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Recommended practice for site characterisation, data management and data integration for submarine cable landing projects

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ABSTRACT

There is an increased need for submarine cable infrastructure across the world to serve the offshore wind power industry and the expansion of the submarine interconnectors and telecommunication networks. Cable landfall projects are complex as land, intertidal, nearshore, and offshore environments all coverage, creating an array of dynamic processes, constraints, hazards, and engineering challenges that an asset may face over its lifespan.

Robust site characterisation and ground modelling is key for the success of these projects, to allow for the effective, safe, and economical site selection, design, installation, and operation of an asset. In order to accomplish this, the integration of engineering and geoscientific datasets, obtained through several data sources and survey techniques is required; as well as collaboration and integration between multiple technical disciplines.

This paper lists the key stages, techniques, and sources available for obtaining the required data. We then consider how the data can be managed and integrated to obtain a holistic ground model for use in the design, construction, and operation of the asset. We discuss the value these models can provide throughout the lifecycle of landfall projects.

Keywords: Geophysics, Geotechnical Engineering, Cable Engineering, Site investigation, Cable Landfall

1. Introduction

The need for suitable cable landfall sites is increasing, due to the rapid expansion of offshore wind farm developments, interconnector power transmission cables, telecommunication cables, and other offshore infrastructure projects. Stablished sites are increasingly congested and new developers are required to consider more constrained siting. New projects need to connect into existing infrastructure networks, and face more restrictive local access considerations and more complicated ground conditions.

The selection of a landing site will have a significant impact on a project, as site conditions can dictate construction techniques (trenched or trenchless), installation equipment requirements, construction schedule, project risks and costs (Burley, et al., 2024).

The land-sea boundary of cable landings presents a unique array of challenges. Within a relatively small distance, a site occupies four distinct site investigation environments: Land, Intertidal, Nearshore and Offshore. Each posing its own set of challenges and restrictions on data acquisition and asset construction and. Multiple active anthropogenic and geomorphological processes (erosion, sediment mobility and deposition, wave action, tides, etc.), are found across these environments adding to the complexity. In addition, many coastal areas are environmentally sensitive or Sites of Special Scientific Interest (SSSI), adding further challenges to projects. As such, detailed site characterisation is critical to ensure the successful design, installation, and longevity of the proposed infrastructure, as well as understanding how the asset affects the local environment and infrastructure overtime.

2. Investigation Stages and Data Requirements

When characterising a site, several sequential steps are often carried out to build a model of the surface and subsurface which is used to develop an understanding of the natural, anthropogenic, and environmental hazards, and the constraints to development, installation, and operation of an asset. To successfully achieve this, available data must be fully integrated at each stage to minimise project risk and prevent unforeseen costs and wastage. Several professional bodies such as the Society for Underwater Technology (SUT, 2022) present recommended steps required to understand ground risk for offshore developments. Figure 1 presents an approach to this workflow modified to the specific requirements of landfall projects.

Prior to any study, preliminary planning should be considered (project budget, timescales, critical milestones). Ensuring sufficient time for each stage of investigation and interpretation is as important as the investigation specification itself, as rushed surveys or interpretation can result in significantly degraded results. The desktop study (DTS) should be the first step of a cable landfall site characterization project. The DTS collates all available publicly available, proprietary, and historic mapping data for a site, and any undertaken site walkover observations, to increase the understanding of an area before planning investigation campaigns. The DTS provides a high-level understanding of the expected ground conditions, geological and anthropogenic hazards, and environmental restrictions that may be encountered. This is achieved by producing an initial ground model (GM) and risk register (RR). The GM summarises the spatial variability of expected site conditions and processes. A landfall DTS should also capture the possible coordinate reference system (CRS) and reference datum systems available for a site. As different coordinate systems are often used for land and offshore surveys, the DTS should identify a reference CRS and datum to be used across all survey environments. At this stage, establishing a data management strategy of standardised file nomenclature and a data storage library structure, are simple strategies that can yield significant efficiencies throughout the project.

Correct use of the DTS allows for considered site investigation planning, spatial understanding of the hazards and risks to an asset, and locates existing structures. Table 1 captures some of the possible data inputs, study outputs and potential uses of the results of a well-considered DTS.

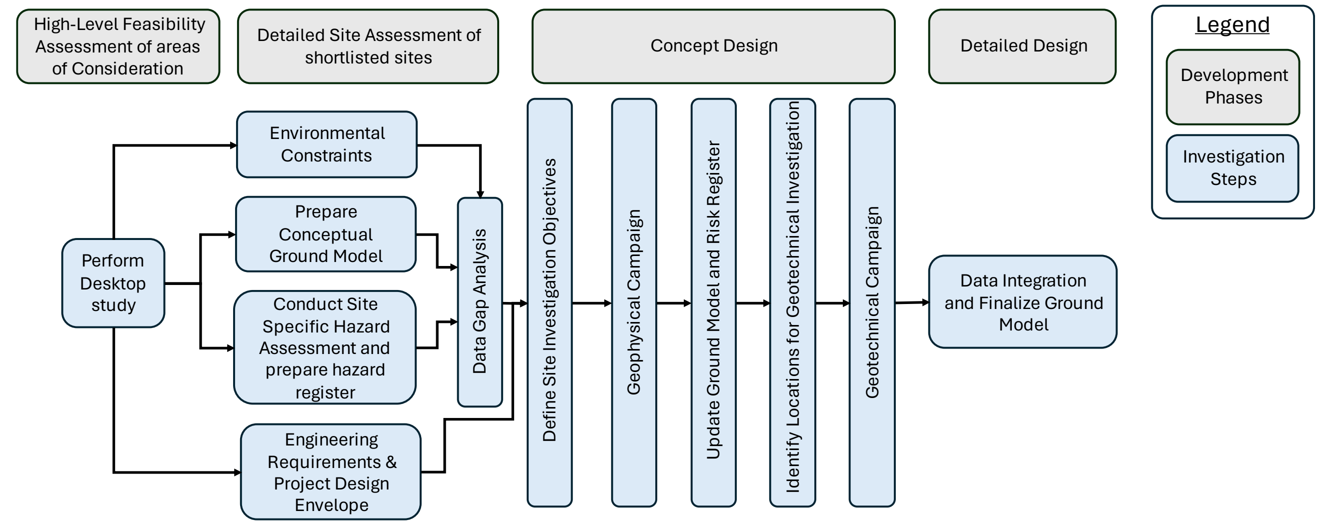

Figure 1*: Flowchart of typical steps for a cable landfall site characterisation related to design concept stages*

Data collated for the DTS can be presented as a GIS knowledge base and combined 2D GM. Data is generally presented as a series of layouts, cross sections, and interpolated surfaces. Identified hazards and associated risks are recorded in a RR. A 3D GM may be created if there is sufficient historical, geological, mapping, and surface datasets to allow this.

Table 1: Summary of inputs, outputs, and uses for a DTS

Potential Data Inputs	Study Outputs	Study Uses
Topo-Bathymetric, geological, & historic land use mapping, Historic geophysics & geotechnical data, Hydrology data, Land designations & environmental boundaries, Published literature, Military records, Utilities & infrastructure plans Coastal recession & accretion rates, Sea defences locations, Site Walkover	Desktop study report Preliminary conceptual GM Site specific RR Project coordinate reference system alignment	Identifying unsuitable survey techniques Planning objectives for additional phases of investigation Determine preferred installation methods List site constraints and limitations

The GM and RR are both live documents that should be continuously updated throughout the lifecycle of a project as additional information becomes available and as risk mitigation progresses.

Environmental constraints must also be considered at the DTS stage. Many coastal environments are protected or contain sensitive habitats that can limit site access, survey strategy, or installation location. The environmental and land designations of a DTS are critical to identifying restrictions prior to the survey of the project. The results of this DTS should then be used for planning further investigations, excluding landfall installation techniques unsuitable to the expected site conditions.

Once the initial understanding of the site is achieved, a feasibility study can be undertaken to select appropriate installation methods for further consideration. Requirements for the most common installation options can vary significantly (Table 2). The chosen installation method can also affect which hazards are more likely to impact construction and operation and must be considered when specifying site investigation data requirements. To begin planning the site investigation, the results of the DTS, RR (for each considered installation method) and initial GM are subjected to a gap analysis exercise. This analysis identifies regions of data adequacy, uncertainty, or increased risk, where additional information would be of benefit to the understanding of the site. The gap analysis results are combined with the environmental constraints, and the engineering data requirements of the project to specify the objectives of the site investigation campaigns.

The objectives of the site investigation are to confirm and expand on the DTS's site description and identify information not captured during the DTS. Collaboration between geoscientists and engineers is key to inform strategy and specification requirements, ensuring surveys are planned to meet all these requirements for the cable installation techniques under consideration. Understanding factors such as depth of burial, geohazards, and installation method are all key to producing a suitable survey scope and specification. In many countries survey scopes and specifications must also include environmental protection elements such as marine mammal observation in the UK. To assist with the scope and specification of site investigations numerous detailed regulatory and advisory documentation is available within the industry to assist with the planning and execution of these investigations; examples of which include EUROCODE 7, ASTM. (2022), SUT (2022), DNVGL-RP-0360.

Table 2. Installation Technique Considerations

Technique	Consideration
Trenched	Requires sufficient clearance for excavation operations. Sensitive to ground conditions i.e., rippability of the ground type, strong bedrock generally not suitable. Sensitive to environmental conditions i.e., tidal range, metocean conditions and topography (not suitable for steep profiles or significant topographic changes). Environmental considerations including visual impact (particularly in sensitive areas).
Horizontal Directional Drilling (HDD)	Requires sufficient clearance for onshore operations HDD rig etc. at drill site including access for vehicles etc. Fractured rocks or extensive areas of coarse deposits may not be suitable. Generally restricted to <2km. Usually requires deep burial (risk of cable overheating). Settlement of existing structures. Spoil management.
Direct Pipe (DP)	Expensive solution; typically requires tunnelling equipment and recovery with jack ups. Large set up area required. Large cobbles and boulders are generally not suitable/challenging. Typically requires deep burial (risk of cable overheating). Requires sufficient clearance for operations tunnelling equipment etc. May need personnel to enter duct for maintenance. Settlement of existing structures. Environmental considerations including project layout, spoil management and offshore operations required to recover drill head.

Once the objectives are defined, site investigations should begin with geophysics. Geophysical investigations aim to better understand the site conditions by measuring and interpreting the surface and subsurface using a series of non-intrusive methods. Geophysical investigations facilitate the interpretation of soil or rock units, delineation of geological structures, and mapping of features that may pose a hazard to installation works. Geophysical investigations can assure the efficiency of a geotechnical campaign, allowing exploratory holes to be positioned on ‘representative’ or ‘anomalous’ sections of the ground. Numerous geophysical survey techniques are available across the four encountered environments (Section 3.1, Table 3). The scope of the geophysical survey will be dependent on the required objectives and conditions of the investigation with the most effective techniques dependent on several factors. Engineering requirements and geological conditions such as required depth of burial and depth to bedrock, UXO characterisation requirements, and environmental conditions, can all affect which acquisition methods are most appropriate.

When specifying investigation scope, we recommend that the survey captures at least 5 m below the planned duct trajectory. This allows for any required adjustment to the planned duct trajectory caused by identified hazards and prevents processing and interpreting artefacts occasionally observed at the edge of geophysical datasets. Geophysical data should be acquired at a suitable data density to capture the required level of detail, to confirm known structures, infill knowledge gaps identified in the DTS, and improve the initial RR, and GM. This requires collection of data as a series of 2D cross sections and surfaces along a grid of suitable line spacing, or a 3D data volume. Where hazards such as surface or sub-surface boulders, or UXO are expected; data should be acquired at a suitable resolution for the detection of these hazards (Wetton, et al., 2024). Following the completion of the geophysical survey and data interpretation, the GM and RR should be updated to include the latest information. The updated GM can then be used to determine the locations of intrusive geotechnical investigation to provide an optimised and targeted investigation.

Geotechnical investigations are implemented to define key engineering parameters of the subsurface, acquire test samples for the chosen design methodology, and provide ground truthing information to calibrate and depth convert geophysical interpretation. As with geophysics, multiple geotechnical investigation techniques are available across the four environments encountered at a cable landfall (Section 3.2, Table 4). The planning of a ground investigation should consider the results of the DTS, as available historical data may allow for the number of new exploratory holes or monitoring locations to be reduced. The calculated placement of positions can allow ground truthing of the geophysical results by providing geological unitization to interpreted geophysical structures. They should also consider proposed infrastructure and allow offsets where necessary to avoid installation risks. Similar to geophysical investigations, differing site parameters such as cable depth of burial, rock head position, entry and exit points affect which methods are most appropriate. Likewise, it is recommended that the survey captures at least of 5 m below the planned trajectory. Data should be collected with sufficient sample locations and at a density to adequately describe the full length of the trajectory. However, for trenchless methods data should not be acquired directly along the planned installation trajectory, (due to possible frack out during installation) thereby requiring integration between geophysical and geotechnical data to extrapolate the results of the geotechnical investigation to the installation trajectory.

Following the completion of the geotechnical investigation all available datasets and interpretation should be integrated and aligned within final GM and RR, forming the design basis for the landfall. Early and continuous integration of geophysical and geotechnical data is key for a robust site characterisation and GM. The early construction of such an integrated GM can in turn be used to identify potential ground hazards which can then be mitigated against through an adequate conceptual design and planning.

3. Survey Techniques and Data Management

At a landfall site four characteristic environments exist within a relatively small area: Land, Intertidal, Nearshore and Offshore. We define the land environment as above the high-water mark. Intertidal is between high and low water marks. Nearshore is from low water mark to the 10 m water depth contour, and offshore as > 10 m water depth. Obtaining geophysical and geotechnical data across these four environments usually requires multiple phases of survey campaign.

Each of the four environments poses its own set of challenges and restrictions on data acquisition. With geographical, environmental, and access considerations, adding to the complexity of site characterisation. Some data acquisition techniques are more suited to, or cannot be used, in certain environments, whereas others can span multiple regions. To overcome the challenges, detailed knowledge, and correct deployment of the full range of investigation techniques, coupled with use of the appropriate acquisition methodology and sensor platform is critical to ensure the acquisition of suitable data for a landfall site. Employing the most suitable sensor platform is as important as selecting the correct technique and can allow for datasets to cover multiple survey environments.

3.1 Geophysical Investigations

Geophysical investigations are able to make use of a host of data acquisition techniques and sensor platforms. Methods for the acquisition of land and offshore data are well established, whereas the intertidal and nearshore environments are often subject to significant data gaps. Recent developments of newer technologies have been able to reduce some of these gaps. The use of drone mounted sensor systems; shallow draft unmanned autonomous surface vessels (ASVs), and Distributed Acoustic Sensing (DAS) have allowed for cross environment data acquisition to be undertaken more readily. A summary the currently available, relevant, geophysical techniques and sensor platforms for each environment is shown in Table 3.

Table 3: Common geophysical investigation techniques, their potential uses and appropriate environments

Survey Technique	Data Outputs	Potential Data Uses	Applicable Environments*	Sensor Platform Options
LIDAR	Topographic surface Bathymetric surface	Ground elevation, Water depth, Bedform mapping Hazard mapping, Archaeology	L.I.N[3]	Drone Aerial
Multibeam Echosounder	Bathymetric surface Backscatter intensity map	Water depth, Bedform mapping, Sediment classification, Hazard mapping, Archaeology	*N[2].O*	*Drone* *Survey vessel[2, 5]*
Sidescan Sonar	Acoustic reflection intensity map	Bedform mapping, Sediment classification, Hazard mapping, Archaeology	N[2].O	Drone[3] Survey vessel[2, 5]
Magnetometry	Magnetic field strength map	Ferrous Metal detection, UXO detection, Archaeology	L.I.N.O	Hand carried[1] Drone[3] Survey vessel[2, 5]
Electromagnetics	Bulk subsurface electrical conductivity map In-phase map	Metal detection, Shallow geology mapping, Hydrological variations, Archaeology	L.I.N.O	Hand carried[1] Drone[3] Survey vessel[2, 5]
Seismic Refraction	Subsurface seismic velocity cross-section (2D) or data volume (3D)	Geological structure, Velocity modelling	L.I.N.O	Ground Deployed[1] Geophones[1] Seabed hydrophone Cable Optical fibre DAS
Seismic Reflection	Subsurface acoustic impedance changes cross-section (2D) or data volume (3D)	Geological structure	L.I.N[2, 4].O[4]	Ground Deployed[1] Geophones[1] Survey Vessel[5] Optical fibre DAS
Multichannel Analysis of Surface Waves	Subsurface Rayleigh wave velocity cross-section (2D) or data volume (3D)	Geological structure, S-wave velocity modelling, Stiffness Parameters, Voids	L.I.N.O	Ground deployed geophones[1] Seabed hydrophone cable Optical fibre DAS
Ground Penetrating Radar	Contrast in dielectric permittivity cross-section (2D) or data volume (3D)	Geological structure, Utilities mapping, Archaeology	L	Hand carried[1] Drone
Electrical Resistivity Tomography	Subsurface electrical resistivity cross-section (2D) or data volume (3D)	Geological structure, Hydrological variations, Voids	L.I.N.O	Ground deployed probes[1] Survey vessel[2, 5]

[1] Ground deployed and Hand Carried techniques in the intertidal zone are subject to significant safety, environmental, and tidal considerations.

[2] May be limited by water depth.

[3] The effectiveness of most aerial and drone deployed sensor systems in the nearshore typically decreases as water depth increases

[4] Seismic Reflection in the Nearshore and Offshore environments include multiple equipment options dependant on the survey objectives

[5] Multiple survey vessel options, e.g., crewed, and unmanned vessels, are available dependant on survey objects, water depth, coastal conditions etc

*L = Land, I = Intertidal, N = Nearshore O = Offshore

Geophysical data is presented across multiple data formats with no single standard practice for the industry. Across the different survey environments, the practice of selecting CRS and reference datums varies significantly, with legacy and modern coordinate systems varying between teams, projects, developers, and geographic regions. Data formats are often determined by choice of acquisition tool, tool manufacturer, and software package. Seismic techniques are the most consistent, as common practice is to use the SEGY data format (SEG, 2017). For others such as sidescan sonar, magnetometry, and topography/bathymetry a combination of ASCII and Geotiff files are commonly generated from proprietary data formats for transfer and display. Data is typically stored, visualised, and presented in a combination of technique-specific bespoke industry software and dedicated GIS workspaces. Data can then be integrated into a GM by exporting from the relevant workspaces into an integrated GM visualisation package.

3.2 Geotechnical Investigations

Geotechnical investigations can make use of a host of data acquisition, exploratory hole, and installations and monitoring techniques as shown in Table 4. The use of each investigation technique can depend on the asset type being planned, site conditions, and environmental consenting, as these will affect depth of interest and engineering parameters that needs to be investigated.

Acquired geotechnical data is stored and transferred in the common data format AGS (AGS, 2022). The data is typically interpreted and visualised in bespoke industry software and dedicated GIS workspaces. Interpreted data is stored and presented in interpreted AGS files, a series of CSV files, a series of parameters visualisation plots, reports, polygon features, and interpreted surfaces.

Historic maps, exploratory holes and geological maps can be combined into the geotechnical data management system, creating a database of known information around the site. This allows for the unitization of the ground conditions to be undertaken. In addition, being able to view the historic data in conjunction with the environmental and geotechnical data allows for a design of a refined site investigation, building upon the existing knowledge and context of the site.

Table 4:Key geotechnical parameters - their acquisition method, lab testing strategy

Required data	Acquisition Method	Lab testing strategy (main tests & index/classification tests)
Stratigraphy	Offshore: BH, CPTU, VC Onshore: BH, CPTU, IP, TP, WS	WS (only can provide samples suitable for environmental testing)
Soil type	In situ test data – CPTU, Sample description methods. Laboratory tests on sample specimens.	Classification tests – PSD, Atterberg limits organic content etc.
Unit weight	Laboratory tests on specimens.	Moisture content, density
Grain size	Sample description methods, Laboratory tests on specimens.	PSD
Relative density in coarse soils	CPTU (design data and relevant information for specimen reconstitution), SPT data (empirical correlations).	Max/min density tests
Monotonic strength in sand	CPTU data, Selected laboratory tests to correlate results	Shear box tests
Monotonic strength in clay (undrained shear strength)	CPTU and analyse the effect of anisotropy (direct shear/compression/tension)	UU triaxial tests, Laboratory vane tests, DSS tests
Monotonic strength in clay (drained strength)	CPTU, laboratory testing	Atterberg Tests (correlations), Triaxial tests
Sensitivity of fine soils	CPTU data, Sensitivity in clay: laboratory tests on remolded specimens, Correlations with Atterberg tests	Laboratory vane tests, Atterberg Tests
Organic content	Sample description methods, Laboratory tests on specimens	Organic content, Mineralogical Assessment
Abrasivity	Sample description methods, Laboratory tests on specimens	Carbonate content, Mineralogical Assessment, Cerchar tests on rock
Permeability	Double packer dissipation tests (soil and rock), CPTU Dissipation tests (soil), Laboratory tests on rock and soil specimens.	Permeability tests
Rock Compressive Strength/Tensile Strength	In situ test data – SPT (in weak rock), Core description methods, Laboratory tests on specimens	UCS on specimens, PLT tests on sub samples, Brazilian strength Test
Rock Shear strength/ deformation parameters	In situ test data HPD, Core description methods, Laboratory tests on specimens	Shear box tests, Tilt box tests
Rock mass structure	In situ test data – HRAT, Core description methods, Laboratory tests on specimens.	
In situ stress – direction & level	In situ test data – HPD.	
Small strain stiffness	In situ test data PS logging, Laboratory tests.	
Soil stiffness at larger strain	In situ test data HPD.	
Thermal conductivity	Sample description methods, Laboratory tests on specimens.	Needle probe tests on soil sample specimens

Required data	Acquisition Method	Lab testing strategy (main tests & index/classification tests)
Ground water regime	Ground water monitoring.	
Ground Temperature Regime	Ground temperature monitoring	
Environmental and consenting	Grab samples can be used offshore, Testing of Soil and ground water samples	

4. Data Integration

When building a GM, the integration of geophysical and geotechnical interpretations is critical for robust ground modelling. Geophysical data provides wide lateral coverage across the site where geotechnical data provides discrete point information. The geotechnical data provides truthing information to the geophysical data, and the geophysical data allows for the extrapolation of measured geology and engineering parameters, derived from the geotechnical data. Due to different data types, survey environments, and processing and interpretation process; it is recommended that data integration for cable landings utilises a three-pronged approach: Geoscience dataset integration, Cross-environment integration, and Geoscience – Engineering integration. Figure 2 illustrates the process for a typical landfall project and demonstrates the iterative and cyclic process by which different investigation stages, and data management systems feed into one another and the GM and RR throughout the project.

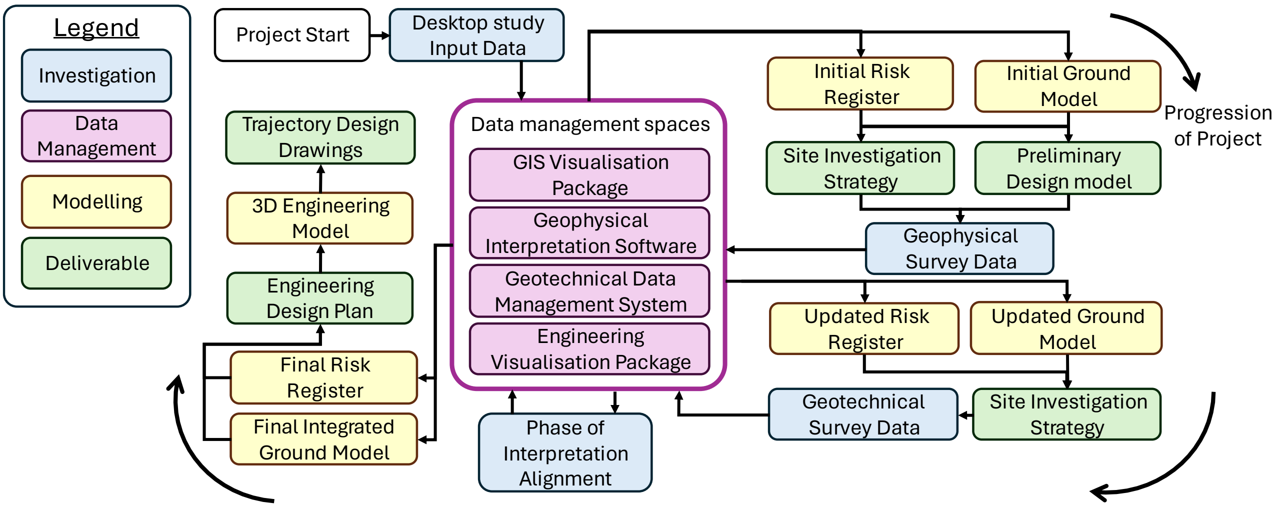

Figure 2: Flowchart of continuous data integration and GM evolution throughout the lifecycle of a project.

4.1 Geoscience Dataset Integration

The integration of geophysical, geotechnical, and other geoscientific datasets is the cornerstone of robust ground modelling. This requires an alignment between the interpretation of each data type, with close agreement of site conditions between disciplines. Without this alignment, a mismatch between the datasets will occur where different interpretive opinions result in difference in the positioning of unit boundaries. Temporal changes should also be accounted for at this stage. In areas of high sediment mobility, the seabed is not a fixed datum. Data referenced to the seabed should therefore be tied to a fixed geospatial datum (e.g. LAT).

Successful integration is facilitated by quality data management combined with a coherent co-ordinate and datum reference strategy, and detailed data visualisation and GIS workspaces established in the early stages of a project. This allows datasets to be viewed in context with each other and the proposed design, resulting in efficient and considered interpretation of data and understanding of the site conditions. Collaboration between geophysicists, geospatial specialists, and geotechnical engineers is key to ensuring successful data integration for a project.

Utilisation of techniques that can provide comparable parameters between geophysical and geotechnical datasets are beneficial. Correlation of calculated small strain data derived from MASW can be cross referenced to in-situ geotechnical measurements to indicate how parameters such as rock stiffness vary across a site. Cross correlation between datasets such as sediment mapping from SSS data grab sampling, and land-based sediment mapping can be used to interpret soil distribution and shallow geology in areas of limited intrusive sample data.

Visualisation of the geotechnical monitoring and test data can also be integrated into a GM by assigning measured parameters to geological units. Ideally these should be visualised in multiple parameter plots where integration of multiple variables can be made at the same time. Plots should be presented in elevation relative to datum to identify specific unit parameter trends. This can assist in identifying areas of anomalous ground conditions and provide refinement of geological unitisation prior to the creation or update of an engineering stratigraphic model.

4.2 Cross Environment Integration

The cross-environmental integration of data is unique to landfall projects. Working across multiple environments, it is common to see different co-ordinate and datum systems used for each setting, with historical data often increasing this complexity introducing outdated coordinate systems and geological classifications. At the start of a landfall project a common datum should be established across all project environments and survey scopes, together with standard geology classifications, facilitating consistency of interpretation and integration of datasets within a single GM. This cross-environment GM ensures the required data coverage is achieved coherently across the entire site, providing validity to the spatial understanding of risk.

Selection of suitable survey techniques that can be deployed across multiple environments, and integrating the data acquired in each environment allows for a reduction in data gaps. Techniques such as lidar topo-bathymetry, drone deployed magnetometer, DAS measured seismic techniques, and intertidal geotechnical platforms allow for data collection in the more challenging parts of a site, providing continuation of, and integration between, land and marine datasets. Successful cross environment integration serves to minimise and identify risk in the most geomorphologically dynamic areas of a site. Figure 3 highlights the potential benefit of such an integration. Integrating data collected in only the onshore and offshore environments may not identify the hazards found in the intertidal region of a site; however, acquiring and including data from each survey environment allows for a more complete picture of the site hazards.

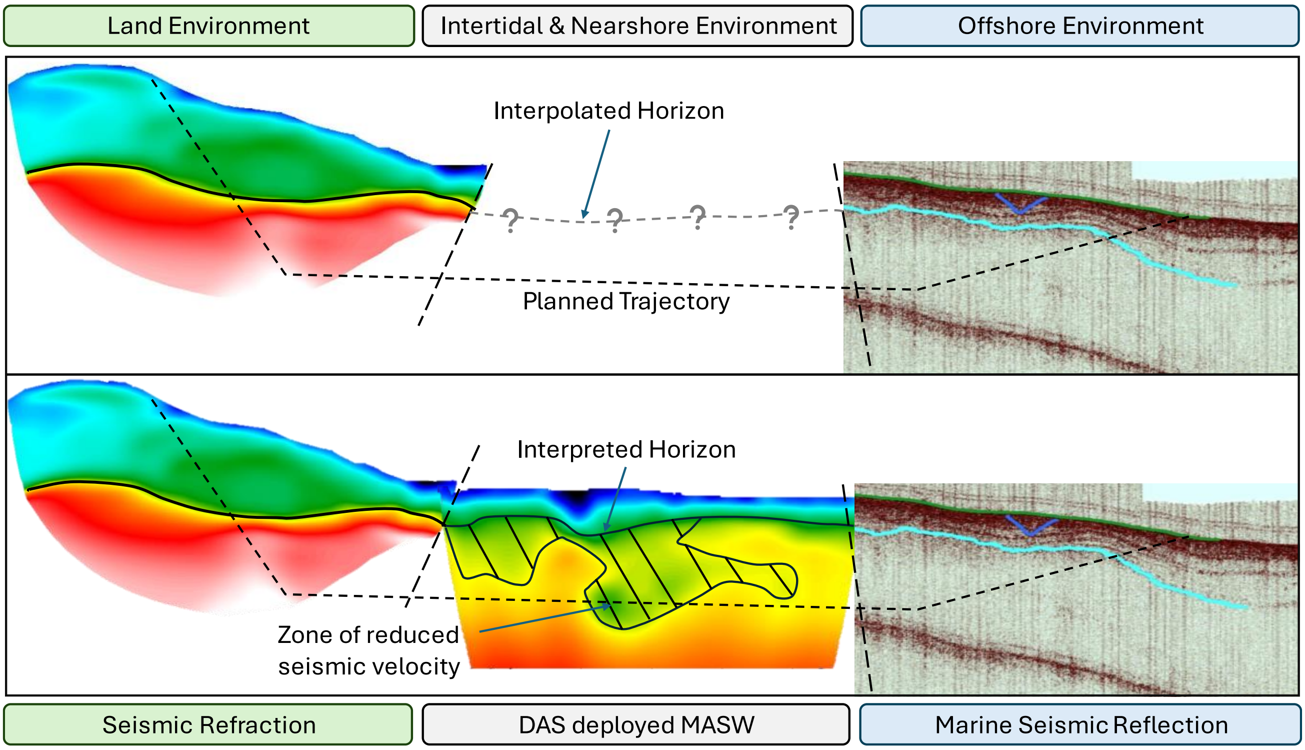

Figure 3: *A hypothetical example of integrating multiple data types and interpretation across survey*

4.3 Integrating Geoscience and Engineering

The integration of the GM into the installation's engineering design is the next step in the process. It is essential that the cross-environment integration has been carried out prior to this stage, with all datasets in the same coordinate system and datum, allowing all relevant information to exist in a single model space. By moving the model from specialist geoscientific and geospatial software packages into a space accessible to designers, installers, and O&M teams, can greatly aid collaboration and data sharing between design teams, construction contractors, and any other relevant stakeholders, and allows visualisation of the installation design with the geological structure of the site. Improving the accessibility and visibility of the ground model across a wide array of teams also serves to improve the ownership of risk. Providing all the available data to design teams may allow a reduction in the over-engineering of infrastructure as risk tolerances are better constrained.

The engineering model enables engineering tasks such as the incorporation of proposed structures and earthwork calculations to be made in context of the geological structure of the site. This enables the design alignment to be visually evaluated throughout the lifetime of the asset. Potential construction obstructions and operational risks can be pinpointed, appropriate installation methods for the site conditions can be selected, and any future site investigations requirements can be determined. Beginning this integration immediately after the creation of the initial GM at the DTS stage would provide further efficiencies. Assessing the DTS data in relation to the engineering design within the model environment, may allow for a more targeted geophysical or geotechnical investigation scope, reducing project time and cost for the client.

Combining the engineering model and GM with forward modelling of a site's sediment mobility and coastline evolution may provide insight into the lifespan of an asset and help identify future hazards. Understanding coastal recession or accretion rates and how the site will change over the lifetime of a project allows the ability to model the impact of present or future permanent and temporary works on the current and future ground conditions.

5. Conclusions

Landfalls are challenging and dynamic sites at the transition between land and sea. These environments are constantly changing throughout a project and assets lifecycle. Across the four environments seen at a landfall (Land, Intertidal, Nearshore, Offshore) numerous conditions, constraints, and hazards require consideration. Multiple geophysical and geotechnical survey investigation techniques can be deployed to investigate these items. To ensure a robust understanding of a site, integration of multiple techniques is recommended when creating a GM.

The development and use of a fully integrated GM containing subsurface geology, surface features, and geotechnical data can provide significant value for design teams throughout the lifecycle of any projects. Combining these GMs with engineering design to produce a 3D engineering model brings multiple benefits to a project.

To produce these models, data is collected from multiple data sources and survey campaigns, which are then integrated. The nature of these surveys is subject to the predicted site conditions and potential risks. In order to maximise the value of these surveys, careful and considered planning should be undertaken. This includes:

- Digitisation and use of historic ground investigation data as the first step of a site characterisation project
- Thorough understanding of a site prior to survey campaign, yielding efficiencies throughout the ground investigation cycle.
- Collaborative survey planning across the four landfall environments. Offshore and land-based ground investigations should not be undertaken in isolation.
- Utilisation of cross environment survey techniques and platforms, improving survey results and data coverage.
- Consideration of design requirements during survey planning, ensuring surveys are specified to adequate exploration depths, data coverage, and offsets
- Use of standard common data formats, and structured data management, to facilitate the integration of all elements of a landfall project.

Following the practice outlined in this paper, continuously updated models, supported by a coherent site characterisation strategy, and owned by a consistent, knowledgeable team, should be used in partnership with forward modelling to allow developers to make informed decisions during the design stage on suitable installation techniques and risk mitigation for the lifetime of an asset. Models can be passed on to construction teams delivering informative site knowledge without incurring additional cost. The model can be updated with the as-built information and passed onto the future teams for use in planning maintenance and decommissioning or sharing with other potential stakeholders.

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