Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-680

ECSMGE 24
XVIII EUROPEAN CONFERENCE
ON SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

Seabed and sub-seabed boulders as an engineering hazard in the marine environment; methods of detection and quantification

Les risques techniques liés aux blocs rocheux de surface et enfouis dans l'environnement marin; une stratégie d'atténuation des risques pour les câbles sous-marins

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Abstract: Seabed and sub-seabed boulders are a significant design constraint, and financial risk to the design and installation of foundations for offshore Wind Turbine Generators, the trenching and installation of export and intra-array cables, and project design. Many windfarms under development in northern Europe and USA are built on geological formations which are either a direct product of, or subsequently influenced by, glaciation. These formations often contain high numbers of seabed and sub-seabed boulders; for example, the Marr Bank Formation of the North Sea. A primary objective for pre-construction geophysical surveys is to provide data to support a boulder mitigation strategy. This is required prior to installation to allow for an optimised construction methodology to be selected. The detection and quantification of boulders is the first step in a proposed five-step mitigation strategy. In this paper, we present an overview of the geophysical methods utilised for the detection of seabed and sub-seabed boulders, including the key considerations for the boulder detection requirements and subsequent survey specifications to meet these requirements. We present the technical and practical limitations to detection, as well as state-of-the-art solutions. The detection of boulders is followed by a detailed quantification of boulders, in order to understand the risks posed to engineering activities. The overall objective is to reduce engineering risk by better informing the location, design, and installation associated with emplacing infrastructure at and below the seabed.

Résumé: Les blocs rocheux présents sur le fond marin ou enfouis sous sa surface constituent une contrainte de conception importante et un risque financier non négligeable pour la conception et l'installation des fondations des générateurs d'éoliennes en mer, l'ensouillage et l'installation des câbles d'exportation et des câbles inter-éoliennes, ainsi que la conception du projet. De nombreux parcs éoliens en développement en Europe du Nord et aux États-Unis sont construits sur des formations géologiques qui sont soit le produit direct de la glaciation, soit qui ont été influencées ultérieurement par celle-ci. Ces formations contiennent souvent un grand nombre de blocs rocheux en surface et sous la surface; par exemple, la formation Marr Bank de la mer du Nord. L'un des principaux objectifs des études géophysiques préalables à la construction est de fournir des données permettant d'étayer une stratégie d'atténuation des risques liés aux blocs rocheux. Il est nécessaire de disposer de ces données avant l'installation, afin de permettre la sélection d'une méthodologie de construction optimale. La détection et la quantification des blocs rocheux constituent la première des cinq étapes d'une stratégie d'atténuation des risques. Dans cet article, nous présentons une vue d'ensemble des méthodes géophysiques utilisées pour la détection des blocs rocheux de surface et enfouis, incluant les considérations clés pour les exigences de détection des blocs rocheux et les spécifications des levés associés pour répondre à ces exigences. Nous présentons les limites techniques et pratiques de la détection, ainsi que les solutions les plus récentes. La détection des blocs rocheux est suivie d'une quantification détaillée de ceux-ci, afin de comprendre les risques posés aux activités d'ingénierie. L'objectif global consiste à réduire les risques techniques en informant mieux sur leur emplacement et fournir des données pour la conception et l'installation associés à la mise en place d'infrastructures sur et sous le fond marin.

Keywords: Geophysics; geophysical survey; boulders; hazard mitigation; risk analysis.

1 INTRODUCTION

Licenses for new offshore windfarm developments are being awarded with increasing frequency, with a trend towards larger lease areas as the size of turbines increases to meet power generation demand. Across some of the most active offshore wind regions (North Sea, Baltic Sea, and northeast USA), the geology at these sites is shaped or influenced by glaciation. Glacial sediments, typically till, consisting of a heterogenous mixture of clay, sand, gravel, and boulders varying widely in size and shape (McMillan & Powell, 1999) is often a source of seabed and sub-seabed boulders, in these environments.

The presence of boulders can have significant impact on the engineering works associated with development of a windfarm. They represent a significant constraint to a wide range of activities including: the installation of foundations; cable routing; trenching; design operations; installation operations for export and inter-array cables; and jack up operations. Failure to sufficiently identify and quantify the magnitude of the constraint can lead to considerable financial risk to a project. This may lead to problems where developers exceed project budgets, with increased installation timescales, encounter unexpected delays, and have to mitigate for wear or damage to installation equipment.

Where boulders are potentially present, a clear strategy is required to successfully manage the potential constraint using a risk-based approach. A five-step mitigation strategy is presented, the objective of which is to reduce the risk boulders may present to a practical and commercially viable level (Figure 1). This strategy can be employed at any stage of the project life cycle prior to construction, from desktop study to final engineering corridor planning. However, the greatest benefits result from implementation at the earliest stages of planning.

This paper focuses on the first stage of the strategy: the identification of the hazard and quantification of the risk, to allow for further mitigation to take place. The detection of boulders followed by a detailed quantification, allows for an improved understanding of the risks to engineering activities. Resulting in improved design, and installation of engineering infrastructure at and below the seabed.

2 DETECTION

The detection of boulders on and below the seabed is generally achieved through acoustic geophysical survey techniques. Geophysical surveys are often performed to inform a range of development activities concurrently, for example, cable thermal design, seabed mobility, UXO risk mitigation, and other constraints like anthropogenic material and infrastructure. Knowledge of the requirements for each constraint may allow for a single integrated survey to capture all the required data, with minimal risk of unanticipated re-survey requirements.

Geophysical techniques for this purpose are used throughout the world as a matter of routine. However, the regulations governing data acquisition, processing, and interpretation, vary significantly. In the USA and Germany, regulatory bodies publish exacting minimum standards of survey data accuracy and detectability (BOEM, 2017; BSH, 2014), whereas in other territories, less specific guidelines are available (BSI, 2015). Some of these guidelines are derived from oil and gas pipeline and rig site survey, standard industry practice, updated to meet the requirements of the renewables industry. Others originate from bodies such as the Carbon Trust (Carbon Trust, 2020) and offer a recommended practice when planning a marine geophysical survey.

Beyond aligning with regulatory requirements, successful detection, and quantification of boulder hazards at a given site first requires understanding the minimum object detection size and the sequence of site-characterisation operations (e.g., route selection and corridor alignment). Smaller objects are more challenging to detect so require a more highly specified survey to enable identification. The minimum object detection size would ideally be established at an early stage of planning the survey, as it defines a key objective of the data collection. Collaboration with engineers and designers to inform strategy and specification requirements is key to ensuring surveys are planned to meet the requirements for designing a mitigation strategy, (Burley et al., 2023; Carbon Trust, 2020).

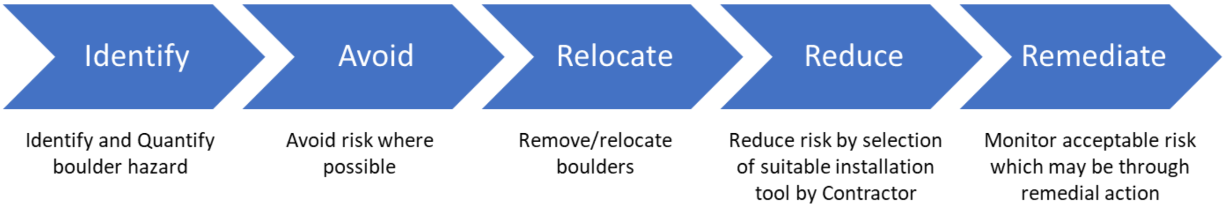

Figure 1. A five-step mitigation strategy, beginning with the identification of boulders followed by each mitigation option.

2.1 Seabed boulder detection techniques

For detection of seabed boulders, a combination of sidescan sonar (SSS), and multibeam echosounder (MBES) data, would typically be acquired, with new methods such as synthetic aperture sonar also becoming more common. A SSS system is a deep-towed sensor, flying a few meters above the seabed, scanning the seabed at a low angle of incidence. This setup allows a minimised distance between sensor and target, resulting in reduced travel time of the acoustic energy and typically giving a high resolution. The low angle of incidence produces the 'shadow', allowing for the measurement of object height. However, the accuracy is limited by underwater acoustic positioning which typically has an accuracy of +/- 2 m. The sensor operates a port and starboard channel (both sides of the sensor), but cannot look vertically down, resulting in a stripe of null coverage known as the "nadir" along the track of each survey line. Surveys specifications usually require a 200% coverage of SSS data. The overlapping adjacent swathes of data provides coverage of the nadir and can create multiple ensonifications of seabed objects from different directions, improving detection potential. The need to achieve this overlap contributes to the line spacing requirements of the survey and the swathe range of the SSS.

The MBES system is typically a hull mounted sensor, which then benefits from accurate Global Navigation Satellite System (GNSS) positioning and delivers a quantitative depth of objects, where SSS does not. MBES images a swath centred on the survey track. MBES systems can be mounted on subsea remotely operated vehicles (ROVs) and autonomous underwater vehicle (AUVs), that can overcome these shortcomings and provide solutions for challenging deep-water environments.

The key factor limiting object detectability for both systems, is the number of acoustic signal beams which might be expected to hit or illuminate a target of a given size. The higher the density of 'hits', the greater the potential to image smaller targets.

To reliably detect seabed boulders, a certain number of hits is required. For MBES a minimum of 9 hits is recommend for resolving an object from its surroundings (IHO, 2011) Objects can theoretically be interpreted from a one pixel footprint hit, however, to increase interpretation certainty, a 2-3 pixel footprint is preferred (IHO, 2011). If a survey is required to detect small objects, there will be an upper limit on the detection range (swathe) of each sensor. By definition wider swathes cover a larger footprint, but suffer from lower ping rates, and increased signal attenuation at higher frequencies, limiting resolution.

Once the engineering requirement is known, the survey specification to support detection of the minimum object size can be calculated. An indicative set of smallest resolvable sizes are provided for a range of typical equipment settings for SSS (Table 1), and MBES data (Table 2). These values are indicative and must be confirmed for survey planning, as specific equipment and survey conditions will cause variability in performance. Note that these values are specified to achieve a one-pixel footprint only.

Table 1. The maximum SSS range and suggested survey specification to detect various sizes of item.

Smallest resolvable item [m]	Maximum Range [m]	Line spacing (200% coverage) [m]	Suggested Frequency [kHz]
0.30	45	30	540
0.40	60	45	540
0.50	85	70	410
0.60	100	80	410

Table 2. The maximum MBES range and suggested survey specification to detect various sizes of item, for a 400 kHz sensor and water depth of 50 m.

Smallest resolvable item [m]	Required Ping density [/0.5 m^2]	Maximum Range [m]	Line spacing [m]
0.30	53	30	25
0.40	31	45	40
0.50	20	60	55
0.60	15.5	70	65

In this case, note that SSS data is higher resolution for any given range. This is fairly representative, although may not always be the case if a particularly high specification MBES system is deployed.

2.2 Sub-seabed boulder detection techniques

The detection of sub-seabed boulders is more challenging than seabed boulders. Industry standard practice is to utilise 2D sub bottom profiler (SBP) or 2D ultra-high resolution seismic reflection (2D UHRS) data. As with seabed methods, an appropriate survey plan and equipment specification is critical to ensure the detection of the required minimum size object.

SBP data is typified by high frequency content, which provides high vertical resolutions at the expense of a limited penetration of approximately 5 – 10 m below seabed depending on geological conditions. SBP systems often have a short firing interval (5Hz), providing high lateral resolution. SBP data is normally acquired for structural mapping of very shallow geological units but can be used to identify boulders in the sub-seabed through the interpretation of diffraction hyperbolae of the buried boulders.

2D UHRS data generates a more powerful signal at lower frequencies. Achieving deeper penetration of 50 – 100 m, depending on geological conditions, but with reduced vertical resolution. 2D UHRS data is useful for structural mapping of geological units, which can present a valuable input into boulder risk analysis, tracing the depth and extent of boulder-bearing units such as glacial till. A indicative set of parameters with the same limitations as Table 1 and Table 2 is provided in Table 3.

2D sub-seabed seismic techniques are limited by profiling in a narrow volume vertically below the sensor track, cannot reliably return precise locations of boulders below a survey-defined size limit, and boulder sizes are not precisely determined. However, 2D methods are useful to discover boulder-bearing strata, particularly in conjunction with geological interpretive ground models. As such, these techniques can only provide estimations for the spatial distribution of geological units and boulder density.

Table 3. Table outlining how expected vertical resolution and penetration of seismic data vary with frequency.

Data Type	Frequency (Hz)	Estimated Penetration* (m)	Approx. Vertical Resolution (m)*
SBP	5,000	10	0.10
	10,000	5	0.05
UHRS	500	100	0.40
(Sparker)	1000	50	0.20

* Based on typical glacial geology, with an assumed seismic velocity 1600 m/s

To reduce uncertainty, and increase the boulder detection potential, 3D seismic data may offer an alternative approach. The use of 3D data for offshore wind is currently limited but increasing. As demand to further understand the sub-seabed grows, new technologies and methods applicable to boulder detection are becoming available. 3D is available at all scales including: SBP-like, Sparker source UHRS, and airgun site survey and exploration data. In the very near seabed methods such as 3D high resolution imaging may provide an alternative to 2D profile data for the detection of boulders. Although costs for 3D seismic are higher than 2D, the increased information for sub-seabed boulder positioning, burial depth, and size estimates provides advantages not available with 2D methods.

3 QUANTIFICATION

Quantification begins, after the completion of acquisition and processing, with a full interpretation of all the available datasets. The interpretation should identify and measure the dimensions of each individual contact that poses a constraint to the engineering requirements. For seabed boulders this task is usually carried out on high frequency SSS data, utilising MBES data to verify positioning. The result is a contact list, with interpreted objects given a unique ID, X and Y coordinate, and dimensions (length, width, and height). For sub-seabed boulders, this typically requires interpretive mapping of the extent of boulder bearing units, ground modelling, and the identification of diffraction hyperbolae. Here emerging technologies such as automated or machine learning interpretation are becoming increasingly available.

Quantification of boulders does not always require interpretation of each ensonified object. Interpretation specifications should be proportional to the risk, engineering requirements, and mitigation strategy. For example, in areas of high-density boulders (boulder fields), knowledge of the exact dimensions and position of each boulder is not required, should an appropriate mitigation strategy be available (Burley et al., 2023).

The presence of boulders can then be assigned a risk rating across the site. Risk is typically calculated by assessing the impact, the consequence that encountering the hazard would have, and the likelihood of encountering the hazard. Hazards may be split into subcategories. In this example the risk level associated with boulders of different sizes is presented (Table 4). As the risk level impacts individual engineering methods differently, a method specific strategy is then required to mitigate the risk (Burley et al., 2023).

Table 4. Example of a typical risk register.

Boulder size [m]	Impact	Likelihood	Risk
0.2 – 0.5	Very Low	High	Low
0.5 – 1.5	Low	High	Medium
1.5 – 2.0	High	Low	Medium
> 2.0	Very High	Low	High

This simplistic risk register can be expanded further by considering size (dimensions) alongside density (distribution) and location (seabed or buried).

These three attributes are relevant to most engineering activities associated with wind farm development, and the constraints on each activity. By considering the contribution of each attribute to the risk register allows for a more thorough analysis and more specific mitigation.

As the impact of the boulder attributes are different for each engineering activity, the quantification of boulder risk should be tailored to the specific task.

Knowledge of the constraints for each task can then directly link to the risk value. Using an example of cable installation constraints (Table 5), the risk register can be expanded and tailored to the given engineering task (Table 6). This quantified risk can then be assessed with assigned risk values within the five-step mitigation strategy (Figure 1) for the most appropriate action (Burley et al., 2023).

Table 5. Relating boulder hazard to cable design constraint.

Individual Boulders	**Boulder Fields**	**Constraint Level**	
Size [m]	Density		
< 0.5	Low	Soft Constraint	Low
0.5 - 1.5	Medium		Medium
1.5 - 2	High		High
> 2	-	Hard Constraint	

Table 6. Example of an expanded risk register, for the installation of subsea cables.

Boulder Attribute		**Impact**	**Likelihood**	**Risk**
Size [m]	< 0.5	Low	High	Low
	0.5 – 1.5	Medium	High	High
	1.5 – 2.0	High	Low	Medium
	> 2.0	V. High	Low	High
Density	Low	Low	Medium	Low
	Medium	Medium	High	High
	High	High	Medium	High
Location	Seabed	High	Medium	High
	Sub-seabed	Medium	Low	Low

This type of analysis is well suited to risk-mapping. As the boulder attributes are spatially variable, so too is their risk. Risk-mapping can delineate and present the lateral variability of each attribute, allowing the complexity of the risk to be properly captured, and representing the geological conditions across the site. This method is particularly useful to delineate areas of boulder field, which are commonly encountered in previously glaciated terrains.

Illustrative maps presenting the risks of boulder size, density, and location, for the installation of subsea cables across a site, are presented as a series of figures below. Boulder size risk and its constraint on installation tools is presented in Figure 2 as a series of colour coded exclusion zones. Boulder density risk is presented in Figure 3, and boulder location risk as a function of the depth below seabed of interpreted boulder bearing units is presented in Figure 4.

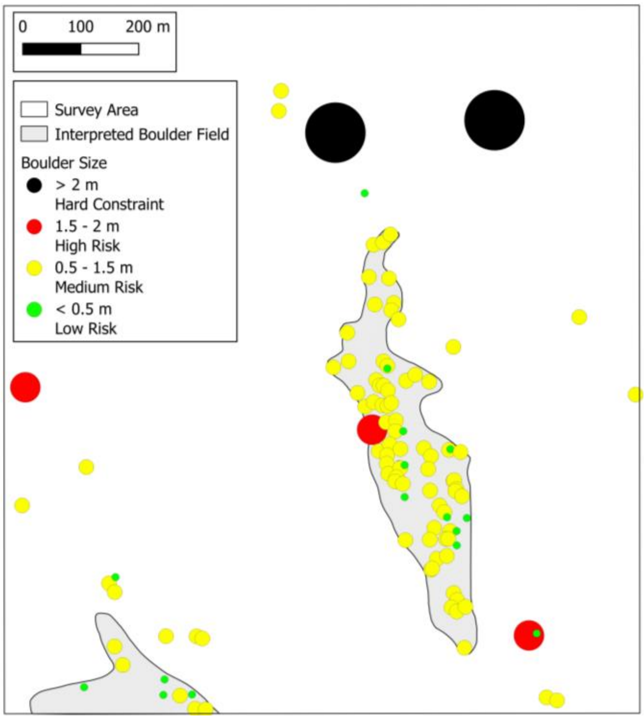

Figure 2. Lateral distribution of boulders and size dependant risk.

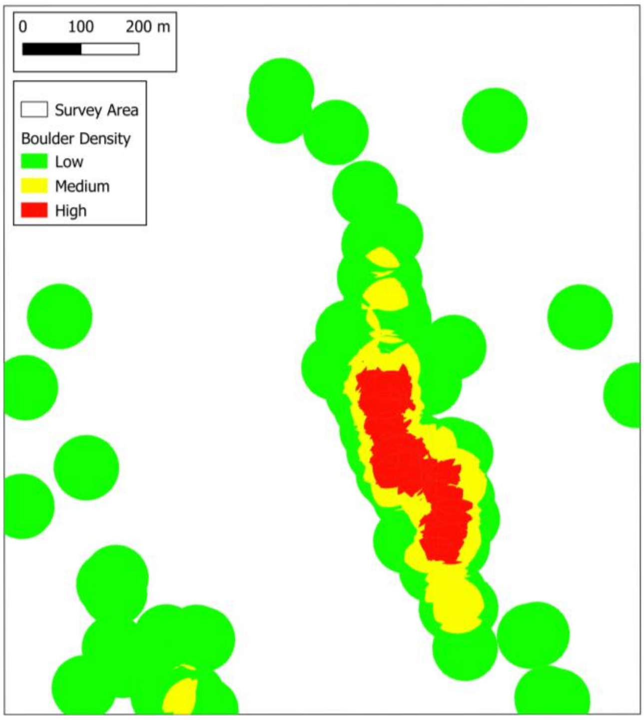

Figure 3. Density of interpreted boulders for a specified area.

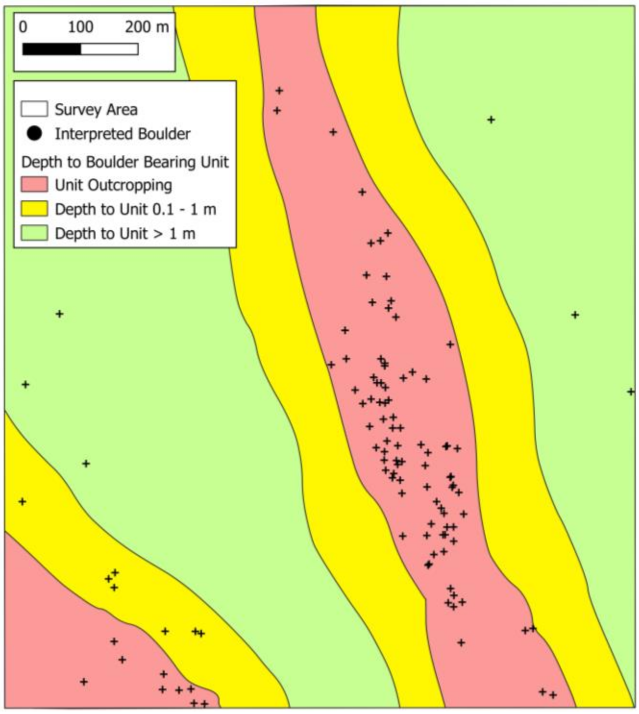

Figure 4. Risk of boulders as a function of location, through mapped boulder bearing geological units.

4 CONCLUSIONS AND OPPORTUNITIES

Boulder risk mitigation is not a new process, however this paper seeks to describe a systematic and best practice approach to the first stage of the risk mitigation process, by highlighting areas of potential optimisation and improvement.

By beginning the risk analysis process early in a development's schedule, survey campaigns can be designed and specified to identify the hazards that constrain engineering activities. This risk-based approach then defines the success of a campaign as achieving the level of understanding needed to mitigate against the risks. Engagement in risk-based thinking at an early stage may also provide additional efficiencies throughout the development cycle. Data acquired at an early stage of a project can be specified to meet the requirements of risk considerations that may not become relevant until later stages of a project. Conversely, this approach can also ensure surveys are not over specified, preventing time and resource from being spent on acquiring information that will never be used.

By increasing our understanding of the risks from boulders and how they can vary across a site, the mitigation strategies proposed can be more effectively planned. Identification of high risk or hard constraint areas can reduce the risk to engineering activities and increase the efficiency of installation.

Emerging technologies such as automated boulder interpretation, and synthetic aperture sonar may be influential in facilitating this growth of understanding, but are not a substitute for careful planning, detailed quality assurance, and well understood survey requirements. Which can be packaged into a bespoke, precise survey, detection, and quantification workflow, which can ultimately save a client time, resources, and money over the lifetime of a development.

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