		Ground Elevation LAT (m)	Total Hole Depth (m)	Data Source	Technique	Remarks	Data Quality Assessment
	Eastings (m)	Northings (m)						
507905			6.03	20.00	BGS – Borehole database	Analogue CPT	Gravel re-evaluated as Raised Beach Deposits	Original CPT has been re-evaluated; suitable for proving top of Late Glacial Deposits
507908			5.88	21.00	BGS – Borehole database	Analogue CPT	Sand and gravel on CPT evaluated as Raised Beach Deposits	CPT only penetrates Raised Beach Deposit
507909			6.03	13.00	BGS – Borehole database	Analogue CPT	Alluvial Sands re-evaluated as Raised Beach Deposits	Original CPT has been re-evaluated; suitable for proving top of Raised Beach Deposits
507910			5.43	15.00	BGS – Borehole database	Analogue CPT	Alluvial Sands re-evaluated as Raised Beach Deposits	Original CPT has been re-evaluated; suitable for proving top of Raised Beach Deposits
507912			5.43	20.00	BGS – Borehole database	Analogue CPT	Re-interpreted geology based on the re-evaluation of Holocene Alluvial Sands to Raised Beach Deposits	Original interpretation on log is questionable; has been re-evaluated; suitable for proving top and base of Late Glacial Deposits & top of Raised Beach Deposits

Uncertainty in elevation of geological surfaces Visualised based on data coverage, suitability/type of data and inherent complexity of the geology

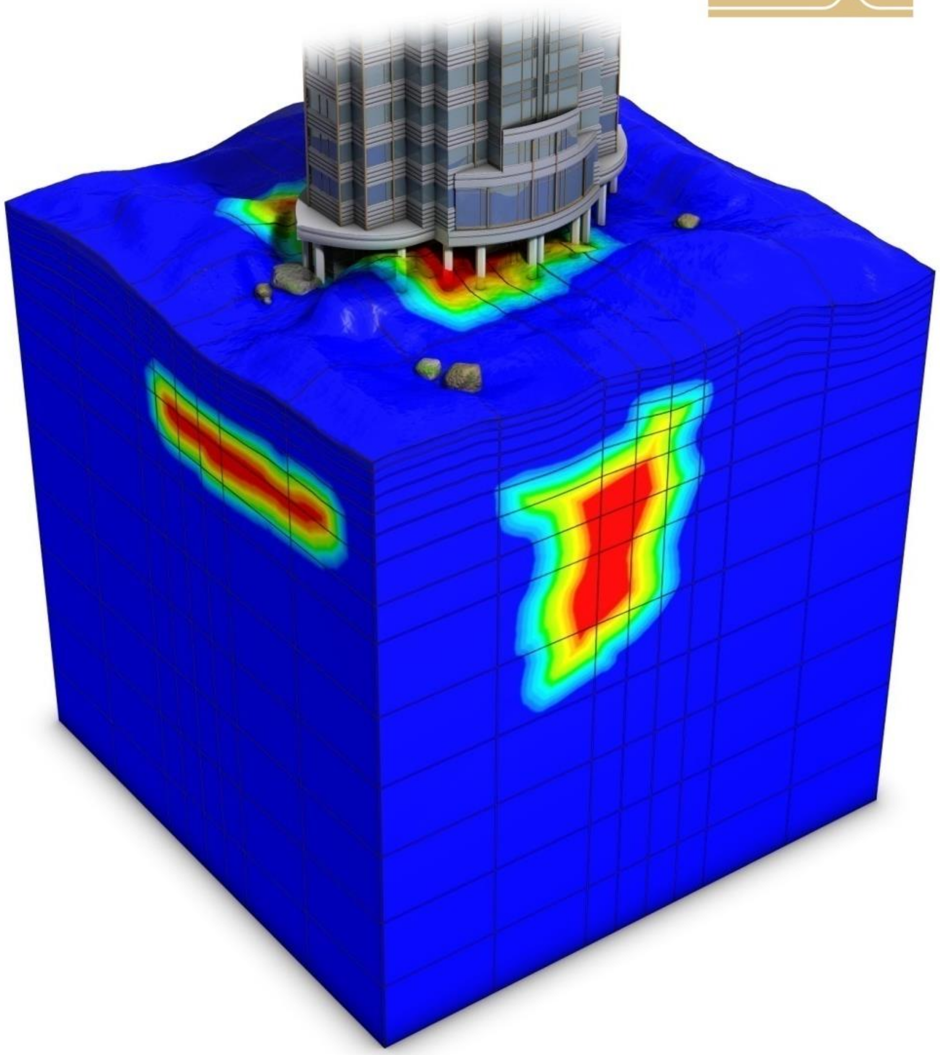




Combined Uncertainty

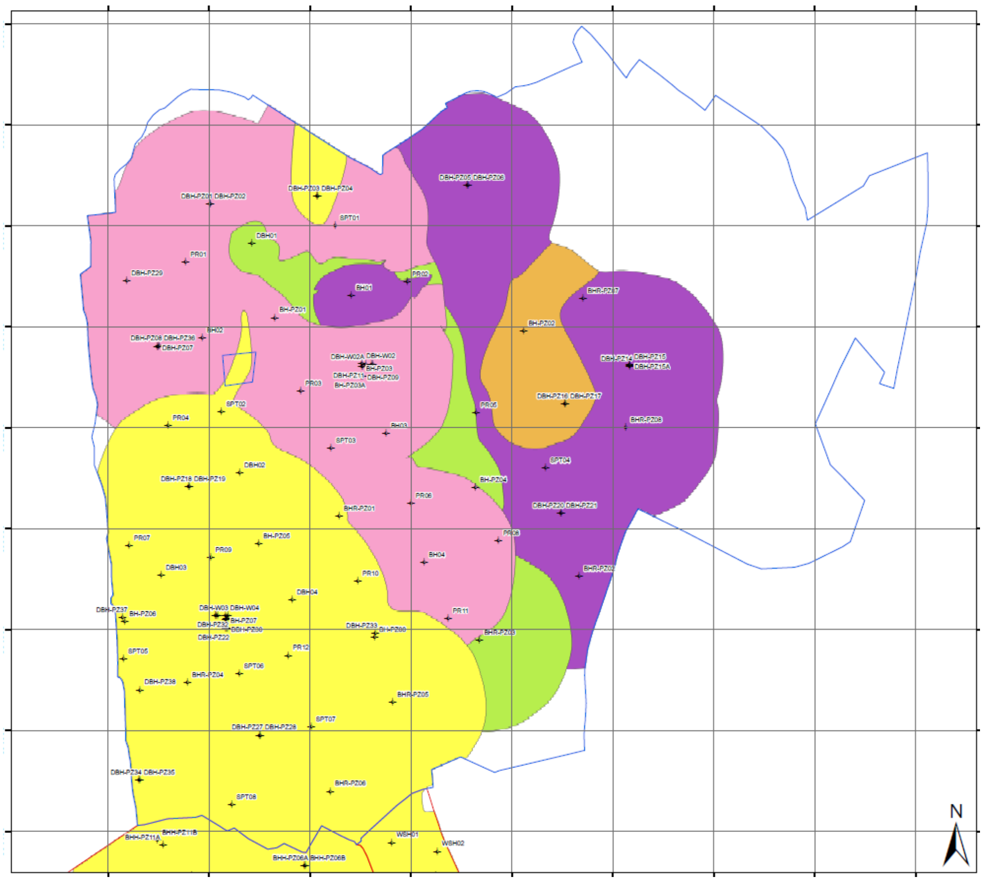


Analysis and Decision Making

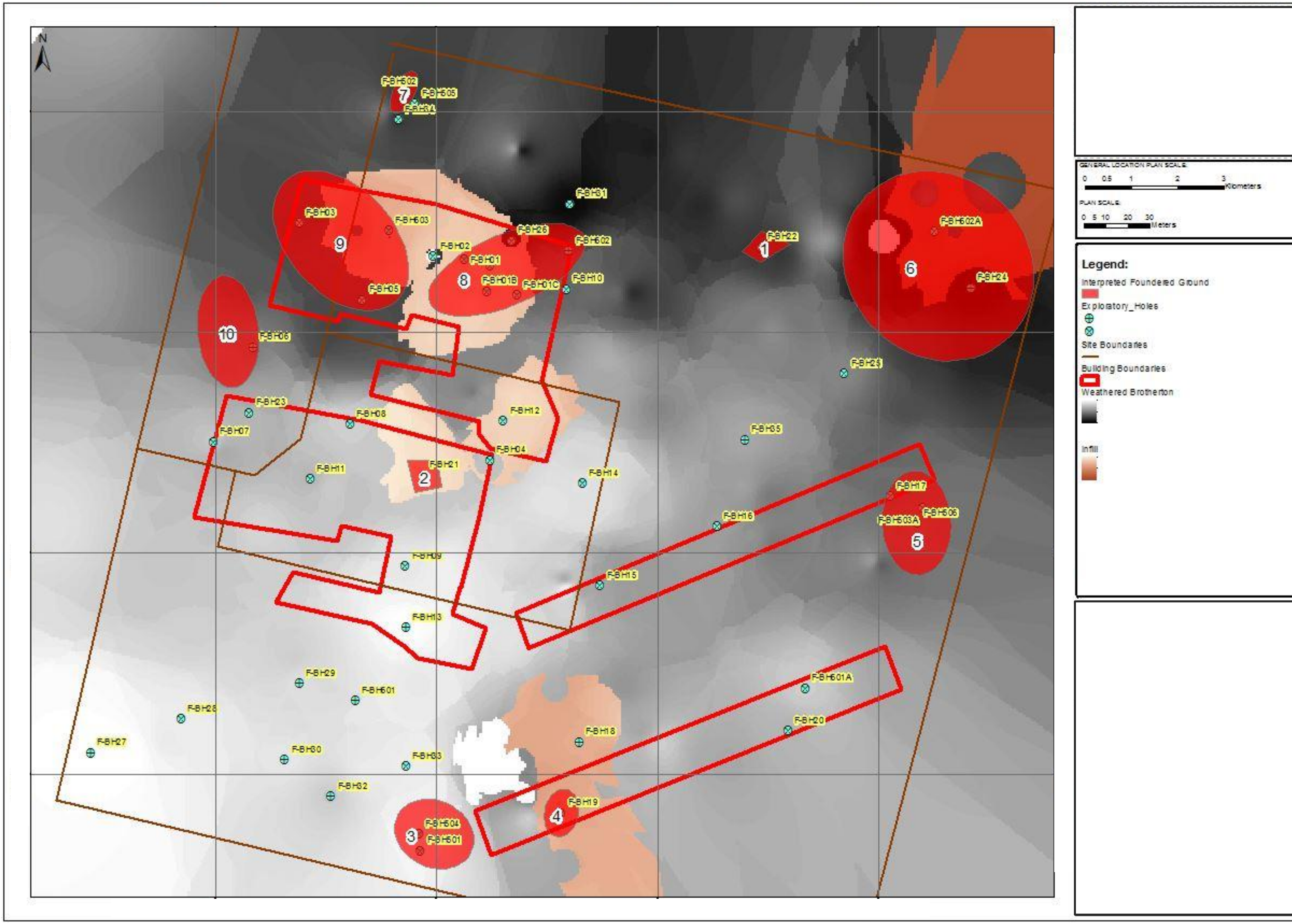


Establish bounding criteria (geotechnical parameters, unit presence/absence, unit thickness) and interrogate the GIS model to provide mapping content:

- Site selection
- Site layout
- Route Planning



Identified Geohazards

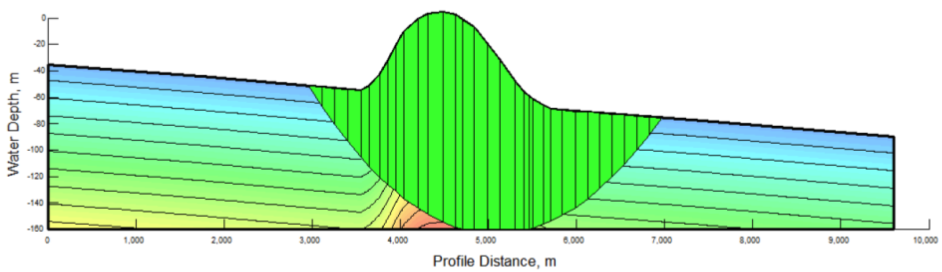


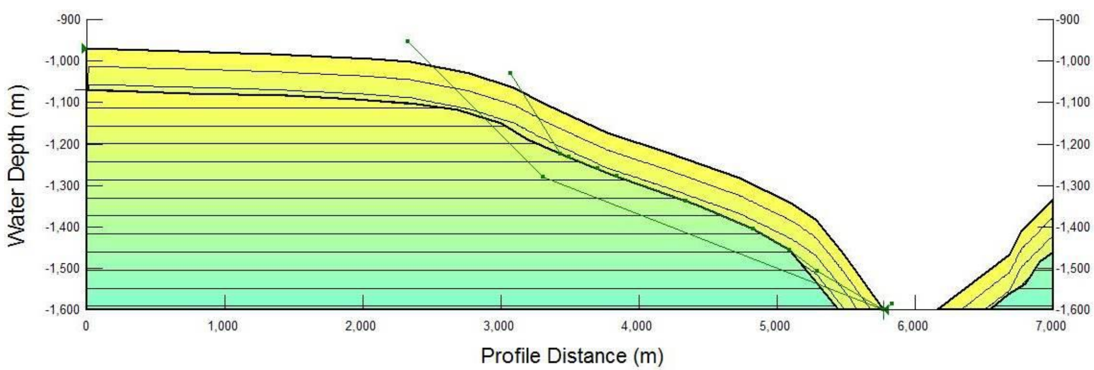
Engineering Constraints

Table 10.1 Geohazard Risk Assessment Matrix					
Approach	**Hazard**	**Constraint(s) imposed by the Hazard**	**Probability of the hazard being realised**	**Considerations/ Mitigation**	**Significance and Manageability of the Constraint**
Deep Horizontal Directional Drill	Drilling through Holocene Alluvial Sands or Raised Beach Deposits	Possible loss of flush pressure/hole collapse	Very likely in loose sands at surface Likely below ~5m where Alluvial Sands are typically silty fine sand and generally not free draining. Very likely below ~10-15m bgl where sands typically become cleaner and together with Raised Beach Deposits become free-draining.	Consider use of casing whilst advancing hole to top of till if possible. Unlikely to be able to case exit route of hole through sands Attempt to control by use of thick drill mud Consider excavation of sealed shaft for access to below depth of deposits, particularly on landward side of route where casing will not be possible (likely high cost)	Manageable/Potentially Unmanageable Major constraint: HDD Contractor to advise on viability of drilling through sands and gravels
	Sands with high liquefaction potential (i.e. encountering a palaeochannel within Holocene Alluvial Sands)	Running Sands coming up casing: Possible seizing of rotary drilling wash-over pipework	Uncertain probability if drilling from seaward extent of route as insufficient data to assess extent of sands with high liquefaction potential in this area. Considered likely that the exit leg of the route may encounter such ground conditions due to the mapped frequency of buried channels in land	Utilise geophysical survey techniques to map area around proposed HDD start and end points and adjust to avoid hazard. May be able to control running sands with addition of large volume of water/flush. Will likely require casing for seaward start of drill. Consider construction of sealed pit/shaft to below depth of these deposits on seaward and landward entry /exit points	Potential Manageable Major Constraint: Additional cost for further geophysical survey and re-position start/end of HDD if required. HDD Contractor to advise on viability of drilling through and managing sands with high liquefaction potential
		Sands possibly blowing out of hole if drill started in pit below sea bed with unequal water pressures.	As above	As above	
		Creation of voids leading to subsidence	As above, considered unlikely that significant voids will form	As above	
		Loss of flush pressure and hole collapse	As above	As above	
	Flush fracturing of near-surface soils	Near surface soils (Holocene Alluvium) has insufficient strength to hold flush pressure at start or end of drill runs leading to fracturing and eventual outbursts of flush to surface May lead to subsequent collapse of mudflat surface where voids are created	Likely to occur at reception point due to inability to control flush accurately at this distance. Unlikely to occur at start point due to control of flush pressure	Some flush burst out at reception may be unavoidable but unlikely to form a major constraint	Minor Unmanageable Constraint at reception point Minor Manageable Constraint at start point
	Encountering Lateglacial Deposit including peat	Flush erosion of low strength clays and peats leading to flush pressure loss and potential limited hole collapse	Lateglacial Deposits potentially very extensive and thick locally present at seaward start point; Likely Only infrequently identified and where present found only as a <0.50m thick layer close to endpoint onshore; considered unlikely deposit will be encountered in this location	Reduce probability of encountering Lateglacial Deposits using Geomodel. Reduce consequence of encountering this deposit by controlling advancement speed and flush pressure during strata boundary transitions and maintain mud pressure in hole to avoid collapse	Potentially only a Minor Manageable Constraint; HDD Contractor to advise on constraints
	Very Dense Raised Beach / Glacifluvial Deposits	Potential drill deflection if at shallow angle when encountering deposits	Extensive and poorly defined but likely thick coverage close to seaward start point; considered very likely such deposits will be encountered Raised Beach Deposits only locally present and not very thick at landward exit point; Unlikely	Certainty that a deep HDD route would have to pass through these deposits Possibly could reduce consequence of encountering this deposit by controlling advancement speed during strata boundary transitions Consider construction of sealed shaft to base of deposits and undertaken drill from base of shaft (likely very high cost)	Possibly a Major Unmanageable Constraint HDD Contractor to advise on viability of progressing HDD without subsequent hole collapse through thick gravels at this distance
		Flush loss and potential hole collapse in free-draining gravels	As above	Attempt to maintain flush pressure and use very thick muds. Consider use of casing to top of tills at seaward start point	
	Incised glacifluvial channels in till surface infilled with lower density sands/gravels	Potential deflection if channel encountered at wrong geometry	Probability depends on planned HDD profile; those channels mapped are located in the centre of Tunnel Valley feature into surface of Lowestoft Formation Till. Assuming known features can be avoided; considered unlikely to encounter unknown features	Plan HDD profile to avoid all known features. Identification of known features does not preclude the presence of other such features of similar of smaller scale. May prove to be difficult to manage flush loss if such a feature is encountered	Possible Major Manageable Constraint
		Flush loss and potential hole collapse in free-draining gravels			
	Drilling of deep cohesive soils	Variability in shear strength of tills and Kimmeridge Clay: average undrained shear strengths not considered to be outside capabilities of even small HDD plant however, observation of high and low strength outliers particularly in Lower Till and Kimmeridge Clay may result in deflection if associated beds are encountered at specific geometries	Certainty of encountering variable strength beds in tills and Kimmeridge Clay if HDD profile passes through these deposits.	Lower Till and Kimmeridge Clay show highest number of shear strength outliers. May reduce the variability by planning route through Lowestoft Formation Till only. Drill advancement rate to be considered in light of variable ground conditions	HDD Contractor to advise on drill capabilities and plan works accordingly: Likely to be a Minor Manageable Constraint

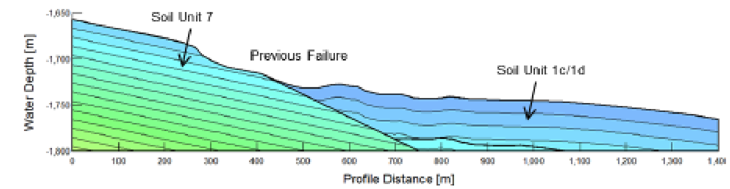
Engineering Analysis

- Cross sections: Export to design software/slope stability software
- Export of parameters, hydrogeological surfaces etc to design software/slope stability software
- Visualisation of geotechnical parameters
- Analytical models: FE analysis
- Rapidly accessible databases allows multiple model/engineering analysis runs



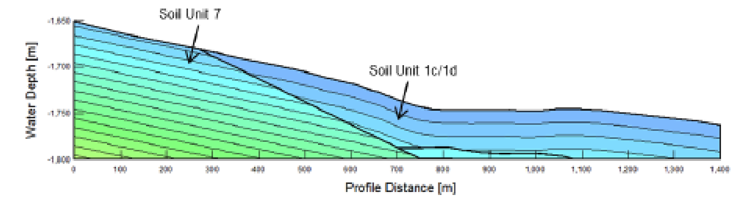


Failed Profile adjacent to Profile 2



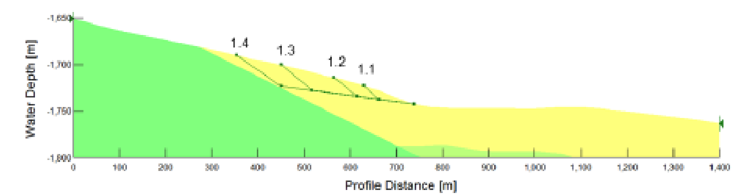
Vertical exaggeration = 2
Colour shading represents change in s_u

Profile 2 Geomechanical Model



Colour shading represents change in s_u

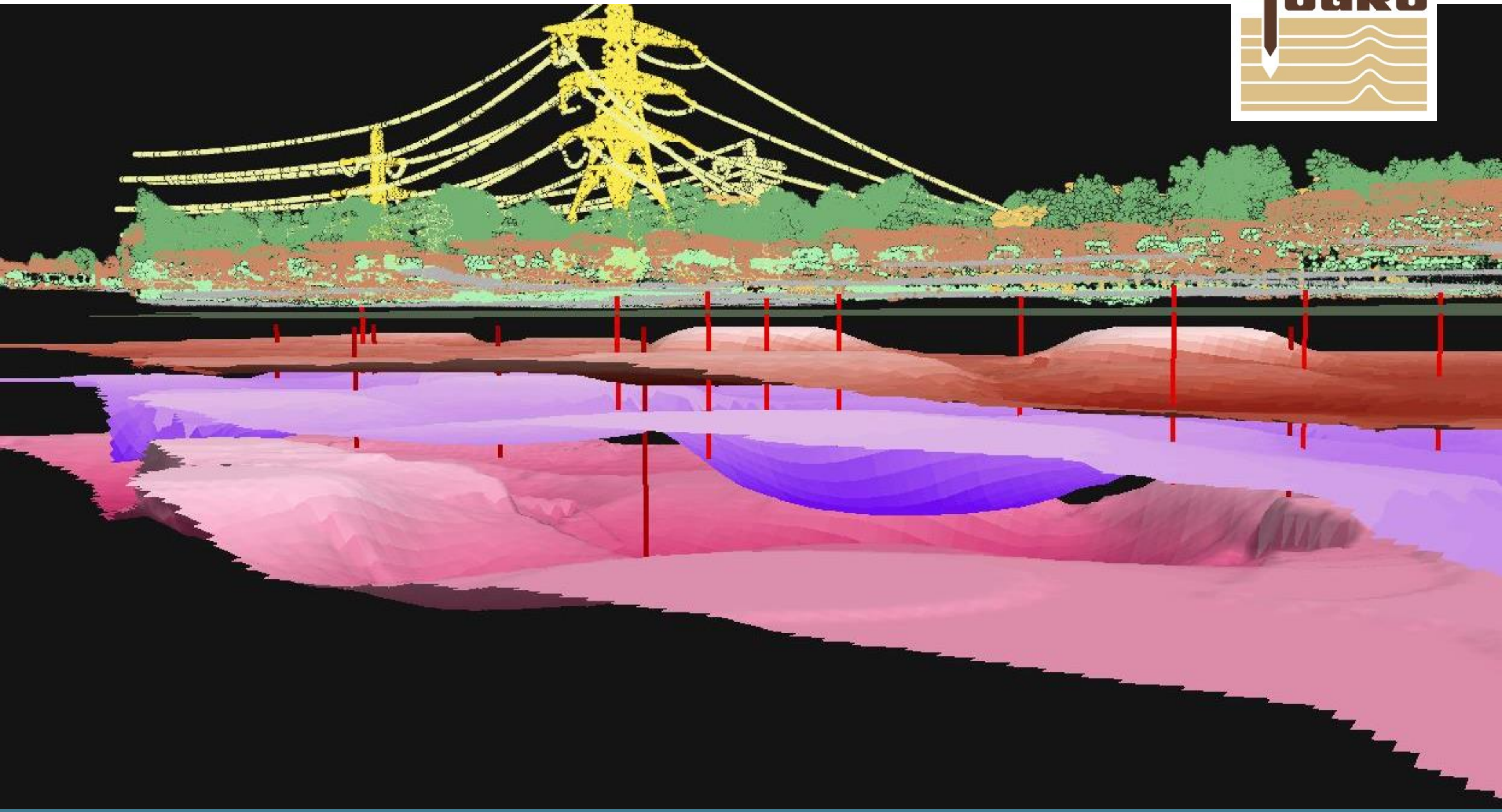
Profile 2 - Failure Surfaces



Colour shading represents individual geotechncial soil units

Failure Surface Number	Average Depth [m BSF]	Gravity Loading (FOS)	Earthquake Return Period [Years]				
			100 (FOS)	500 (FOS)	2,500 (FOS)	5,000 (FOS)	10,000 (FOS)
1.1	5	2.43	1.90	1.54	1.24	1.10	0.97
1.2	7.5	2.62	1.76	1.41	1.12	0.99	0.87
1.3	10	3.34	1.80	1.42	1.11	0.97	0.84
1.4	12.5	2.41	1.86	1.47	1.13	1.00	0.86

Figure 5.7: Results for Slope/W Analyses at Profile 2



Integrated Site Characterisation: Case Studies

Engineering Assessment for Cable Landfall :

Advanced site characterisation:

Phased approach

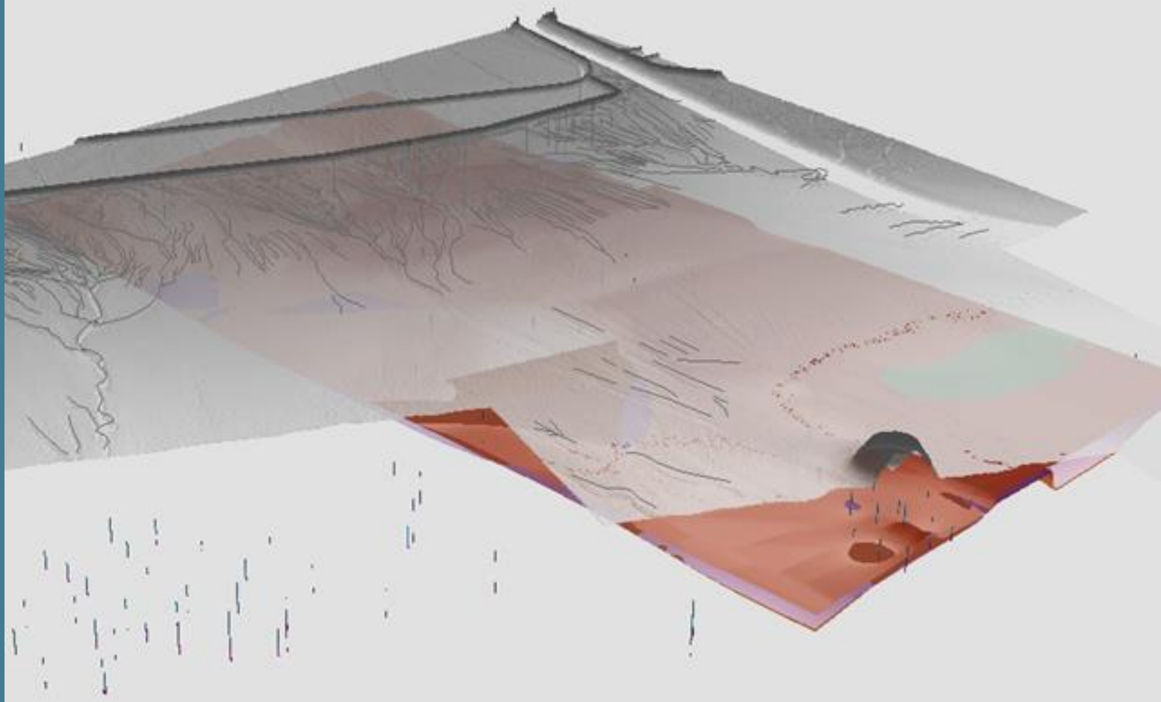
Range of Geophysics

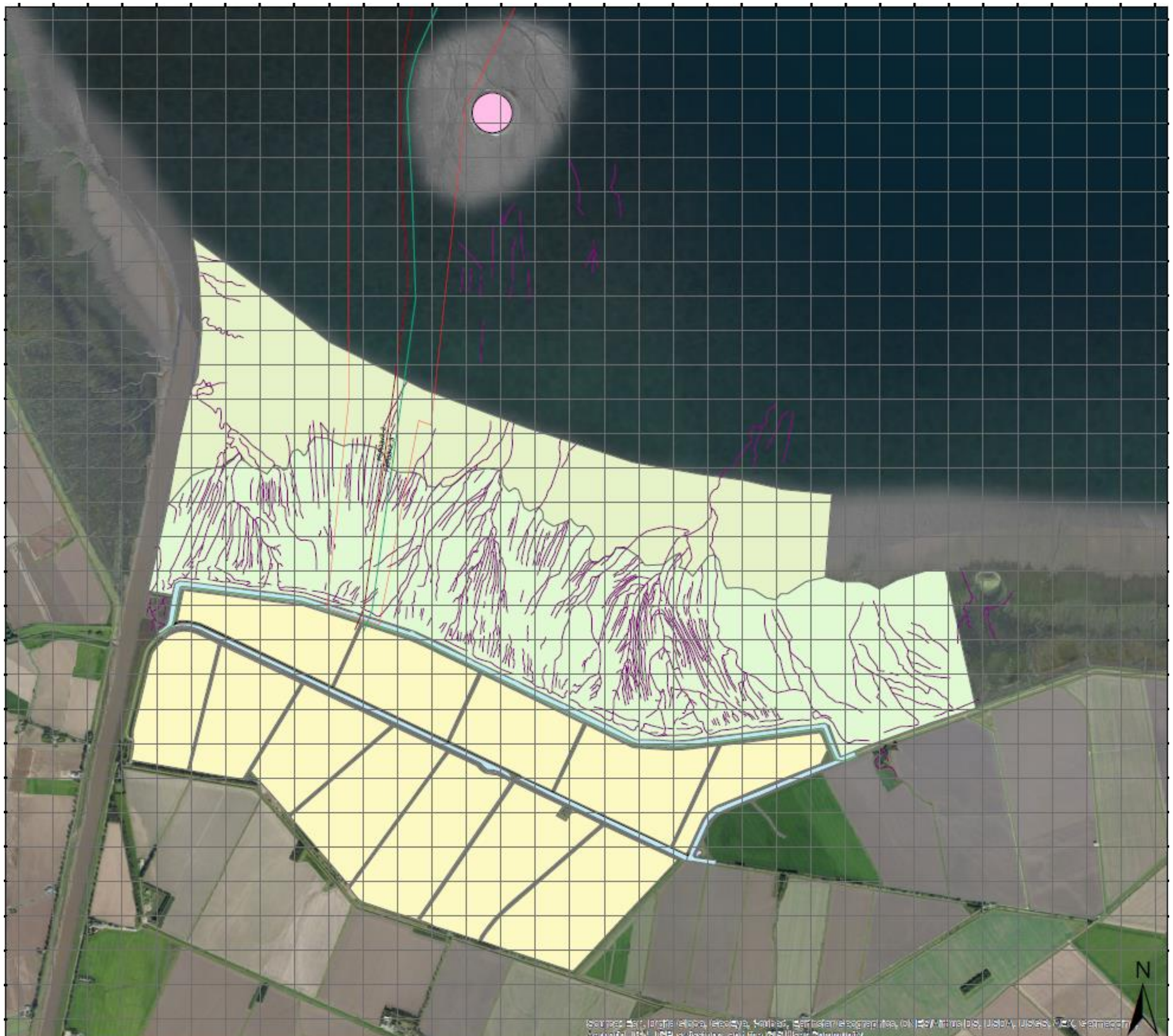
Intrusive SI

Use of historical data

Ground modelling

Engineering assessment




N

Planning Investigations In Complex Terrains

Need to consider:

- **Nature and likely complexity**; internal heterogeniety and geometry of beds (**specialist knowledge**),
- Objectives in relation to the ground engineering task,

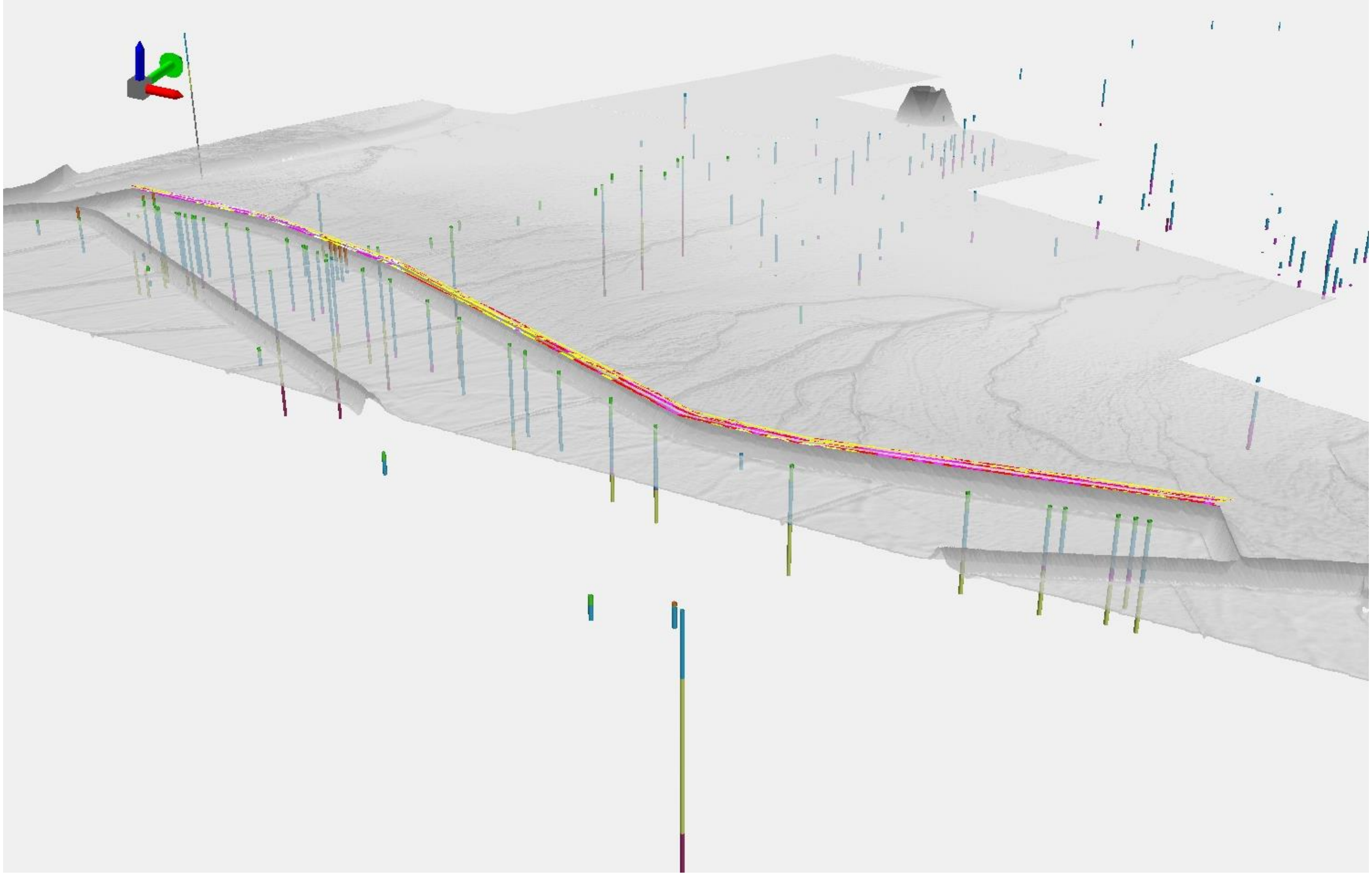
to then define:

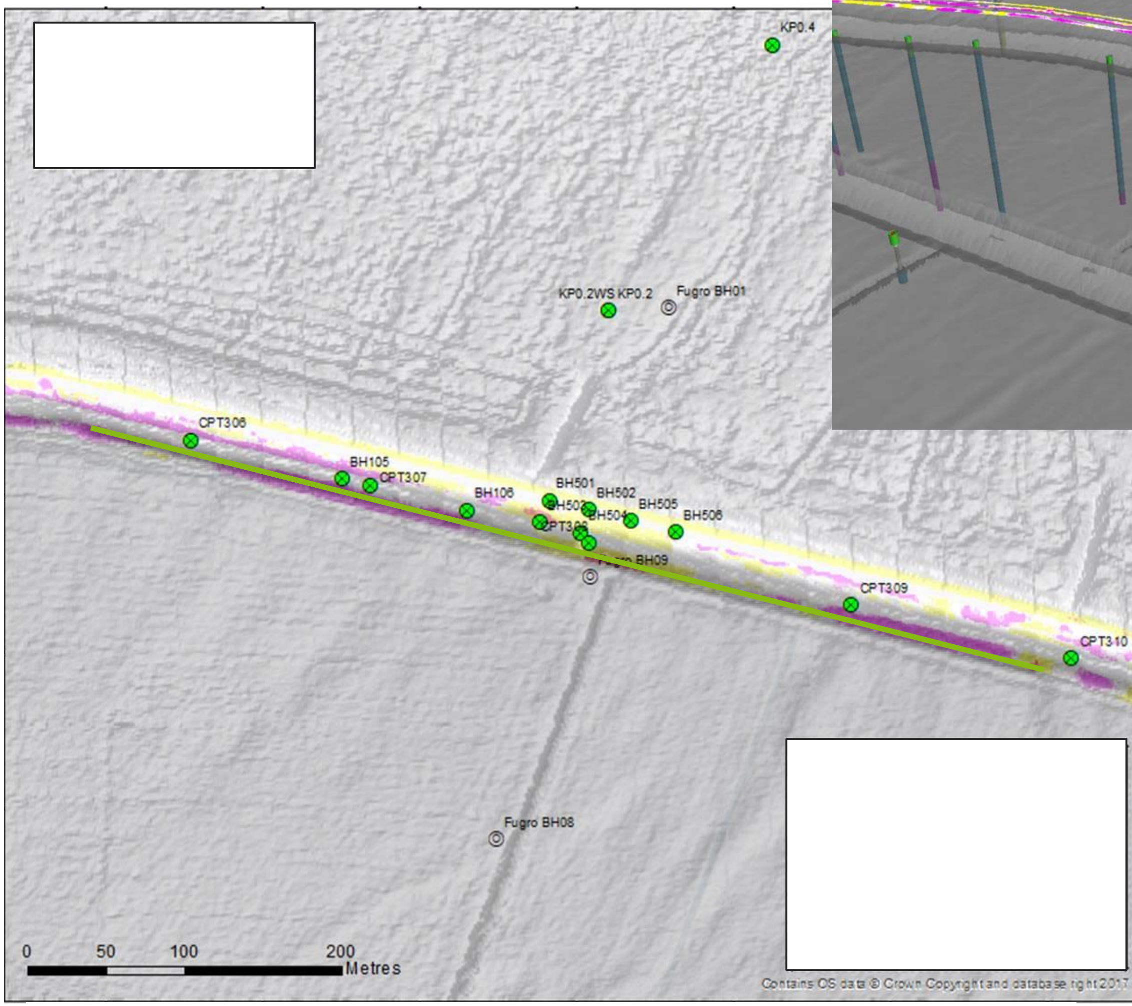
- The need for near surface geophysics
- **Intrusive site investigation; technique, depth, sample recovery, spacing of positions,**

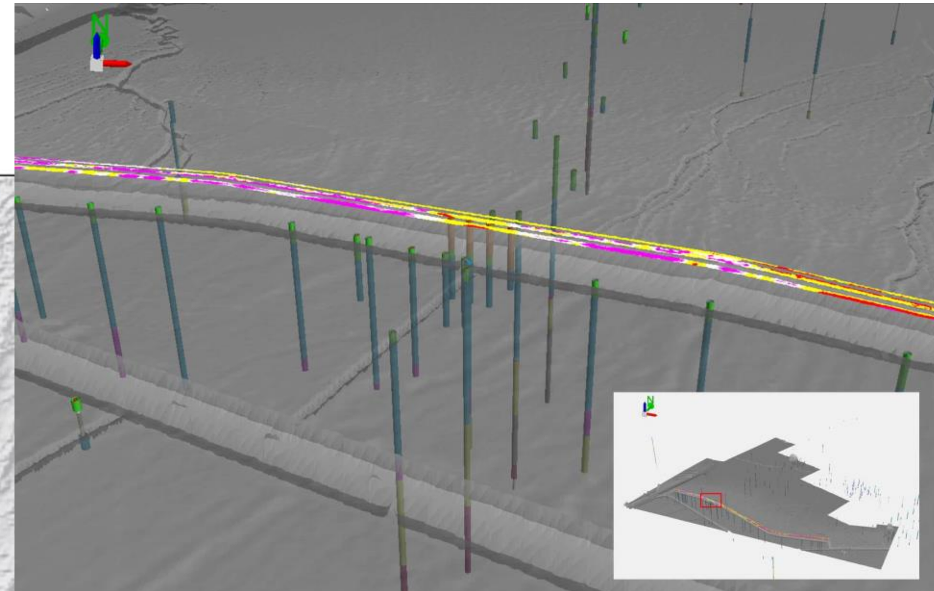
so you can then produce:

- **The observational ground model** (format, how to integrate, **specialist knowledge**?)
- Geotechnical model
- Design/engineering assessment

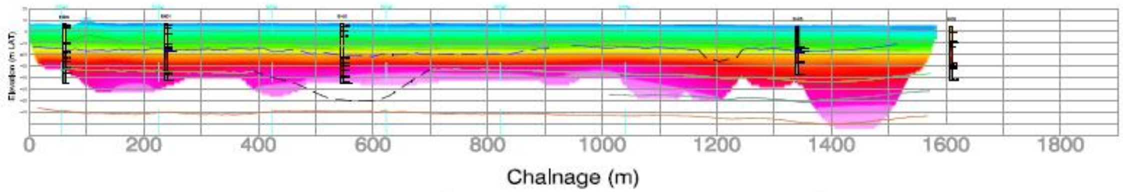
1st Model Phase (site screening): EM31 and CPT



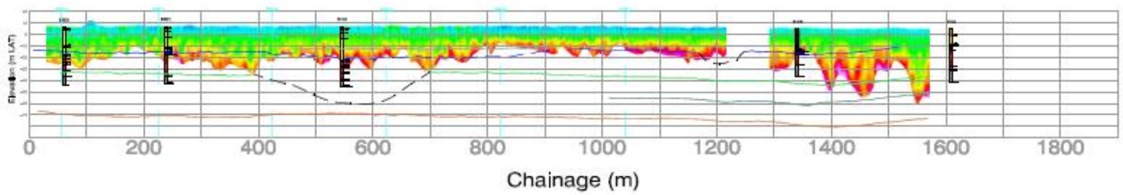

KP0.4
KP0.2WS KP0.2
Fugro BH01
CPT306
BH105
CPT307
BH106
BH501
BH502
BH505
BH506
BH504
BH09
CPT309
CPT310
Fugro BH08
0
50
100
200
Metres
Contains OS data © Crown Copyright and database right 2017



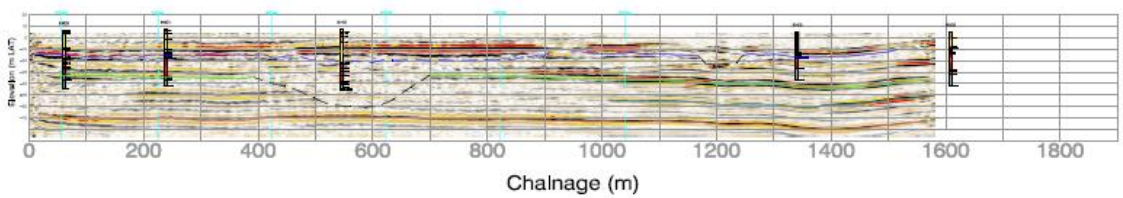
3rd Model Phase (assess route): Surface geophysics across mudflats



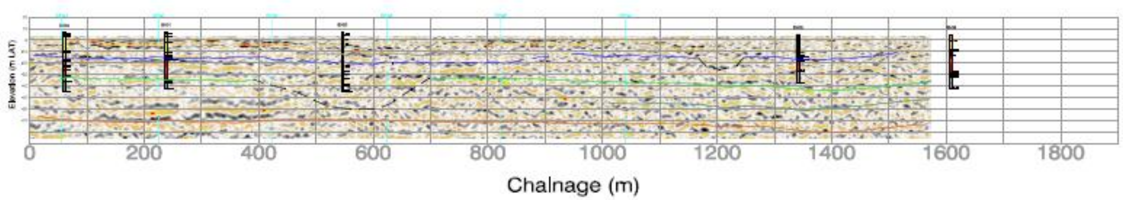
Route 1 - S-wave velocity from SRT



Route 1 - S-wave velocity from MASW



Route 1 - P-wave reflection stack



Route 1 - S-wave reflection stack

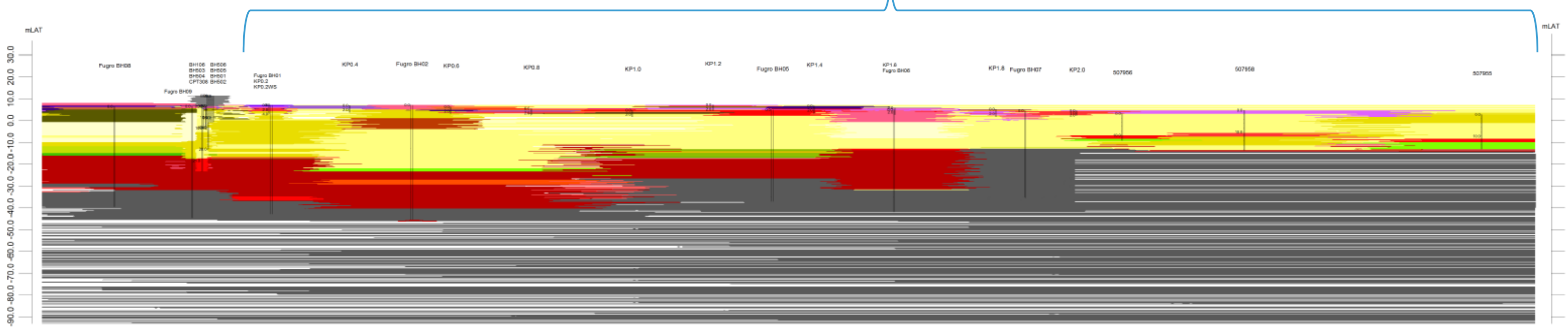
Plus reinterpretation of the marine geophysics for the route and incorporation of that into model

4th Model Phase (ground truth route): Near-shore and saltmarsh SI

In addition to new SI data: 120+ historical BH and CPT records:

Onshore

Offshore



Grey: Mudstone

Red: Clay/Clay Till

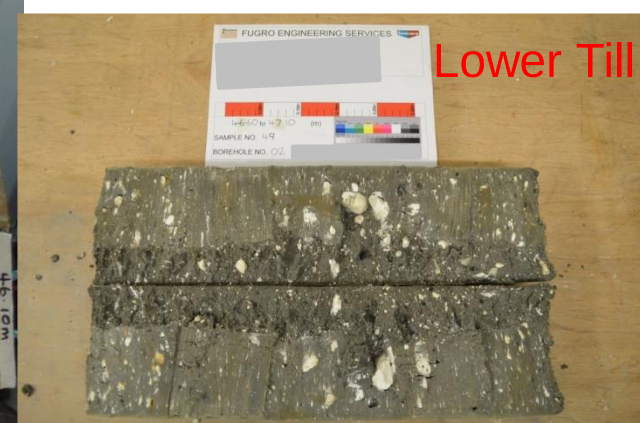
Green: Gravel

Yellow: Sands

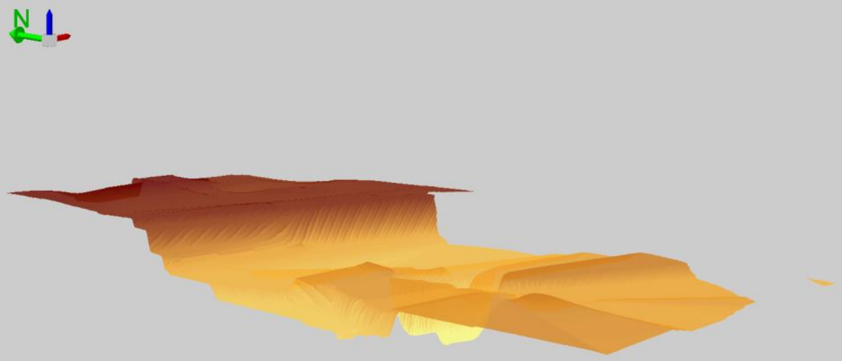
Upper Till

Lower Till

Upper and Lower Tills

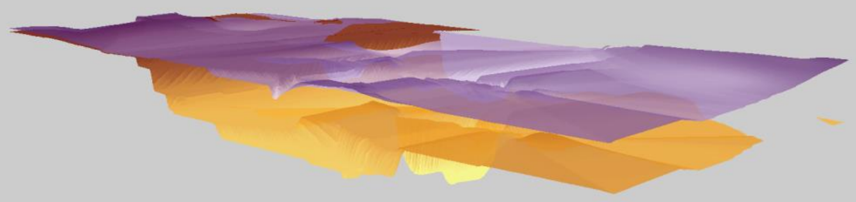


Final Model (Integrated): geological, geotechnical and geohazards

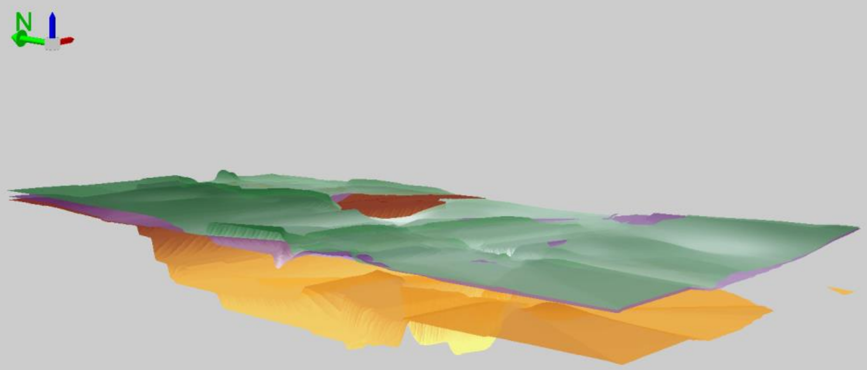


Bedrock; large channel and deeper erosional features

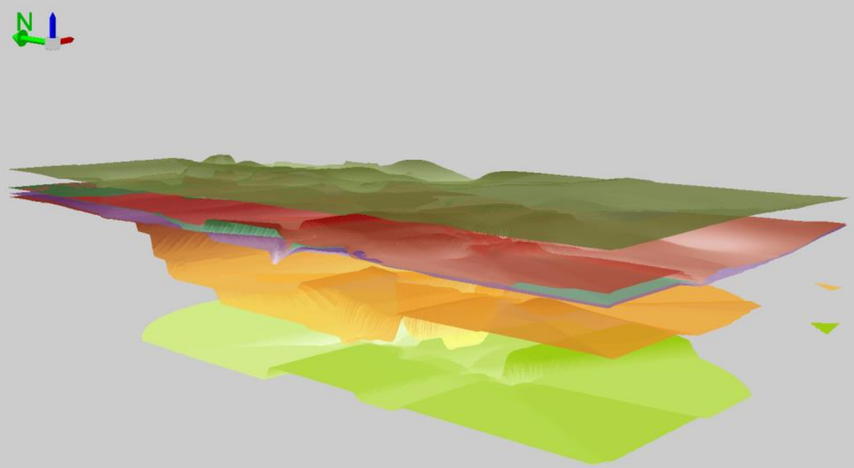
Upper Till: Dark grey, homogenous diamicton with chalk clasts; (sl. sandy, to sandy, sl. gravelly to gravelly CLAY)



Lower Till: Lighter grey, some yellow grey, locally dark grey and light grey matrix, more heterogeneous with chalk, mudstone and some mixed lithology including red sandstone, limestone and metamorphic and igneous (sl. sandy, to sandy, gravelly CLAY, locally up to medium chalk cobble content)

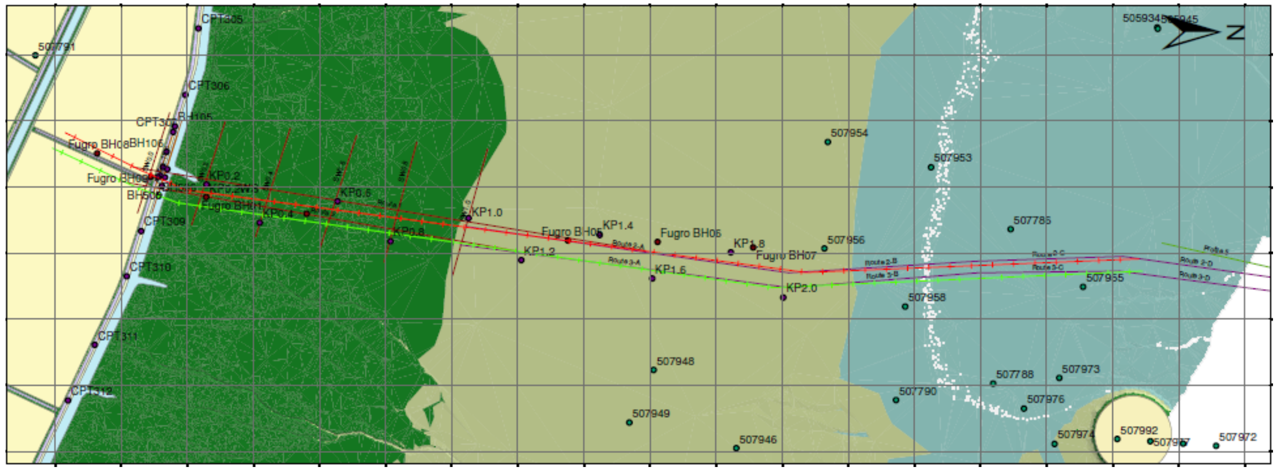


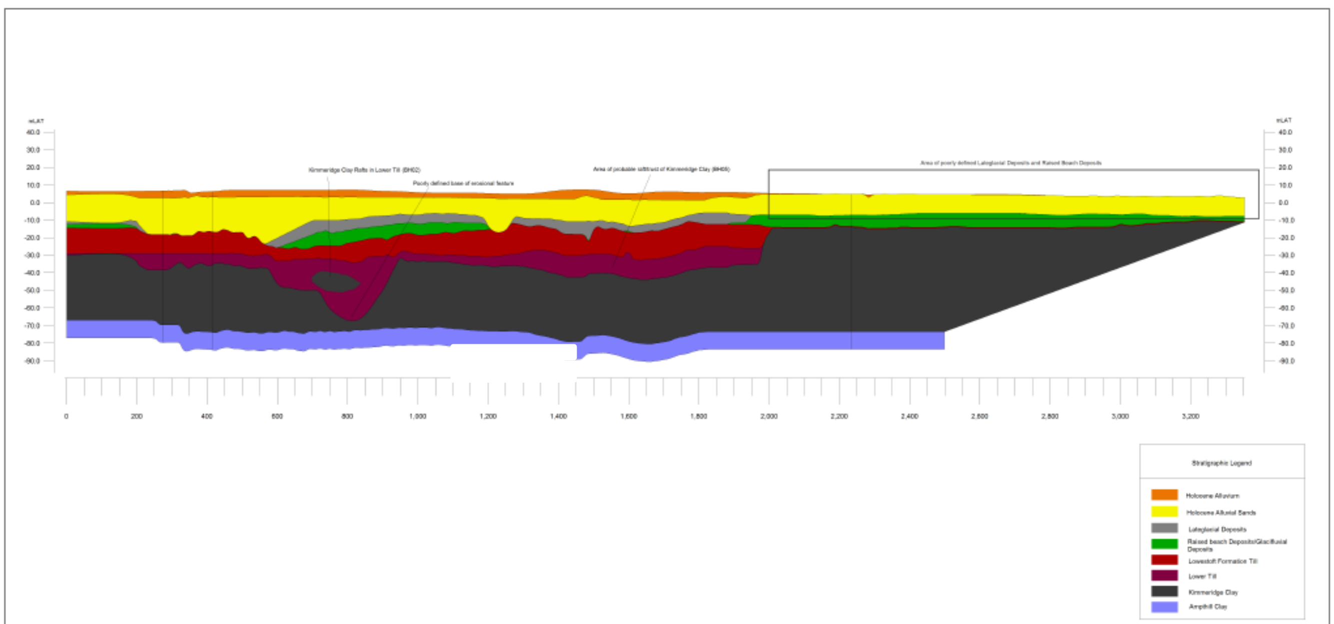
Outwash gravels



Lateglacial Unit (clay with peat/organic mud beds) over Holocene marine sands and intertidal deposits

Integrated Model: Cross section





Engineering Risk Assessment Matrix

Table 10.1 Geohazard Risk Assessment Matrix

Approach	Hazard	Constraint(s) imposed by the Hazard	Probability of the hazard being realised	Considerations/ Mitigation	Significance and Manageability of the Constraint
Deep Horizontal Directional Drill	Drilling through Holocene Alluvial Sands or Raised Beach Deposits	Possible loss of flush pressure/hole collapse	Very likely in loose sands at surface Likely below ~5m where Alluvial Sands are typically silty fine sand and generally not free draining. Very likely below ~10-15m bgl where sands typically become cleaner and together with Raised Beach Deposits become free-draining.	Consider use of casing whilst advancing hole to top of till if possible. Unlikely to be able to case exit route of hole through sands Attempt to control by use of thick drill mud Consider excavation of sealed shaft for access to below depth of deposits, particularly on landward side of route where casing will not be possible (likely high cost)	Manageable/Potentially Unmanageable Major constraint: HDD Contractor to advise on viability of drilling through sands and gravels
	Sands with high liquefaction potential (i.e. encountering a palaeochannel within Holocene Alluvial Sands)	Running Sands coming up casing: Possible seizing of rotary drilling wash-over pipework	Uncertain probability if drilling from seaward extent of route as insufficient data to assess extent of sands with high liquefaction potential in this area. Considered likely that the exit leg of the route may encounter such ground conditions due to the mapped frequency of buried channels in land	Utilise geophysical survey techniques to map area around proposed HDD start and end points and adjust to avoid hazard. May be able to control running sands with addition of large volume of water/flush. Will likely require casing for seaward start of drill. Consider construction of sealed pit/shaft to below depth of these deposits on seaward and landward entry /exit points	Potential Manageable Major Constraint: Additional cost for further geophysical survey and re-position start/end of HDD if required. HDD Contractor to advise on viability of drilling through and managing sands with high liquefaction potential
		Sands possibly blowing out of hole if drill started in pit below sea bed with unequal water pressures.	As above	As above	
		Creation of voids leading to subsidence	As above, considered unlikely that significant voids will form	As above	
		Loss of flush pressure and hole collapse	As above	As above	
	Flush fracturing of near-surface soils	Near surface soils (Holocene Alluvium) has insufficient strength to hold flush pressure at start or end of drill runs leading to fracturing and eventual outbursts of flush to surface May lead to subsequent collapse of mudflat surface where voids are created	Likely to occur at reception point due to inability to control flush accurately at this distance. Unlikely to occur at start point due to control of flush pressure	Some flush burst out at reception may be unavoidable but unlikely to form a major constraint	Minor Unmanageable Constraint at reception point Minor Manageable Constraint at start point
	Encountering Lateglacial Deposit including peat	Flush erosion of low strength clays and peats leading to flush pressure loss and potential limited hole collapse	Lateglacial Deposits potentially very extensive and thick locally present at seaward start point; Likely Only infrequently identified and where present found only as a <0.50m thick layer close to endpoint onshore; considered unlikely deposit will be encountered in this location	Reduce probability of encountering Lateglacial Deposits using Geomodel. Reduce consequence of encountering this deposit by controlling advancement speed and flush pressure during strata boundary transitions and maintain mud pressure in hole to avoid collapse	Potentially only a Minor Manageable Constraint; HDD Contractor to advise on constraints
	Very Dense Raised Beach / Glacifluvial Deposits	Potential drill deflection if at shallow angle when encountering deposits	Extensive and poorly defined but likely thick coverage close to seaward start point; considered very likely such deposits will be encountered Raised Beach Deposits only locally present and not very thick at landward exit point; Unlikely	Certainty that a deep HDD route would have to pass through these deposits Possibly could reduce consequence of encountering this deposit by controlling advancement speed during strata boundary transitions Consider construction of sealed shaft to base of deposits and undertaken drill from base of shaft (likely very high cost)	Possibly a Major Unmanageable Constraint HDD Contractor to advise on viability of progressing HDD without subsequent hole collapse through thick gravels at this distance
		Flush loss and potential hole collapse in free-draining gravels	As above	Attempt to maintain flush pressure and use very thick muds. Consider use of casing to top of tills at seaward start point	
	Incised glacifluvial channels in till surface infilled with lower density sands/gravels	Potential deflection if channel encountered at wrong geometry	Probability depends on planned HDD profile; those channels mapped are located in the centre of Tunnel Valley feature into surface of Lowestoft Formation Till. Assuming known features can be avoided; considered unlikely to encounter unknown features	Plan HDD profile to avoid all known features. Identification of known features does not preclude the presence of other such features of similar of smaller scale. May prove to be difficult to manage flush loss if such a feature is encountered	Possible Major Manageable Constraint
		Flush loss and potential hole collapse in free-draining gravels			
	Drilling of deep cohesive soils	Variability in shear strength of tills and Kimmeridge Clay: average undrained shear strengths not considered to be outside capabilities of even small HDD plant however, observation of high and low strength outliers particularly in Lower Till and Kimmeridge Clay may result in deflection if associated beds are encountered at specific geometries	Certainty of encountering variable strength beds in tills and Kimmeridge Clay if HDD profile passes through these deposits.	Lower Till and Kimmeridge Clay show highest number of shear strength outliers. May reduce the variability by planning route through Lowestoft Formation Till only. Drill advancement rate to be considered in light of variable ground conditions	HDD Contractor to advise on drill capabilities and plan works accordingly: Likely to be a Minor Manageable Constraint

Dynamic Site Characterisation:

Gypsum dissolution geohazards beneath a proposed power station

Desk study: Initial conceptual models

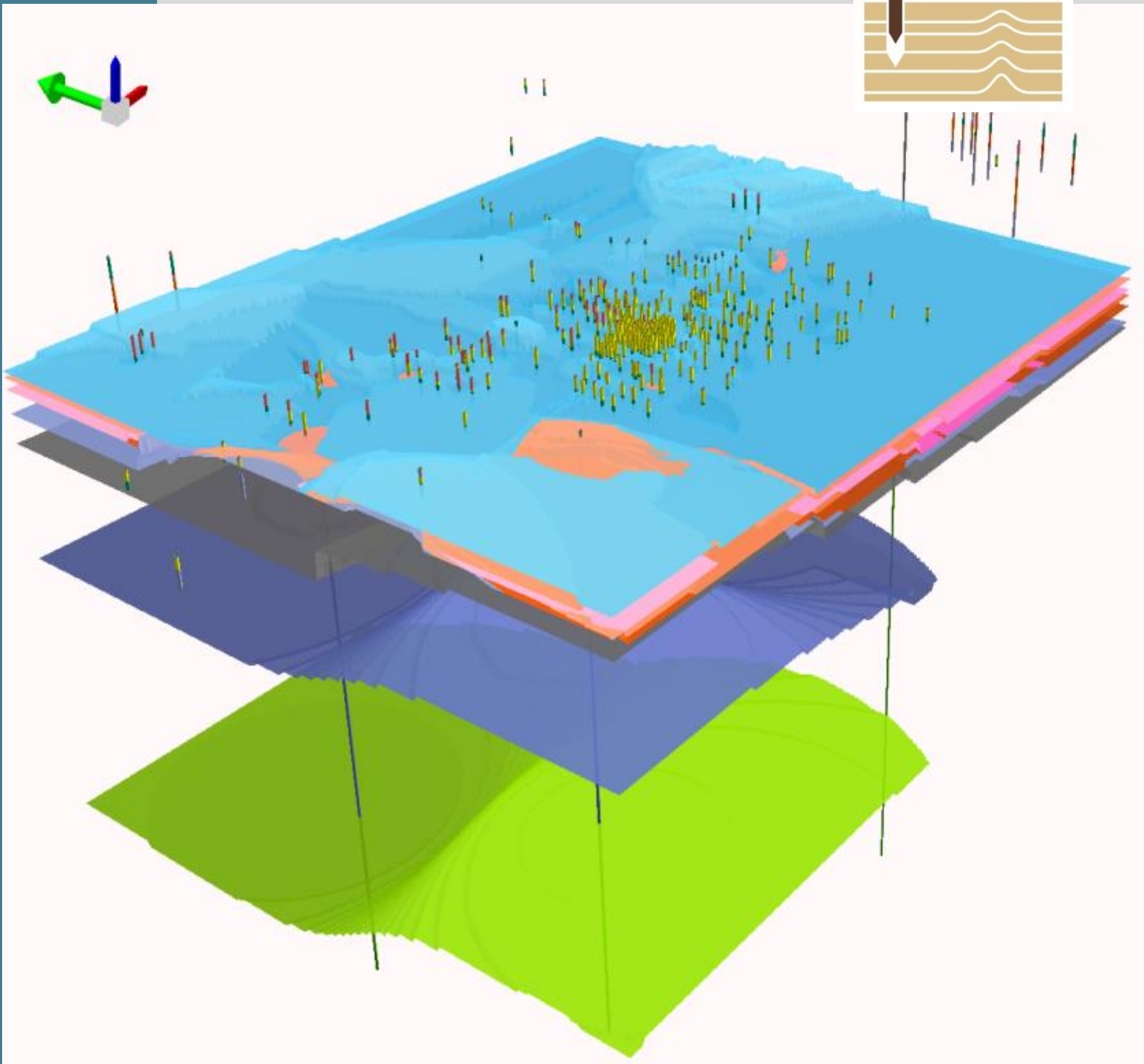
Desk study: front end 3D models

Screening geophysics trials

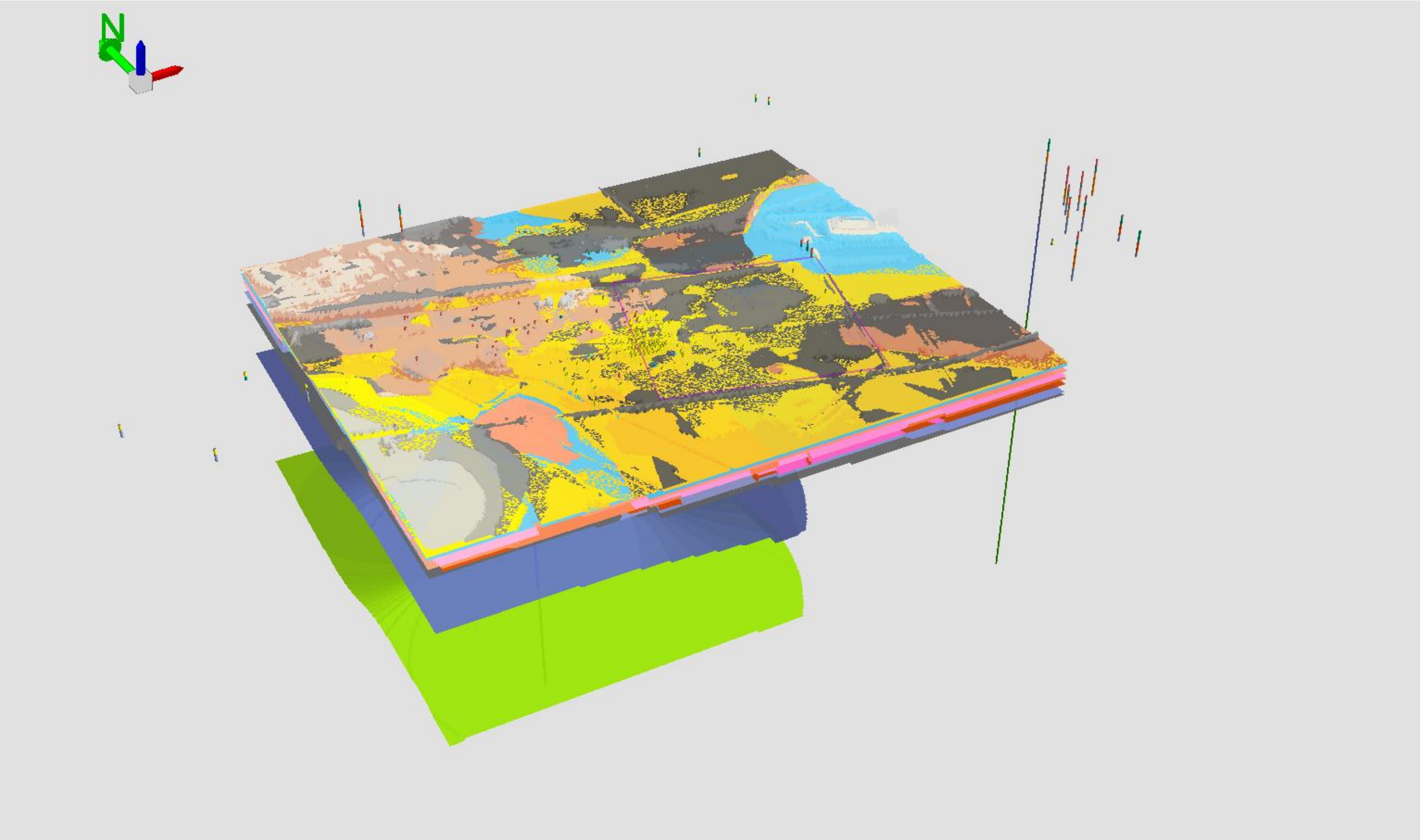
Main phase geophysics concurrent with initial borings; dynamic model update

50% of Geotech boreholes optimised

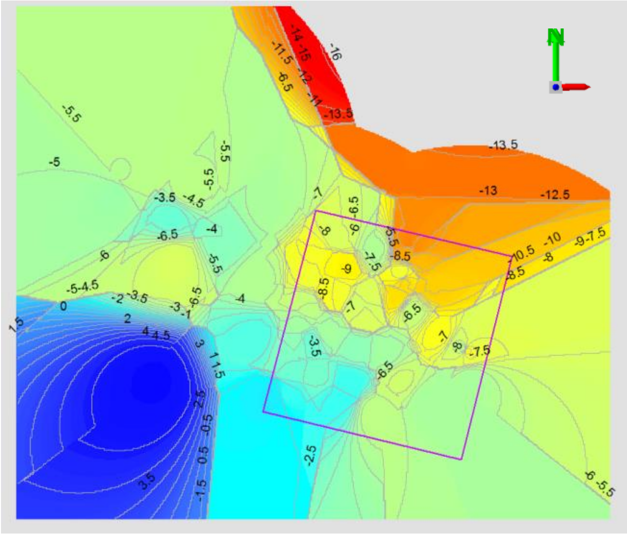
Geohazards mapped

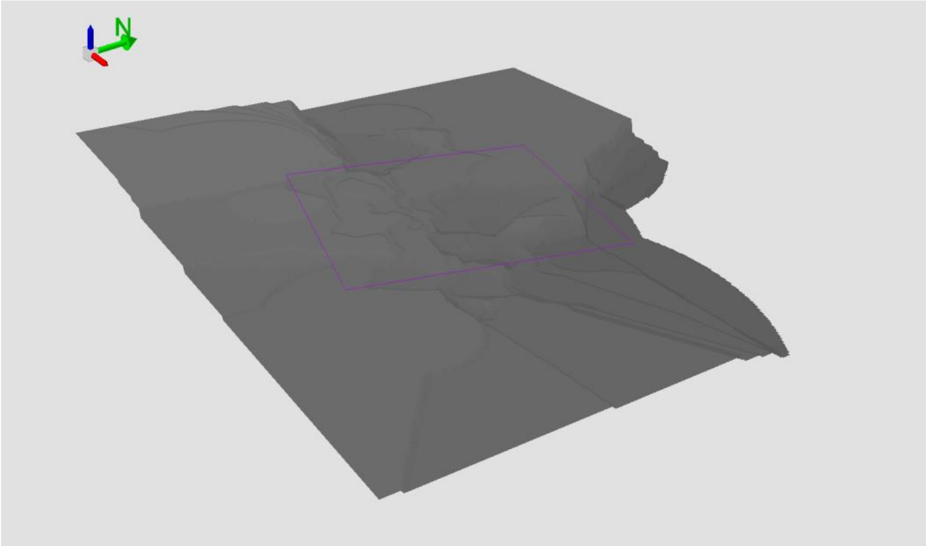


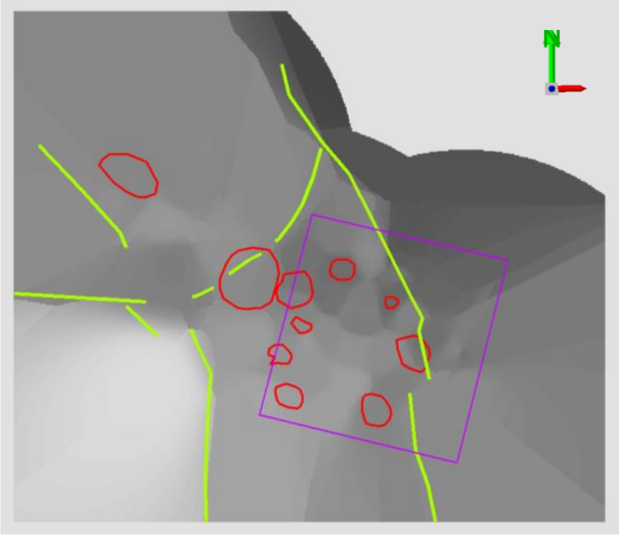
3D model from historical data

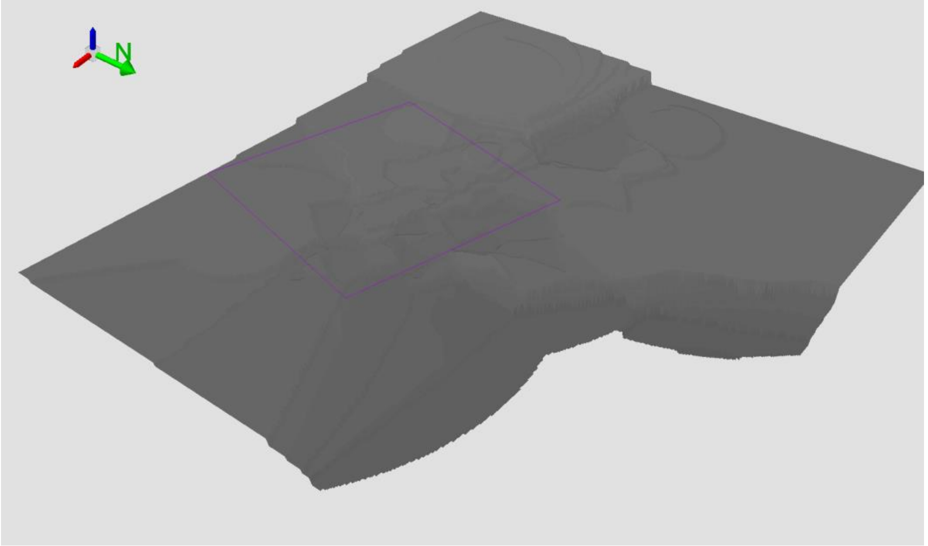


Potential Collapse Features in Modelled Bedrock Surface

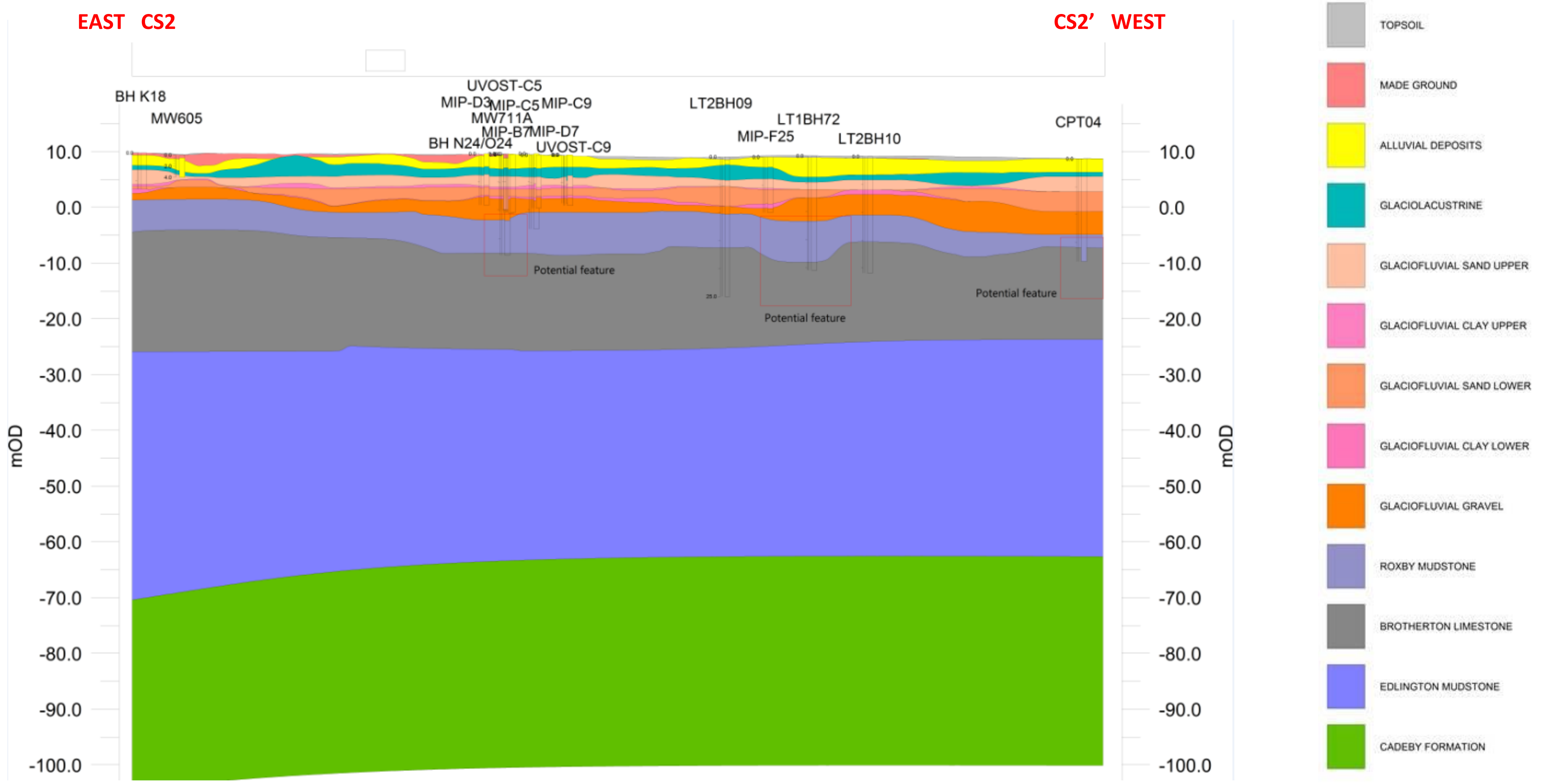




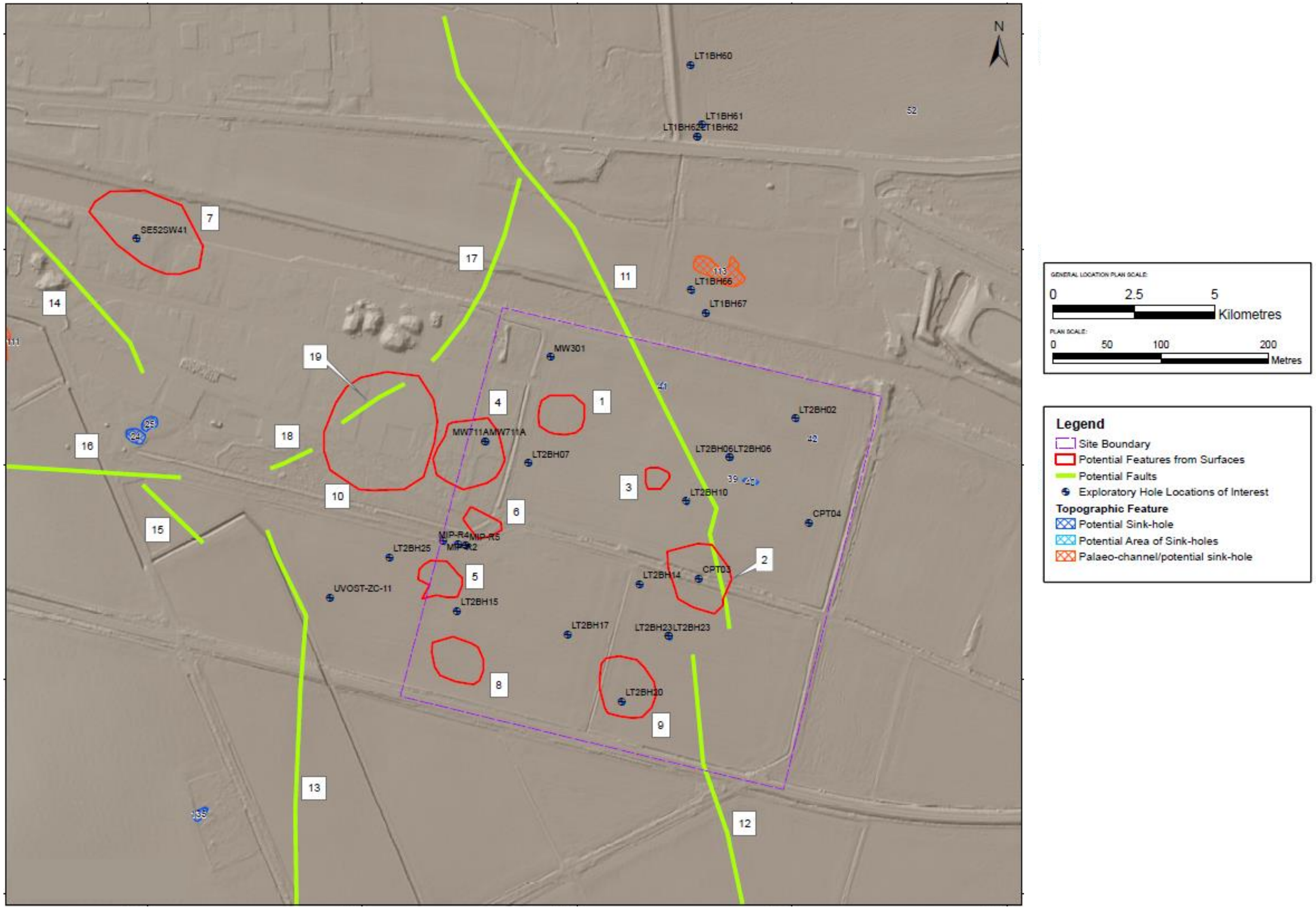


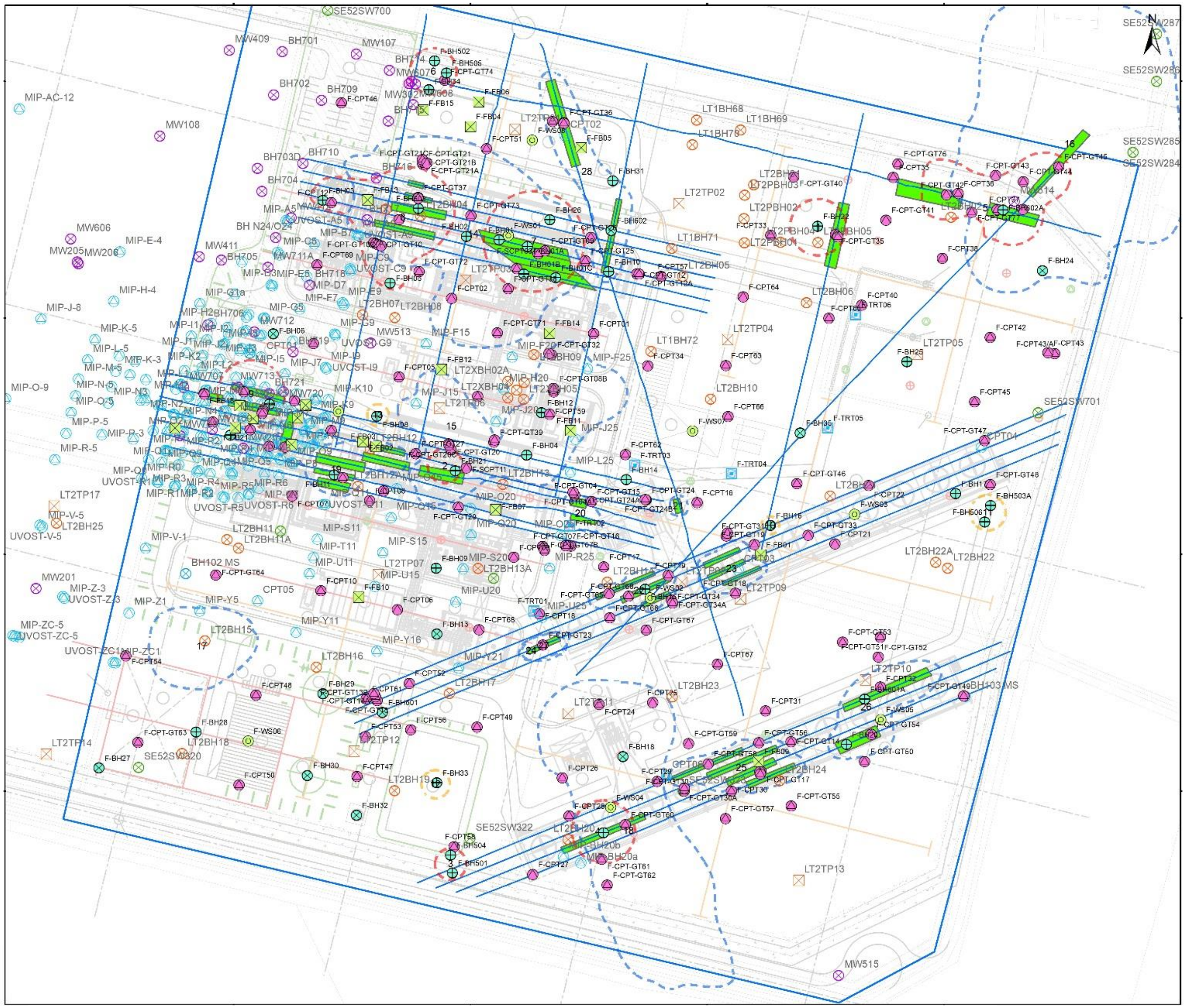


Cross Sections (CS2)



Features of Interest





GENERAL LOCATION PLAN:

GENERAL LOCATION PLAN SCALE:

0 1.25 2.5 5 km

PLAN SCALE:

0 20 40 80 m

Legend:

Historical Locations

- Borehole (BGS)
- Borehole
- Trial Pit
- Borehole (Fugro)
- CPT (Fugro)
- Borehole

Geophysical Lines

Geophysical Anomaly

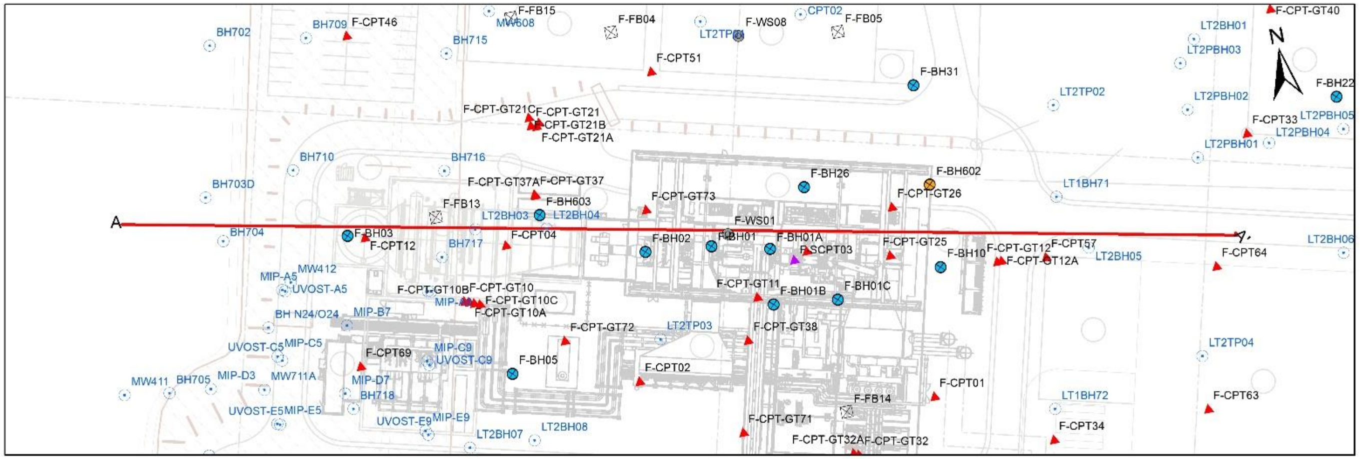
Confirmed Features

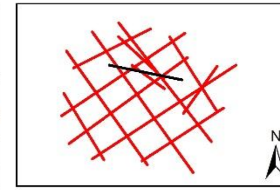
Type

- 1
- 2
- 3

Site Boundary

Notes:
1. Inset map provided by ESRI UK
2. Sheet size: A3
3. Coordinate system: British National Grid





All Cross Section Scale:

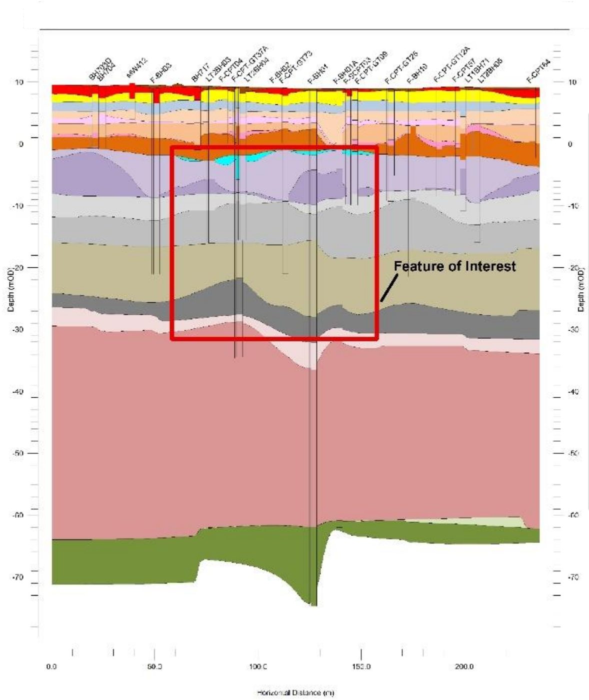
0 75 150 300 450 Meters

PLAN SCALE:

0 5 10 20 30 40 Meters

Legend:

- CP
- CP&RC
- CPTu
- Dynamic Sampler
- Flux Box
- Hand Dug Trial Pit
- Siesmic CPT
- Existing Locations
- Section Lines

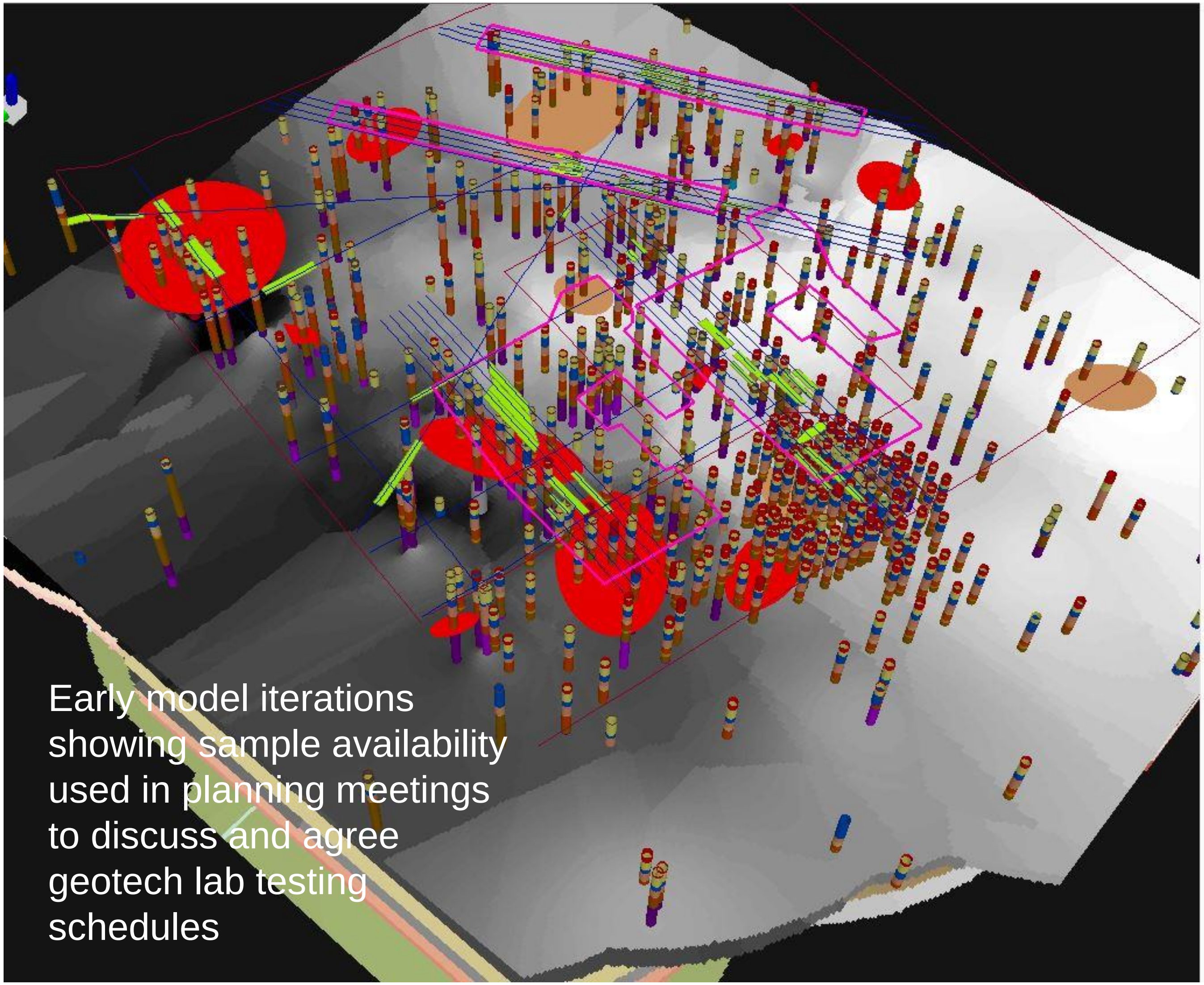


Stratigraphy Index

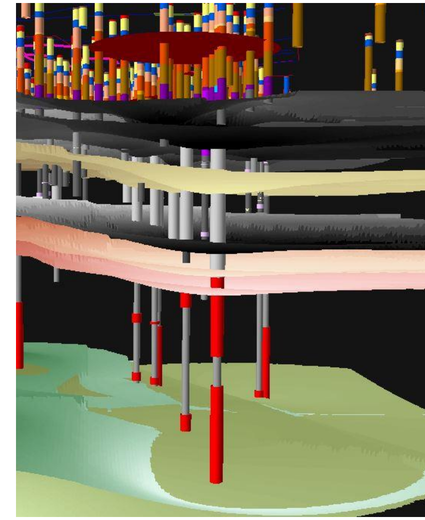
- TOPSOIL
- MADE GROUND
- BREIGHTON SANDS
- GLACIOLACUSTRINE
- GLACIOFLUVIAL SAND UPPER
- GLACIOFLUVIAL CLAY UPPER
- GLACIOFLUVIAL SAND LOWER
- GLACIOFLUVIAL CLAY LOWER
- GLACIOFLUVIAL GRAVEL
- INFILL MATERIAL
- RESIDUAL SOIL OF ROXBY
- ROXBY
- WEATHERED BROTHERTON
- UPPER COMPETENT BROTHERTON
- FRACTURED AND VUGHY BROTHERTON
- LOWER COMPETENT BROTHERTON
- UPPER GREY EDLINGTON
- LOWER RED EDLINGTON
- DE-DOLOMITISED CADEBY
- CADEBY

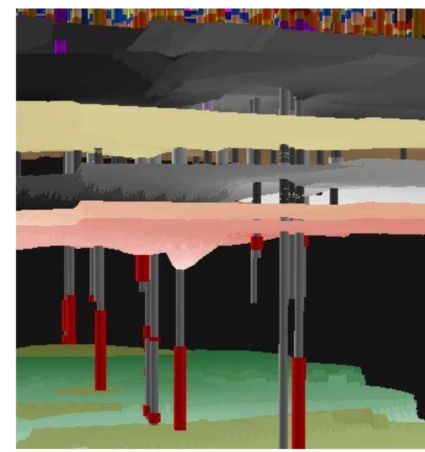
Notes:
1. Sheet size: A3
2. Coordinate system: British National Grid
3. Vertical Exaggeration x3

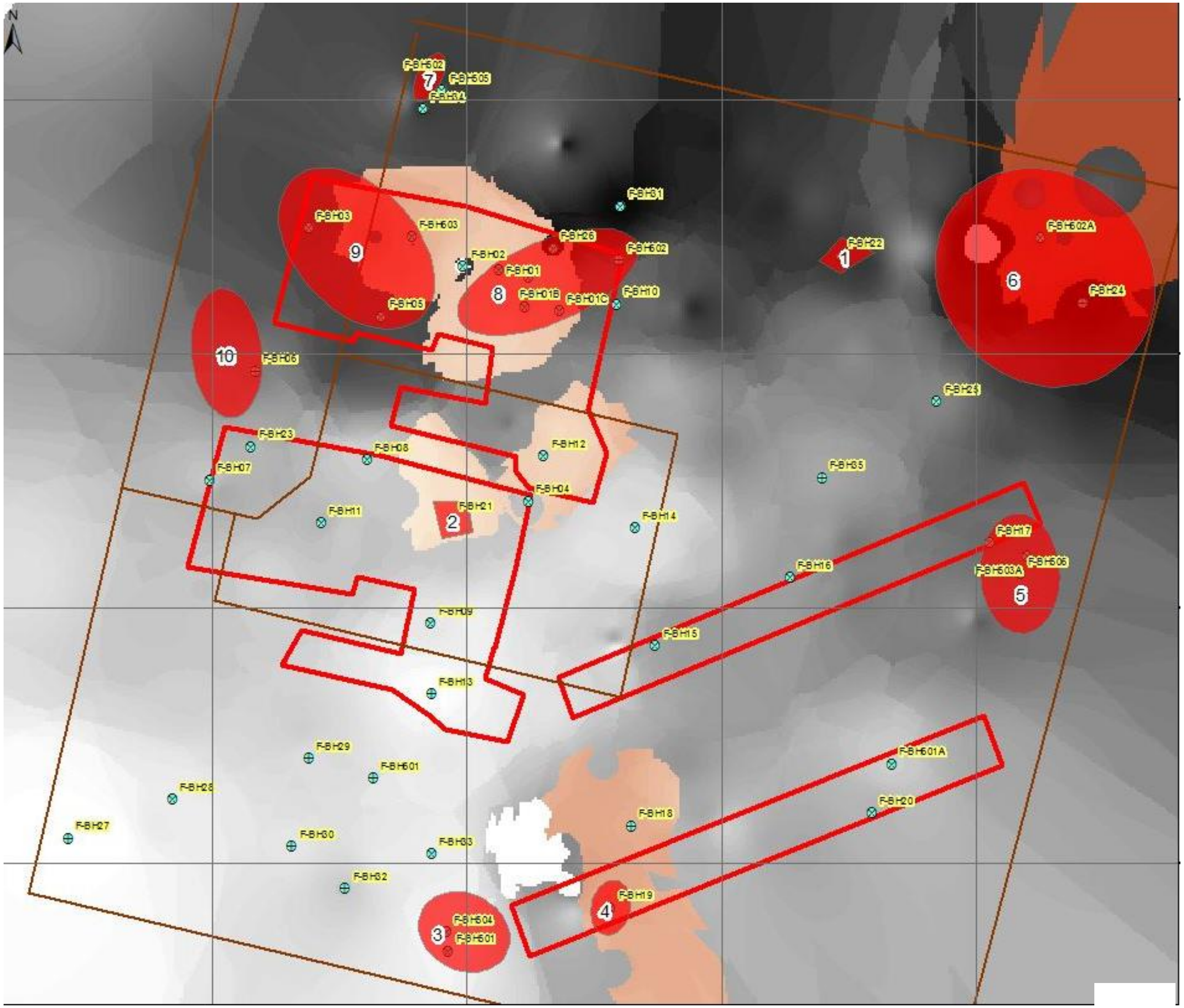
Integrated Geophysics and Targeted Boreholes



Early model iterations showing sample availability used in planning meetings to discuss and agree geotech lab testing schedules







Thank you…

Questions?

c.coleman@fugro.com