A Multidisciplinary Ground Model Approach to Geotechnical and Geohazard Site Appraisal for Large Infrastructure Developments

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ABSTRACT: A major geotechnical challenge for large and mega infrastructure developments is to economically appraise the geotechnical conditions of the development area early enough for concept design, with sufficient resolution for detailed design and with sufficient spatial coverage to provide flexibility for layout changes. In active geological settings, characterisation and mitigation of potential geohazards presents a significant additional challenge. This paper describes the use of a multidisciplinary ground model as a tool to support both geotechnical site appraisal and geohazard appraisal. The combined use of a geographical information system with a ground model is also described, to manage the spatially extensive data associated with large infrastructure developments and to perform geotechnical and geohazard spatial analysis over large areas. Examples of successful application of this approach from major offshore developments are described and the importance of a competent and experienced geoteam of discipline specialists is highlighted.
Keywords: Ground model, geographic information system, geohazard, spatial analysis

1. INTRODUCTION

Large infrastructure developments can cover several hundreds of kilometres in the case of transport routes, pipelines and cable corridors, or hundreds to thousands of hectares for major building complexes such as power stations, ports and subsea oil and gas developments.

A major geotechnical challenge for such large or mega infrastructure developments is the practical and economic appraisal of the geotechnical variability of the development area sufficient for design. In active geological settings, characterisation and mitigation of potential geohazards presents a significant additional challenge.

The combination of a detailed understanding of past and present geological processes with traditional ground investigation approaches allows a full three- or four-dimensional understanding of the geotechnical conditions of a site to be efficiently characterised in a multidisciplinary ground model.

Rigorous data management using a geographical information system (GIS) allows all relevant data to be hosted and manipulated in an intuitive spatial domain that highlights the geographical interrelations between different datasets and between geotechnical datasets and the planned infrastructure. GIS-based spatial analysis techniques can be employed to rapidly perform geotechnical analysis or geohazard assessment, such as foundation suitability mapping, slope stability screening or seabed sediment transport analysis, over very large areas.

The development and of a multidisciplinary ground model and its use for site characterisation, gap analysis, visualisation and communication are described in this paper. The application of a GIS-based ground model to geotechnical site appraisal is also discussed and is of specific relevance to large infrastructure developments where efficiencies are required over traditional methods due to the scale of the site. The use of a ground model for geohazard appraisal is presented as a spatially consistent and resolute way to identify and characterise geohazards, understand their potential interactions with infrastructure, and mitigate accordingly. In this way, geohazards are managed in a risk-based framework consistent with other routine project risks. Examples of successful application of the ground model approach are presented from major offshore development projects and the importance of a competent and experienced geoteam of discipline specialists is highlighted.

The development and requirements of a ground model is well described by other authors (e.g. Fookes, 1997, Knill, 2003, Evans, 2010). This paper highlights the diverse use and application of a ground model for large infrastructure projects from both a geotechnical and geohazard assessment perspective.

2. MULTIDISCIPLINARY GROUND MODEL

2.1 Data Collation

2.1.1 Desk Study

A desk study is an essential first phase to the development of a multidisciplinary ground model and involves the identification and analysis of all publicly-available data of relevance to the foundation zone of the planned infrastructure. The desk-study should focus on building a first iteration of the ground model, which is likely to be lower resolution than the requirements of the final foundation design but is an initial framework to be iteratively refined. An initial desk study-based ground model would typically divide the study area into broad terrains of similar ground conditions where terrain boundaries are usually defined by significant geological features such as major slope breaks, surface fault expressions, textural boundaries, etc.

In addition to characterising the present-day conditions, which represent a ‘static’ point in time, the desk study should also consider the geomorphological process history of the site to characterise the dynamics of the site and build an understanding of the geotechnical conditions expected to remain for the life of the planned infrastructure, those which may be associated with past processes that are no longer active and those which may arise due to new processes not previously experienced at the site.

A multidisciplinary approach is recommended, even at the desk study phase. Analysis of desk study data should involve geologists and geomorphologists, to interpret data from multiple sources and at variable resolution, into a common format for integration in a ground model. Extrapolation between datasets may be required, which is best-performed by discipline specialists. Geotechnical engineers and geohazard analysts should also be involved at the initial desk study phase to focus the ground model on its end applications to inform foundation design and geohazard assessment.

Key datasets of relevance at the desk study phase will include terrain elevation data, regional geological maps (e.g. solid geology, surficial sediments, geological structure), aerial / satellite imagery for onshore developments, regional seismic lines (more readily available in offshore settings), existing boreholes and other intrusive data, wave and tidal current data for offshore developments, etc.

2.1.2 Data Acquisition

A desk study ground model will form the basis of an initial gap analysis to define data acquisition requirements. To maintain a ground model approach to characterising the site, data acquisition should cover locations of currently planned infrastructure and the surrounding area, to ensure flexibility for revisions to the infrastructure layout and to provide a wider geological and geotechnical context for geohazard assessment. The economic argument to focus acquisition on the current infrastructure layout may provide short-term savings, but the flexibility afforded by a wider site understanding can save significant costs associated with late-stage remobilisation of data acquisition equipment if more data are required.

Newly acquired data are typically used to update the ground model to reflect the improved understanding of the site. Therefore, an integrated multidisciplinary approach should be applied to data acquisition planning, monitoring and results interpretation to optimise the resulting ground model iteration. For example, this includes the specification of combined sample acquisition for geotechnical testing, geochronological dating and sedimentological logging, either from within a single composite borehole or via the specification of clustered boreholes to target multiple requirements from the same location. Where combined geophysical and geotechnical data acquisition is planned, boreholes and in situ tests should be sited to lie on geophysical acquisition lines for optimal correlation and interpolation potential.

As well as the potential to overlap geotechnical and geohazard data acquisition targets, geohazard-specific data acquisition may also require a focus on areas distal to the development area. For example, a pipeline route may be planned along shallow gradient valley floor, surrounded by steeper slopes of the valley sides. Without proper characterisation of the valley sides, which may include data acquisition, the geohazard risk associated with slope instability cannot be fully assessed.

Whilst careful data acquisition planning helps avoid costly late-stage remobilisation of data acquisition equipment, it can be beneficial to adopt a phased approach whereby an initial limited quantity of ‘reconnaissance’ data are acquired and used to make an interim ground model update, from which a further gap analysis and detailed acquisition scope are created.

A further alternative is to ensure the results of the data acquisition are reviewed by a multidisciplinary team, or ‘geoteam’ (described later in the paper), as the acquisition progresses. This approach avoids multiple iterations of data acquisition but provides flexibility for changes to the data acquisition scope in almost real-time. New data are compared with predictions from the existing ground model; where conditions are consistently as predicted the density of data acquisition locations can be reduced and conversely where conditions are not as expected additional data can be specified. Specification of additional data locations during data acquisition can be expedited by pre-defining option locations before mobilisation.

2.2 Geographical Information System Framework

A successful multidisciplinary ground model requires integration of data from each discipline in a common framework. All disciplines of ‘geo-data’ for infrastructure developments have a position in geographical space and therefore a GIS platform provides an intuitive spatial framework in which to integrate all data of relevance to a ground model.

A GIS has a primarily map-based interface built from an ordered set of layers which clearly demonstrate the spatial interrelations between datasets and the planned infrastructure. Continuous surface data are represented as grids and triangular irregular networks (TINs), and discrete features as points, lines and polygons (typically known as vector layers). All vector layers have associated attributes which are used to capture tabular detail about each feature and vector layers are typically symbolised to highlight a specific attribute.

Most GIS software has a powerful set of in-built tools and can typically be customised to develop additional tools. In addition to basic navigation tools, some of the most useful tools for GIS-based ground model manipulation allow users to make composite spatial and attribute queries. A well-structured GIS ground model can be used to make queries such as “*select all locations within 2000m of a planned structure where the soil friction angle is greater than 30° at less than 10 m below ground level”* or “*select all samples on slopes greater than 10° with a unit weight greater than 21kN/m^3”*. This level of data manipulation and combined data and spatial query is not possible unless data are integrated within a GIS-based ground model.

Non-spatial data such as reports, photographs, diagrams, etc. can be made accessible via hyperlinks from a relevant geographical location within the GIS ground model to provide single-interface access to all information.

2.3 Visualisation and Communication

A multidisciplinary ground model is an effective way to visualise the three-dimensional spatial relationships between datasets and to understand the link between the terrain, subsurface, geotechnical conditions and geohazard processes. Communication of this key site understanding is possible via both two-dimensional and three-dimensional GIS interfaces. Typically, specific features or processes will also be illustrated using annotated conceptual block models which make use of a graphical approach to clearly communicate observations and interpretations (Figure 1).

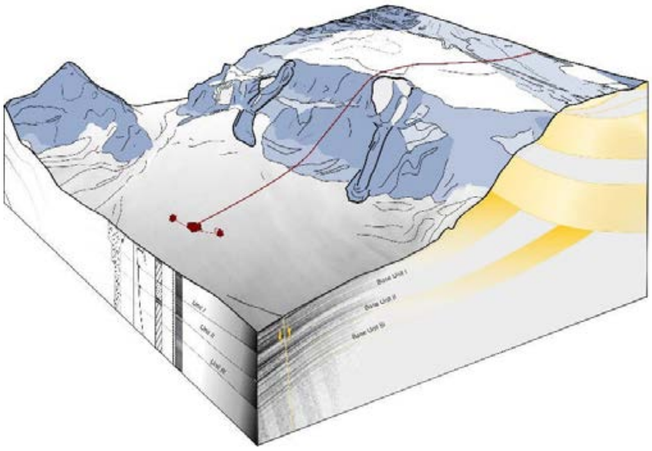

Figure 1 Example of a conceptual block model which uses a graphical approach to clearly communicate key observations and interpretations

3. GEOTECHNICAL SITE APPRAISAL

3.1 Soil Model

A predictive soil model focused on infrastructure engineering requirements is the primary interpretive output from a multidisciplinary ground model for geotechnical engineering application. The predictive soil model comprises soil units and soil provinces. Soil units are used to divide the three-dimensional zone of interest into volumes of similar soil properties and geotechnical conditions, with characteristic geotechnical parameters defined for each unit. Soil provinces are surface zonations which group areas with a similar sequence and thickness of soil units between ground level and the depth of interest below ground level. Soil unit boundaries are interpolated between boreholes and, where geophysical data are available and if acoustically significant, can be mapped as continuous surfaces across a development area (Figure 2). This simple but versatile approach allows the geotechnical conditions to be predicted anywhere in a development area with as much accuracy as the available data will allow and with geologically-informed interpolation where data are absent.

3.2 Geotechnical Application

The predictive soil model can be used directly to provide soil parameters for foundation design associated with a fixed infrastructure layout and, if sufficiently detailed, will include lower bound parameters for capacity calculations, upper bound parameters for installation calculations, etc. However, where the infrastructure layout is not defined, spatial analysis informed by the GIS-based ground model can help refine the layout for optimal geotechnical placement.

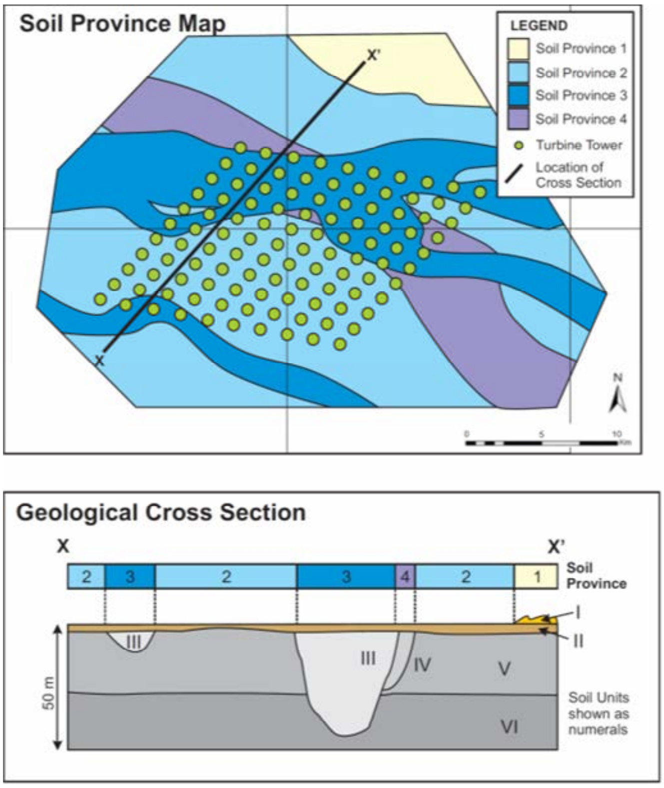

Figure 2 Example soil model for a wind farm development comprising soil units visible on the cross section and soil provinces visible on the plan view map (Clare et al, 2012)

Rushton et al (2017) present examples of geospatial analysis, which includes a method developed to derive GIS-based lateral pile capacity and map the required monopile length sufficient to provide capacity for an offshore wind turbine across an entire licence zone. The method involved development of a regular mesh of analysis points and use of the GIS-based ground model to assign design soil parameters and lateral load-displacement (p-y) soil springs to each mesh node, for use in a one-dimensional finite element analysis of the monopile (Figure 3). An iterative procedure was performed to determine the required monopile lengths: if the monopile was able to withstand the applied lateral load and moment, and remain within the prescribed displacement and rotation tolerances, the pile length was reduced. As soon as either of the tolerances were exceeded, the previous monopile length was taken as the required length.

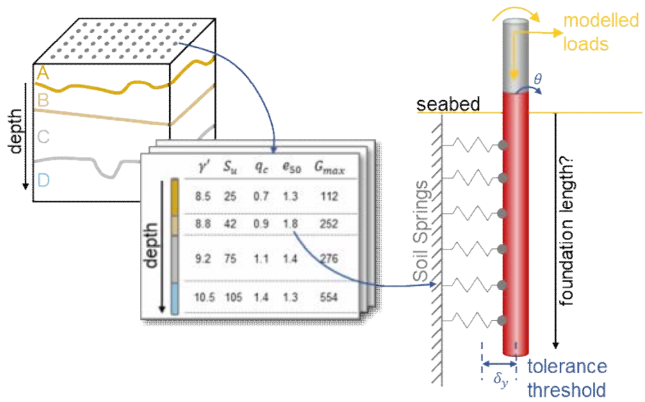

Figure 3 Graphical depiction of ground model sampling via a regular mesh in GIS to provide inputs to an automated sequence of monopile lateral capacity analyses

In another offshore example for a major oil and gas company, a very shallow GIS ground model was built to integrate cone penetrometer test (CPT) data with the reflected amplitude of the acoustic signal from a geophysical source. The aim was to locate areas of hard ground near seafloor which would cause significant problems for the shallow foundations of the planned infrastructure. The hard ground typically caused a high amplitude acoustic response and always caused a high cone resistance CPT response. The GIS-based ground model spatial analysis was combined with a novel use of Receiver Operating Characteristics analysis (Fawcett, 2005) to quantify the confidence and the chance of false positives associated with an acoustic amplitude above which hard grounds were expected.

4. GEOHAZARD APPRAISAL

4.1 Geohazard Model

A geohazard model is the primary interpretive output from a multidisciplinary ground model for geohazard appraisal and assessment. The format of the geohazard model will vary according to the application, but typically includes a geohazard database and register.

The geohazard database records the number of observations of each geohazard occurrence in the ground model datasets, and records key metrics associated with each event. For example, a database of past offshore landslides would be built from observations on hillshaded seafloor elevation data and sub-bottom profiler or seismic data, where available, to characterise the number of events visible, the depth below ground level (and hence inferred age) of each event, and key metrics such as the length, width, thickness, orientation, etc. Where possible, regional seismostratigraphy and geochronological dating will be used to refine estimates of the age of events, with the aim of determining a rate of reoccurrence.

The geohazard register documents all geohazards considered to be credible at the site, summarises the properties of each geohazard based on observations and metrics from the geohazard database, captures initial estimates of the likelihood of each geohazard and, if possible, makes some inference of the consequence of the each geohazard impacting the planned infrastructure. This geohazard register is an important step in documenting which geohazards require further assessment in a full quantitative risk assessment (QRA) and which geohazards are considered of sufficiently low concern to the planned infrastructure to not require further consideration.

4.2 Quantitative Risk Assessment

A QRA takes the largely qualitative geohazard register and advances the assessment of the main threats by further quantified analysis, which should include consideration of all components described in Table 1.

Table 1 Quantitative Risk Assessment Considerations

Component	Description
P(event)	Probability of a geohazard event
P(spatial)	Spatial probability: infrastructure exposure to a geohazard event and likelihood of it being hit given an event occurs
P(hit)	P(event) × P(spatial)
P(damage|hit)	Probability of infrastructure damage in the event of it being hit by a geohazard event. This is assessed via vulnerability analyses
P(damage)	P(hit) × P(damage|hit)
Risk	P(damage) × Consequence, where consequence may be in terms of health and safety, financial, reputational or environmental and is typically assessed by the infrastructure developer

Probability of a geohazard event may be inferred from rates of reoccurrence as described in the Geohazard Model section. In addition to reliance on such historical frequency estimates, it is typical to perform forward modelling to estimate the likely future

P(event) as a result of natural processes and possibly modified by the planned infrastructure development. Rates of reoccurrence and forward modelling results should be compared and reconciled as a sense check.

Again, a GIS-based ground model can be used as an input to GIS spatial analysis to determine P(event) over a large development area. Mackenzie et al (2009) describe spatial analysis of landslides with the use of a ground model to provide the geotechnical soil condition inputs. Dimmock et al (2012) describe a similar GIS-based approach applied probabilistically and with pseudostatic earthquake loading to inform a QRA for a deep water subsea gas development project in the Mediterranean Sea. Rushton et al (2015) describe further advances landslide spatial analysis via the incorporation of the shear band propagation mechanism, rather than limit equilibrium. The example presented by Rushton et al (2015) is for a new deep water oil facility in the Caspian Sea. Figure 4 demonstrates graphically how geotechnical properties are extracted from the ground model as pixel surfaces which are then combined using spatial analysis to perform an infinite slope assessment for each pixel and generate a result of factor of safety for each pixel.

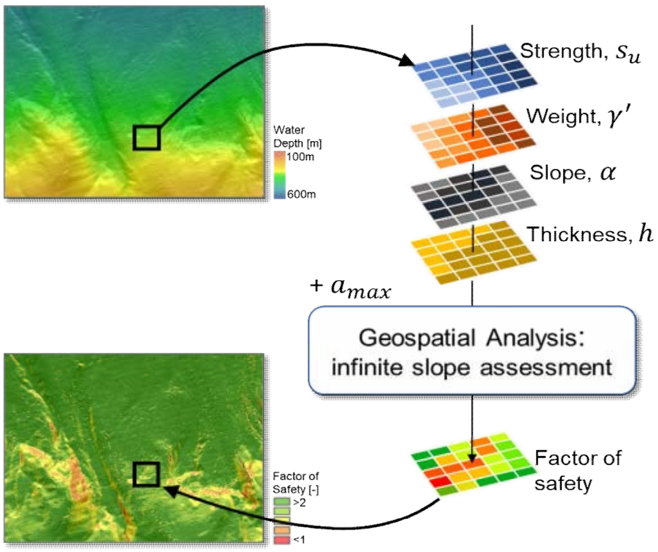

Figure 4 Graphical depiction of GIS-based slope stability assessment which uses geotechnical properties extracted from the ground model as pixel surfaces and generates a further pixel surface of factor of safety

Spatial probability is typically a function of the size of the geohazard event relative to the size of the infrastructure and therefore is usually calculated within the same GIS framework as the ground model. The other QRA components are largely assessed outside of the ground model in a risk workbook, but the interim result of P(hit) and the final results of P(damage) and Risk are most effectively communicated as mapped layers hosted in the GIS ground model and visualised relative to the planned infrastructure layout (e.g. Hill et al, 2015),

5. GEOTEAM

The approach described for the development of a multidisciplinary ground model for application in geotechnical and geohazard site appraisal relies heavily on large and diverse datasets, powerful GIS software applications and cutting-edge analysis. However, the most important component in the development of a multidisciplinary ground model is a competent and experienced geoteam of discipline specialists able to work collaboratively and combine their expertise. The specific skillsets within a geoteam will depend on the requirements of each individual project, but may comprise geologists, geomorphologists, geotechnical engineers, geophysicists, risk analysts, sedimentologists and facility engineers.

6. CONCLUSION

Data acquisition, geotechnical site characterisation and appraisal, and geohazard assessment have been routinely performed as part of infrastructure development projects for decades. However, requirements to deliver large and complex infrastructure projects efficiently, reliably and safely requires traditional approaches to evolve.

For the geotechnical aspect of an infrastructure development, a multidisciplinary ground model is a versatile tool that can bring repeated time and cost efficiencies to a project. Infrastructure developments in geohazardous settings can also benefit from the understanding of the geological processes afforded by the integrated ground model approach.

GIS is an intuitive and spatially resolute software platform with which to build and manage a ground model. Its strength in visualising and querying large volumes of data is of importance for large infrastructure developments. The spatial analysis capability of GIS, when coupled with a detailed ground model, can bring significant efficiencies to geotechnical and geohazard analysis.

This approach has been successfully employed for several large offshore developments, delivered by a competent and experienced geoteam of discipline specialists.

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