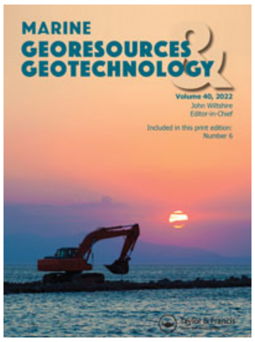

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Marine geohazards exposed: Uncertainties involved

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ABSTRACT

By exhaustively reviewing the literature related to marine geohazards, this paper reports on their uncertainties. Examples of marine geohazards include submarine landslides, fluid flows in the underground, scour events, and seabed gouging by ice. Key uncertain variables of interest to marine geohazard assessments are identified and structured by relating a framework defining the main generic components of any risk description to the task of describing risk in the marine geohazards field. Furthermore, issues related to the sources of uncertainty are scrutinised and some recommendations on how to address the identified large uncertainties in geohazard risk assessments are made. Specific considerations are proposed for analysing geohazards in the Arctic, where exploration and development activities are currently regaining momentum. Ultimately, based on the large uncertainties identified, we also strive to identify knowledge gaps to orientate scientific research efforts in the field of marine geohazards.

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Uncertainty; geohazards; marine geohazards; Arctic; ocean warming

1. Introduction

Despite instability in crude oil prices, global expenditure related to oil and natural gas exploration and development activities has averaged above US$480 billion for at least the last ten years (US Energy Information Administration 2020). In these activities, geohazards have posed significant challenges. This is reflected in the fact that, among the 100 largest property damage losses in the oil and gas industry, incidents in Enchova in Brazil (US$811 million), Treasure Saga in Norway (US$526 million) and Fateh L3 in UAE (US$393 million) have been associated with geohazards. The losses are estimated based on 31 December 2019 values (Marsh Limited and JLT special limited 2020). Geohazards can affect the infrastructure built on the seabed, such as wells, platforms, manifolds, and pipelines. Among the most notable consequences of geohazards occurring are blow outs, loss of the adjacent soil to wells, platform settlements, uncontrolled gas or water flows, water and gas leakage from the well-bore casing, damage to the well-bore casing, loss of wells, and loss of platform foundations. Rupture, excessive deformation and differential settlement, development of unsupported spans, scouring, and removal of backfill are also potential effects considered for pipelines (e.g., Glasby 2003; Devine and Haneberg 2016).

Geohazard uncertainties relate to uncertain variables associated with soil or rock properties and in situ stresses, geological structure, pore pressure and temperature conditions, as well as the occurrence of trigger factors and failure modes (Lacasse 2004; Culshaw 2005). Assessing geohazards involves uncertainties, including not only those originating from scarce data, measurements, or limitations in modelling. This review explores these and other potentially significant and specific marine geohazard uncertainties. More specifically, the research objective is to identify poorly constrained uncertain geohazard variables, along with the sources of their uncertainty.

Identifying poorly constrained uncertain variables, that is, those whose uncertainty is difficult to reduce due to current limitations or issues in gathering, processing, and verifying data, as well as in calibrating, validating, and testing models, might be useful for analysts who conduct applied geohazard assessments. Note that, in modern risk assessments, the analysis of uncertainties is critical for both determining risk significance and driving risk knowledge generation to, in turn, handle risk problems and issues (Aven 2019). In so far as highly uncertain variables of interest to marine geohazard assessments are identified, an analyst should focus attention and resources in order to thoroughly examine them, stimulate more intensive data gathering, research or knowledge production, and drive monitoring programmes coupled with mitigation measures as necessary. As such, the main output of this research is an input to conduct geohazard assessments. Along with this contribution to geohazard assessments, these poorly constrained uncertain variables are likely to represent scientific challenges; therefore, this work also strives to identify them. The development of new approaches and methods might be required to address the targeted uncertainties in both the geohazards and risk analysis fields.

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It is also worth addressing the proposed objective to provide input to specific analysis in the Arctic. Oil and gas exploration and development activities include those in the Arctic (Gulas et al. 2017), which are also exposed to geohazards. Furthermore, due to ocean warming, increased changes in the Arctic are conjectured, comprising significant alterations in sub-bottom fluid flow, erosion and depositional processes, and sea currents' regime, thus generating potentially new geohazard scenarios (Mienert et al. 2010). These alterations would need to be anticipated to responsibly promote activities in the Arctic environment. Therefore, based on the review, particular considerations are proposed, to analyse geohazards in this fragile environment.

As confirmed by our review, the proposed research objective is unique within the realm of marine geohazards. Previous publications have not addressed the proposed research objective. For instance, Ercilla et al. (2021) and Camargo et al. (2019) conducted reviews on marine geohazards, but the uncertainties involved were not analysed. Clare et al. (2017) focused only on uncertainties in geohazard variables whose quantities are highly difficult to reduce due to lack of field-scale validation. These authors limited their enquiries to landslides, flows, underground fluid and gas flows, and scour hazards; they did not explore in depth the sources of uncertainty. By describing international projects, Yonggang et al. (2016) reported research achievements on marine geohazard assessments. Chiocci, Cattaneo, and Urgeles (2011) emphasised seafloor mapping for regional geohazard assessments without an exhaustive consideration of uncertainty. Kvalstad, Nadim, and Arbitz (2001) dealt with deep-water geohazards, but their objective did not include a thorough discussion of the associated uncertainties.

The remainder of the paper is structured as follows. Specifics characterising and limiting the scope of the review are given in the next section. A third section reports on the uncertain variables identified, as well as discussing their sources. In a separate section, Arctic geohazards and their associated uncertain variables are described, coupled with some considerations for their assessment. A last section provides additional discussion and draws some conclusions from this study.

2. Review characteristics' overview and scope

The proposed review focuses on marine geohazards. The analysis started with a search for the word "geohazard(s)" within titles, keywords, and abstracts of published work in the Scopus bibliographic database. On 4th January 2021, this search produced 2773 publications within the period 1982–2021. After examining the abstracts of these publications, 769 publications were selected, since this new set reports on geohazards associated with the marine environment. Of this set, we had access to 545 documents, consisting of 265 journal papers, one book, 5 book chapters, 258 conference papers, 3 editorials and 13 review papers. Of these 545 publications, 360 were examined and, eventually, this latter set provided evidence in the form of 2060 excerpts as input to the review. The remaining publications did not provide useful excerpts regarding uncertainty considerations, which is the topic of the present article. As a result of the paper revision process after the peer review, 25 papers were included in the review, covering some publications produced in 2021 and 2022. Unlike other reviews based only on the analysis of abstracts, this review went further and analysed the body of the papers. This was achieved with the help of data mining tools provided by the software, Orange 3.27.1. Specifically, in the accessed documents' texts, excerpts of interest were captured by extracting the context of keywords associated with the word "uncertainty," which are automatically highlighted throughout the text by the software's filters. The associated keywords are, for example, the word "unknown" and derivations of it, such as "little known." A full list of these filtering keywords is reported in Appendix C. Contributions from specialised literature on geology, geomorphology, sedimentation, tectonics, geotechnics, and geohazards fields formed the set of publications examined. These characteristics reflect the scope and comprehensive nature of the review. This review did not track historic improvements in knowledge. Rather, we focused on the often poorly constrained uncertain variables, as seen by authors in the field of marine geohazards.

The following definitions and specifics determine the scope of the review.

Marine geohazards are defined here as geological materials, features, or processes on the seabed and below associated with risk to infrastructure or the environment (Hough et al. 2011). Submarine landslides, gas and fluid flows in the underground, scour events, and seabed gouging by ice are examples of marine geohazards. Figure 1 shows some more features. According to the definition above, tsunamis or tidal events or equivalent ocean features are not geohazards, but they could possibly be considered here as either potential triggers to or consequences of geohazards.

Uncertainty refers to incomplete information or knowledge about a hypothesis, quantity, or the occurrence of an event (Society for Risk Analysis 2018) and is different from randomness. This broad definition allows diverse types of uncertainty and related issues to be exhaustively analysed in the review.

As mentioned before, this review attempts to identify uncertain variables as seen by the authors in the literature selected, who are specialists, scientists, and geohazard professionals, henceforth termed "analysts."

Geohazard assessments involve the use of models. Unless otherwise stated, physical, numerical, and statistical models are referred to as "models" herein.

Due to ambiguities in the existing literature, we clarify what uncertainties are referring to, especially *what* is uncertain, and *how* uncertainty is measured. To this end and to structure the presentation of the results, we use a general framework for the definition and description of risk (Aven 2019). The framework is illustrated in Figure 2 and described in the following. Important to note is that the framework distinguishes between the concept of risk and the description of risk. Using this framework in a geohazard

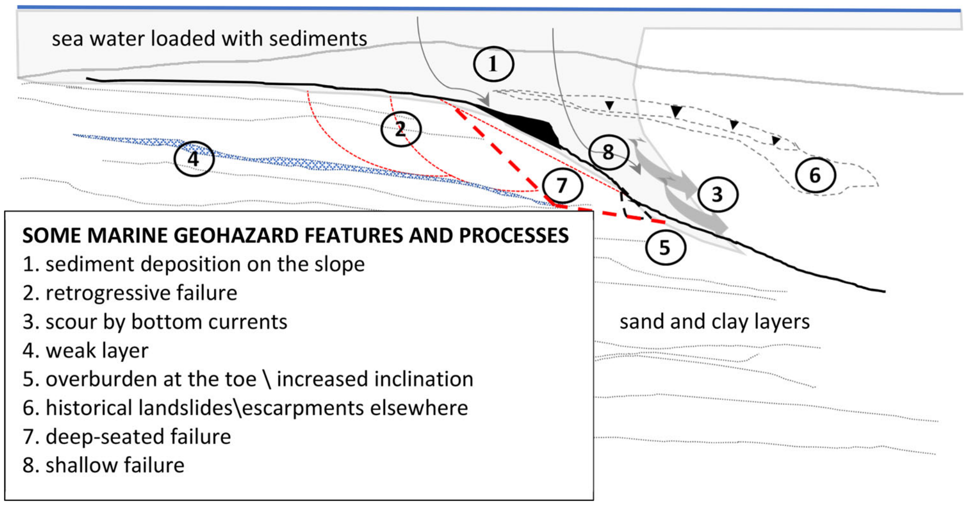

Figure 1. Some marine geohazard features and processes.

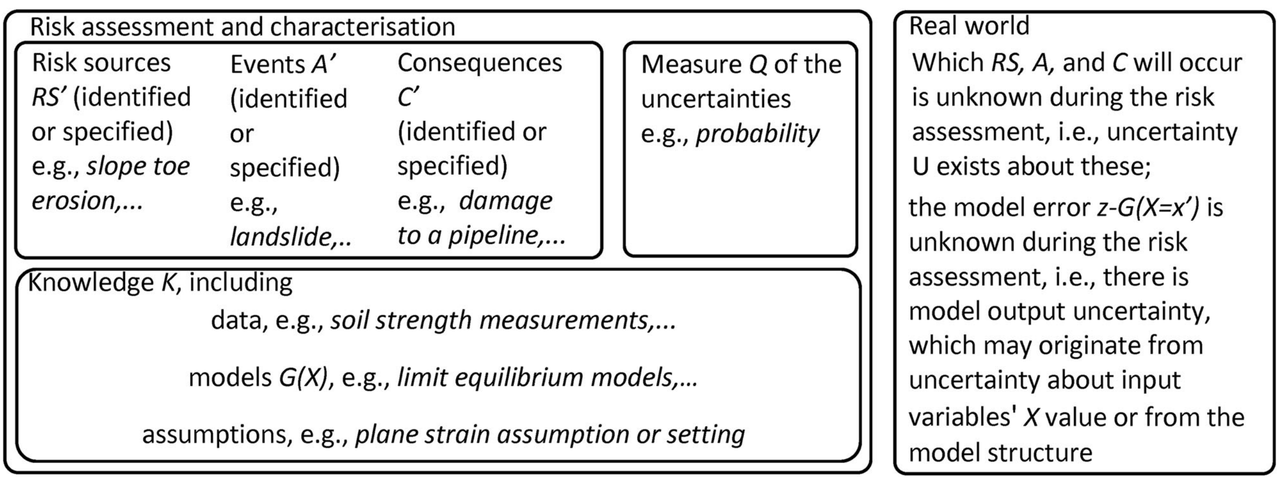

Figure 2. Customised framework to define and describe risk in geohazard assessments. Based on Aven (2019).

assessment context and starting with the latter, risk could be described by the following:

- the *specified* or *identified* set of risk sources, denoted *RS'*, influencing the occurrence of geohazard events. These include triggers and conditioning factors.
- the *specified* or *identified* geohazard events in the assessment, denoted *A'*, which could lead to some consequences.
- the *specified* or identified consequences, denoted, *C'*, which may result from the occurrence of some event in *A'*.

To illustrate this, consider the case of a vulnerable structure exposed to some materials and features, e.g., a suboptimal foundation (structure) on brittle soil. The risk source, a ground condition, namely the *brittle soil*, in combination with the condition of exposure of the foundation, will then lead directly to a geohazard *event* of deformation of the soil and consequently to the deformation of the foundation, the *consequence*.

Note that, sometimes, a specified geohazard event can be seen as a risk source to another geohazard. This is the case of the relationship between earthquakes and landslides. However, by breaking down that relationship, we see that earthquake events produce short-term inertia forces and post-earthquake pore pressure increase, together with fault displacements in upper strata. These are variables affecting the stability of slopes, potentially leading to landslide events. Likewise, note that geohazards, as defined earlier, include materials and features and are not only geohazard *events* as such. Particularly, these geohazard materials and features should be considered as sources of risk rather than as geohazard *events*.

Furthermore, let *RS*, *A*, and *C*, respectively, denote the sources, geohazard events, and consequences that occur during an activity. Before the activity in question is carried out, it is not known what *RS*, *A*, and *C* will be; there is uncertainty, *U*, about *RS*, *A*, and *C*. Writing risk = (*RS*, *A*, *C*, *U*), we have a conceptual definition of risk as the multi-dimensional combination of (future) risk sources, events, and consequences, and the associated uncertainties (which risk sources will materialise, which events will then occur, and what consequences these events will lead to). By distinguishing between the *specified* or *identified* risk sources, events, and consequences (*RS'*, *A'*, *C'*), and the risk sources, events and consequences that actually occur (*RS, A, C*), in a given risk assessment, it is possible that not all elements in *RS*, *A*, or *C* are contained in *RS'*, *A'*, or *C'*, respectively.

In the framework, *Q* denotes the measures used to characterise or represent uncertainty. The commonly used measure is probability. Furthermore, the background knowledge, *K*, includes data, models, and assumptions supporting the risk assessments. *K* can include models when these are justified. Models are simplified representations of the relationships between *variables* and are seen as tools to gain insights and support the assessments. The use of models often entails making assumptions, understood here as justified beliefs (Flage and Askeland 2020).

If a relevant *variable Z*, whose *value* or *quantity z* is realised in the future and is not known at the time of the assessment, a model *G(X)* can be used to predict the outcome of *Z*, denoted *z*. In the model, *X* is a set of *input variables*. When the input variables are set to specific values or quantities *x*', that is *X* = *x*', and fed into the model, the difference between the instantiated model value *z*' = *G*(*X* = *x*') and the actual value *z* constitutes the model error. As this model error is not known at the time of the prediction, this implies uncertainty, more specifically *model output uncertainty*. Figure 2 further illustrates this.

The strength of the knowledge, *K*, can be evaluated by judging, for instance, the reasonability of the assumptions made, the amount and relevancy of data or information, the degree of agreement among experts, the extent to which the phenomena involved are understood and accurate models exist, and the degree to which *K* has been examined in an assessment. Structured methods exist to conduct the assessment of *K* (see, e.g., Aven 2019).

In total, it is possible to fully define and describe geohazard risk as follows: risk = (*RS, A, C, U*), and risk description = (*RS', A', C', Q, K*).

To meet the paper's objective, there will be an emphasis on the uncertainty, *U*, associated with *RS*, *A*, and *C*, as well as on the sources of such uncertainty related to the *strength* (quality, goodness) of the knowledge, *K*, supporting the assessments. Uncertainty measures, *Q*, reported in the literature will also be analysed. Accordingly, the next section has been divided into subsections, addressing each of the components *RS*, *A*, *C*, *Q*, and *K*. Since the background knowledge, *K*, includes data, models, and assumptions supporting the risk assessments, respective subsections have been generated.

We specifically focus on uncertainty associated with *RS*, *A*, and *C* that is highly difficult to reduce due to current limitations or issues in gathering, processing, and verifying data, as well as in calibrating, validating, and testing models. For this research, the targeted uncertainty about *RS*, *A*, and *C* is also that which is driven by situations related to unrecoverable data, controversial or inconclusive evidence, underdeveloped models or lack of them, high disparity of models' outputs, or those models which imply the use of a large number of simplifying or untestable assumptions.

Issues generated by suboptimal use of geohazards assessment or modelling tools due to, for instance, deficiencies in the quality or lack of skills of the professionals involved, communication problems, or suboptimal resource allocation, and similar issues were not investigated.

3. Geohazard risk definition and description

To achieve the paper's objective, this section has been divided into subsections addressing each of the geohazard risk components *RS*, *A*, *C*, *Q*, and *K*. Note that further discussion of the sources of uncertainty about *RS*, *A*, and *C* is given in the subsections *Data*, *Models*, and *Assumptions* later in this paper in the subsection *Knowledge K*. We have included another subsection dealing with the specification of *RS'*, *A'*, and *C'*.

3.1. Geohazard events (A)

Clare et al. (2017) have identified groups of geohazards characterised by key variables which are analysed and discussed in the following. Specifically, landslides, flows, underground fluid and gas flows, scour, and earthquake hazards' associated uncertain variables are analysed. Other geohazards are elaborated in Appendix A.

3.1.1. Submarine landslides

Submarine landslides are sediment movements down a slope on the seabed. In geohazard assessments, probability of failure is a key metric describing this type of event. However, this probability is associated not only with the frequency of the events but also with their size and displacement. We gathered observations by authors in the selected literature regarding these and other relevant quantities identified by them, as follows. Kvalstad, Nadim, and Arbitz (2001) indicated that the potential retrogressive slide development upslope and laterally, as well as the evolution of slide masses into downslope mass wasting processes, typically flows, represent a challenge, requiring improved material models and mechanical analysis tools. Solheim et al. (2005) reported that, for Storegga Slide Complex, initial transition from static sediment to a highly dynamic flow needed further studies. Current models have difficulties explaining the large run-out displacement. Talling et al. (2014) pointed out that, due to the infrequent nature of submarine landslides and the possibility that sedimentary records do not register the events due to reworking, the estimation of landslide frequencies, based on these records, is limited. Clare et al. (2017) mentioned that many numerical based models lack field-scale calibration, and much uncertainty exists about quantities such as the initial soil volumes involved. The authors added that the recurrence time of these events may be far too long to be captured by monitoring techniques. Malgesini et al. (2018) stated that uncertainty remains over the evolution of the failed soil mass from slide initiation to complete run-out. Again, the latter authors suggested investigation of the interplay between fluid and solid mechanics of granular media and the evolution of stresses. For Juanes, Meng, and Primkulov (2020), there is a need for increased understanding of the frictional behaviour of granular material under fluid pressurisation and in the presence of multiphase fluids.

According to the above, soil and fluid mechanical properties' interaction, pore fluid flow, and stresses' evolution are large uncertain input variables affecting the estimation of the frequency, extent, and displacement of landslides. Alongside the scientific challenges mentioned by these authors, an analysis of these uncertainties in a geohazard assessment would require special attention. Even though probabilistic assessments using simulations can potentially constrain uncertainty in these variables, as discussed later, a geohazard analyst would further need to evaluate the amount and relevancy of data or the degree to which the phenomenon is understood and whether accurate models exist to properly inform risk assessments.

3.1.2. Flows and turbidity currents

Unlike a landslide, a debris flow is a downslope flow of sediment which deforms as it moves. The lower part of the flow is often a viscous fluid. The upper part remains in a semi-solid phase and travels on top of the viscous bottom layer. The entire flow may be non-homogeneous. It may contain clasts, varying greatly in size and shape. Conversely, a turbidity current is considered a flow of sediment-laden water, driven by the weight of the sediment, which in turn is kept in suspension by turbulence (Bonnell and Mullee 2000). According to the following, key variables characterising these events are probability of occurrence, run-out distance, height, velocity, and volume. The literature examined provided reservations in their estimation. Bonnell and Mullee (2000) reported that the common place feature of long run-out distances of turbidity flows is associated with high pore-water pressures. The authors embraced the suggestion that more detailed studies are required for excess pore water pressure and shear stresses at the upper and lower boundaries of dense flows. These authors also mentioned that calculation of the velocity of debris flows had a considerable band of uncertainty which depends on shear strength properties and concentration of sediment. Some topics are recommended to be further studied, such as the behaviour of mudflows after transition to turbulent flow, improved estimation of recurrence intervals, and the use of two-dimensional models to characterise flow across its predominant direction. Kvalstad, Nadim, and Arbitz (2001) maintained that flow modelling needs to be coupled with strain softening and remoulding, to entirely cover the process of exceedance of shear strength towards the development of residual strength leading to total remoulding. A similar proposition is given by Elverhøi et al. (2002). These authors further noticed that the classical visco-plastic modelling approaches fall short of fully simulating the long run-out distances for subaqueous debris flows. Bruschi et al. (2006) added that experimental data or field evidence which account for large velocities in turbidity currents are scarce. Next, these authors commented that, for given plastic flow characteristics, trajectory, run-out distance, flow width, velocity, thickness in flows, and flow-structures' interaction are affected by significant uncertainty. According to Boylan et al. (2009), no method has been established to assess the fluid-like properties that a particular intact material will develop, after transitioning from the intact to slurry state during run-out. In a geohazard interpretation, Johnson et al. (2011) reported that there is considerable uncertainty in estimates of the return period based on sediment records, due to the difficulty in distinguishing ancient from modern slope movements caused by very low sedimentation rates. More challenges are seen by Randolph and Gourvenec (2011). For instance, models must capture the range of behaviour from a solid material, capable of resisting shear stresses without significant deformation, to a fluid-like solid-water mixture, prone to large deformations. These authors also argued that the main difficulty in applying any model to the analysis of submarine flows is identifying the appropriate input variables to describe the viscous or fluid-flow behaviour. An additional complication is the fact that characteristics of soils, such as sensitivity and strain rate dependency, should be accounted for when modelling debris flow. Randolph and Gourvenec (2011) also manifested that direct measurement of the velocity of debris flow or turbidity currents and other flow characteristics is not practical; hence, it is common to conduct back analyses of observed flows run-outs to calibrate models. However, turbidity current activity cannot be hindcast in the same way as debris flows, since turbidity current deposits are generally not available to calibrate a model. For Malgesini et al. (2018), significant uncertainty remains in model calibration against full-scale natural flows, because of scarce or non-existent direct monitoring. Along with this, although mudflow velocity appears to be the most important and influential variable for estimating loads to seafloor structures, unfortunately, it is currently the most uncertain. Hodgson et al. (2019) proposed that an improved understanding of the interactions between flow evolution, seabed topography, and the entrainment and abrasion of megaclasts will help to refine estimates of run-out distances. Subaqueous debris flows may partially evolve into turbidity currents, which may under certain conditions ignite and attain high velocity and long run-out, although, according to Vanneste et al. (2019), little work has been done on the rate of this transition.

Clearly, large uncertainties concerning flows and turbidity current hazard events are associated with variables to describe the viscous or fluid flow behaviour, pore pressure, concentration of sediment, as well as those related to the interaction with seafloor and water. These influence the estimation of relevant output variables such as the occurrence of break-up (detachment), which might provide information on its occurrence, velocity, height, extent, and interaction with seafloor structures. We conclude that the evaluation of these uncertainties and the corresponding examination of the supporting knowledge, *K*, ought to be part of an assessment dealing with flows and turbidity currents. We also notice that the most frequent source of these uncertainties is the insufficiency of models, whose pedigree should be established in any assessment, irrespective of whether or not the models can be validated.

3.1.3. Scour and sediments' mobility

The removal of sediment, namely scour, from around a structure in the sea and the associated phenomenon of sediments' mobility are other geohazards to be considered. A relevant variable in a geohazard assessment regarding these events is their potential extension; however, the authors discussed others, along with their uncertainty issues. For instance, Bransby et al. (2010) and Bruschi et al. (2014) stated that considerable uncertainty exists on the mechanics of migration of sediments and depth such as sand waves. Clare et al. (2017) pointed out that the threshold condition for mobility or scour, rate of bedform migration, form and location of scour initiation, rate and extent of scour inception and evolution as the quantities for which uncertainty is large. Han, Chen, and Sun (2019) have mentioned that, due to the complexity of fluid flow, it is rather challenging to theoretically develop precise physical scouring models. Further, few investigations have been conducted to understand and estimate scouring in unsteady currents for offshore areas. Next, complications exist, such as inaccuracy and difficult measurement of testing or field data. All these issues have hampered the understanding and estimation of maximum scour depths. Lin and Wu (2019) mentioned that no generally accepted practical approach exists for determining pile vertical or lateral capacity under local scour conditions, due to uncertainty in characterising the sizes and shapes of scour holes at piles or pile groups and the failure to consider scour-induced changes in soil stress history. In line with the above, of relevance for a geohazard assessment, we suggest location of scour or sediment mobility initiation and the extent of their evolution as the variables whose uncertainty ought to be inspected. The associated models should also be scrutinised for weak predictions, in order to assess risk.

3.1.4. Gas and fluid flows

Water, dissolved salt, gas, and mud flows occurring below and from the seabed surface are considered here as gas and fluid flow hazards. Clare et al. (2017) suggested that location, extension, migration pathways, temporal and spatial variation are key variables characterising this type of flows. However, the literature detailed other variables and inputs, along with the issues driving uncertainty. In a study of potential effects of salt movement on the seafloor geometry, Jeanjean, Hill, and Thomson (2003) reported difficulty in both assessing salt flow velocity and estimating the time of salt flow occurring. Based on geomorphology in conjunction with finite element analysis, the estimates were possible, but they are subject to non-negligible uncertainty. In the case of methane-driven oceanic eruptions, to calculate the maximum exit velocity, Zhang (2003) stressed that a realistic model would require the consideration of shallow water entrainment and disequilibrium between the gas phase and water. Power, Galavazi, and Wood (2005) noted the often-poor resolution in the capturing of gas and fluid flow geohazard features in the upper few hundred metres below the seabed, thus raising doubts over the mapping of these. As to the occurrence of free gas in association with gas hydrate, McConnell, Zhang, and Boswell (2012) argued that determination of the presence and extent of free gas remains difficult. Gas hydrate can easily mask the occurrence of subjacent gas when standard seismic amplitude analyses techniques are used; therefore, new tools are needed. Further, these authors added that shallow water flows are complex to predict and avoid. Andrew Buckley and Cottee (2017) illustrated in a case study that using seismic data alone may support radically different interpretations of ground features, overlooking significant amounts of shallow gas existence. However, these authors have seen that measurement of pore pressures is a common element of geotechnical surveys (e.g., cone penetration test), and hence this variable uncertainty can be more easily constrained. Meanwhile, Loktev, Tokarev, and Chuvilin (2017) have mentioned that low concentrations of shallow gas can completely spoil seismic profiling data because this medium is poorly penetrable by seismic signals. Serié et al. (2017) have shown specific discrepancies and difficulty in mapping the fluid flow regime and the associated plumbing system in the deep-water Kwanza Basin, offshore Angola. The discrepancies are due to lack of calibration against seabed geochemistry. Deeper borehole data, higher resolution of seismic volumes, and electromagnetic data would be required to constrain uncertainty about the plumbing system and any non-aqueous fluid accumulations. Despite the availability of three-dimensional seismic reflection data for a north-western Greenland exploration, Cox et al. (2020) reported the intensive use of human interpretation to distinguish fluid-related geohazard features (e.g., trapped and free gas, gas hydrates, uncompacted sand packages bearing water, fluid flow pipes, gas streaking), recognising that this evaluation was subjective. Li et al. (2021a) considered distinguishing hydrate-bearing sand from water-bearing sediments to be challenging, since water-bearing sediments have the potential to produce the same seismic amplitudes with the presence of natural gas hydrates. According to the above, the variables associated with location, extension, and migration pathways or temporal and spatial variation convey considerable uncertainty under current limitations in practice and science. Some linked uncertain input variables to be considered are the interaction between water and gas phases, alongside pore pressure. In geohazard assessments, this uncertainty should be thoroughly examined, in terms of the data relevancy and the degree of agreement among experts interpreting data, to provide an exhaustive description of the associated risk.

3.1.5. Earthquakes

An earthquake is the shaking of the surface of the earth, resulting from a sudden release of energy in the earth's lithosphere by its rupture or deformation, that creates seismic waves. The magnitude and frequency are considered key variables describing these motions (Fenton et al. 2002). However, Gilbert and Puskar (2005) mentioned that the analysis of this hazard also includes the computation of uncertainties in the earthquake source and, in so doing, the use of alternative seismic models is required because of the usual diversity of sources. These authors also suggested that uncertainty in predicting ground motion at a site for rare seismic events is substantial. Dash et al. (2007) reported difficulty in associating recorded motions with sources (fault or deformation zones) due to unsurmountable interpretation limitations in high-resolution seismic data mapping these sources. Morgan and Baise (2011) considered that the analysis should account for earthquake duration by, e.g., Arias intensity and Newmark displacements, which determine whether slope material will fail catastrophically. For Rodríguez-Ochoa et al. (2015), relevant variables are the peak ground acceleration and the recurrence period. This would allow a connection between earthquake intensity and earthquake recurrence period. Further, these authors note that the static undrained strain rate, and cyclic degradation of shear strength are also important highly uncertain inputs because their reliable measurement entails complications. In conclusion, regardless of the considerable advancements in earthquake analysis, authors in the field referred to the magnitude, frequency, intensity, and duration as variables whose estimation is constrained by current limitations. Uncertainty in these variables is driven by earthquake sources' characteristics (e.g., geometry, focal mechanisms, distribution of rupture magnitudes, and their probability of occurrence for each source), and the static undrained strain rate, and cyclic degradation of shear strength of soils subject to motion. In geohazard assessments involving earthquakes, an analyst should evaluate uncertainty by making a judgment on the existence, reliability, and sufficiency of the input data, e.g., motion records. Next, attention should be paid when it comes to analysing rare events – as strong motions would be. The analyst should verify how the use of certain extreme probability models is justified in situations when data are scarce, taking into account the fact that the future events will not necessarily be reflected by these (Aven, 2019).

3.2. Risk sources (RS)

Risk sources such as rapid deposition of materials on a slope, scour, increased sea water temperature, and iceberg collision influence the occurrence of geohazard events such as, e.g., submarine landslides or flows. These sources can be classified as either trigger factors or conditioning factors. One or more factors alone or in combination have the potential to give rise to a specific geohazard event. In the following two subsections, we discuss key uncertain variables linked to trigger factors and conditioning factors, respectively.

3.2.1. Trigger factors

A considerable number of sources addressed the problem of identifying landslide trigger factors. The following potential trigger factors were summarised by Kvalstad, Nadim, and Arbitz (2001). In the list below, additional specific publication references are attached to some of the triggers considered. Some of them provided controversial evidence, indicating that the conjectured factor is possibly not a trigger for landslides.

a. Rapid deposition leading to excess pore pressure conditions, underconsolidation and increased shear stress level on a slope (Elverhøi et al. 2002; Long et al. 2005). However, based on site specific evidence, Mather, Hartley and Griffiths (2014) reported that the increase in local sedimentation rate is an insignificant factor.
b. Toe erosion or top deposition, giving higher slope inclination and increased gravity forces and shear stress along potential failure surfaces.
c. Melting of gas hydrate, caused by temperature increase or pressure reduction, leading to increased pore pressure and reduced soil strength (Mienert et al. 2005; Nixon and Grozic 2007; Long et al. 2005; Talling et al. 2014; Collett et al. 2015; Handwerger, Rempel, and Skarbek 2017; Zhang et al. 2021).
d. Active fluid or gas flow and expulsion (Best et al. 2004; Collett et al. 2015).
e. Mud volcano eruptions and diapirism, giving rise to mass wasting and soil displacements Zhang et al. (2021).
f. Earthquake activity (Fenton et al. 2002; Rodríguez-Ochoa et al. 2015), causing short-term inertia forces and post-earthquake pore pressure increase and fault displacements in upper strata. Note, however, that Harrison et al. (2018) have reported that, following a seismic event, excess pore-water pressures in some materials can take months or years to dissipate, whereas other types of soils under cyclic loading take a considerable time for excess pore-water pressures to sufficiently develop to trigger a landslide. Therefore, it is difficult to reliably attribute a specific landslide to any given earthquake activity.
g. Sensitive (contractive) and collapsible soils may lead to retrogressive sliding and increased areal extent of failure zones.
h. Sea-level lowering during glacial periods, leading to lower pressure, free gas expansion and gas hydrate melting. Controversial evidence gathered by Urlaub, Talling, and Masson (2013) has shown no strong global correlation of landslide frequency with sea-level changes. Case-based evidence supporting the latter is provided by Allin et al. (2018).
i. Increased sea water temperature at seabed level caused by changes in current regime, leading to temperature increase in the soil mass and melting of hydrates. However, Clare, Talling, and Hunt (2015) have provided evidence showing that periods of future global ocean warming may not necessarily result in more frequent landslide and/or turbidity current activity at non-glacially influenced margins.

While many potential landslide triggers are known, authors in the literature often failed to confidently identify a specific trigger factor (e.g., Nadim, Krunic, and Philippe 2003; Solheim et al. 2005; Hunt et al. 2013; Urlaub, Talling, and Masson 2013; Talling et al. 2014; Wei et al. 2014; Rodríguez-Ochoa et al. 2015; Clare et al. 2016; Pope, Talling, and Carter 2017; Allin et al. 2018; Harrison et al. 2018; Casalbore et al. 2020). Note that the problem is not only restricted to triggering factors associated with landslides. Clare, Talling, and Hunt (2015) and Hodge et al. (2015) have encountered similar situations when analysing turbidity currents and seismic sources, respectively. A particular case is the rupture behaviour of a mapped fault system which obliges the analysis of several disparate hypotheses about the seismic sources: hypotheses which might not encompass all the potential behaviour of the system (Hodge et al. 2015). In some cases, when triggers cannot be specified, such a situation is caused by the impossibility of developing accurate ground models, due to issues revealed later in this paper in the subsection, *Data*. Under these circumstances, the problem of failing to identify the correct trigger factor constitutes a significant uncertainty, which ought to be addressed in an assessment. Gilbert, Habibi, and Nadim (2016) and Nadim, Krunic, and Philippe (2003) have addressed the problem, in a limited fashion, in a Bayesian probabilistic framework. Nonetheless, improved versions of causality analysis (e.g., Beven 2012; Cox 2013; Baldi and Shahbaba 2020; Hund and Schroeder 2020; Ruiz-Tagle, Lopez Droguett, and Groth 2021), in conjunction with elements of Bjerga, Aven, and Flage's (2018) approach to model uncertainty, can be evaluated to optimise the existing methods. For instance, in research parallel to that reported here, we have gathered evidence on the role of some aspects of causal analysis in helping the early identification of marine geohazard events through the investigation of the associated trigger factors. In general, an analyst should be concerned about this potential situation and stimulate improved gathering of data (as in Kopp et al. 2021) and further assessments. Further, the intensive use of probabilistic assessments, using simulations considering several triggers, could be considered; however, this might represent a significant challenge, even for science, in terms of computation methods and coupled modelling capabilities.

Literature refers to a diversity of trigger events. Niedoroda et al. (2003), Boylan et al. (2009), and Zhu and Randolph (2010) have shown that mass wasting processes, such as landslides, debris flows, and turbidity currents, could occur in sequence. There could also be cases in which geohazards can be triggered by a range of processes other than geohazards; for example, turbidity currents were found to be caused by storm waves and hyperpycnal river flood discharge. Alternative mechanisms are known to generate turbidity currents, namely, earthquake shaking, storm surges, sediment loading, submarine groundwater discharge, volcanic explosions, and bolide impacts (Clare, Talling, and Hunt 2015; Ikehara et al. 2021). It has been also proposed that, as river flow expands at the coast, rapid sediment deposition can create unstable slopes prone to failure, resulting in turbidity currents (Clare et al. 2016). Sultan et al. (2020) have also shown that transient groundwater flow through a coastal confined aquifer has an impact on nearshore submarine slope instability. The literature studied revealed many other potential interactions. Table 1 depicts some conjectured and hypothesised interactions, further showing the extraordinary interplay behaviour of marine geohazard features and processes. In any geohazard assessment, these hypotheses require further research and testing, which is not straightforward. The difficulty lies in that these relationships are conditional, as they depend on the local spatial and temporal variation associated with the geohazards involved (Read 2018). Conventional statistical testing tools are almost impracticable, due to the ability of ground investigations to only provide limited information, as further discussed later in this paper in the subsection, *Data*. This entails poorly constrained uncertainty about hypothesised relationships. Alternatively, this uncertainty might possibly be assessed by an analyst, in terms of reasonability of the hypothesis, data availability and reliability, agreement among experts, or their support by accurate models (Aven, 2019).

3.2.2. Conditioning factors

Site and timing conditioning factors give rise to specific hazard events (Clare et al. 2016). Failure to identify these conditions is one of the sources of uncertainty which impedes geohazard events' identification. We define conditioning factors as factors that will contribute to producing geohazard events if, and only if, some triggers materialise. Accordingly, even though some conditioning factors are verified or considered likely to be present in the future, without any trigger factor coming into being, these alone will not give rise to a geohazard event. In geohazard assessments, conditioning factors are typically ground conditions (see Table 1). In the following, we further discuss some of the conditioning factors shown in Table 1.

The geohazard feature of gas hydrates has drawn significant attention in the literature analysed, and this is reflected in Table 1; thus, consideration should be given to this conditioning factor and associated variables, in this review. Gas hydrates consist of ice-like crystalline solids of water molecules encaging gas molecules (Mienert et al. 2005). The majority of naturally occurring hydrate is composed of methane (Camps et al. 2008). Gas hydrates are found within marine sediments where temperatures are low enough for permafrost. The lower limit for the occurrence of hydrates is about 2000 m below the sediment surface, depending on the local geothermal gradient (Glasby 2003). Gas hydrate stability is a function of water depth, bottom water temperature, pressure and thermal gradients in sediments, pore water salinity, gas availability and composition (Milkov and Sassen 2000). Further, key variables such as pore size, fluid saturations, sediment mineralogy and cementation will affect hydrate morphology, distribution, behaviour during dissociation, and potential recovery from porous media (Long et al. 2005; Mienert et al. 2005). A frequent issue raised is that gas hydrate-bearing soils are highly unidentifiable by conventional geophysical tests such as seismic reflection

Table 1. Some conjectured and hypothesised interactions among geohazard features and processes according to the literature reviewed.

Trigger event	Conditioning factor	Geohazard event	Mentioned by
Long-term creep deformation		Localised rupture or soil failure	Silva et al. (1999)
Salt package migration	Hydrate-bearing sediment	Gas hydrate instability	Milkov and Sassen (2000)
Gas chimneys		Geopressure excess	Aminzadeh et al. (2002)
Earthquake followed by liquefaction	Underconsolidated soils with high content of fines	Debris-mud flow	Elverhøi et al. (2002)
Fluid flow through pockmarks	Pockmarks, craters on muddy seabed	Slope failure, seabed instability and earthquakes	Hovland, Gardner, and Judd (2002)
Gas hydrate dissociation	Faults, hydrate-bearing sediment	Landslide	Gettrust, Grossweiler, and Wood (2003)
Sudden release of a large amount of oversaturated methane pore water during, for instance, a large landslide or earthquake	Hydrate-bearing sediment	A methane-driven ocean eruption	Glasby (2003), Zhang (2003)
Gas bubbles formed by gas hydrate melting	Hydrate-bearing sediment	Clay structures fracture	Mienert et al. (2010), Yang and Kvalstad (2010)
Actively deforming ground structures	Subduction margins	Slope failures	Yamada, Yamashita, and Yamamoto (2010)
Gas release suddenly unloading sediments	Gas-bearing sediment	Slope instability	Berndt et al. (2012a)
Cyclic loading by waves	Sandy soils with little fines content	Liquefaction	Bruschi et al. (2014)
Dissociation generating freshwater	Hydrate-bearing sediment	Leaching of marine clays, leading to quick clay behaviour	Talling et al. (2014)
Melting of permafrost as a result of methane hydrate dissociation	Hydrate-bearing sediment	Gas and sediment expulsions	Collett et al. (2015)
Salt movement encouraged water to flow into the soil due to an osmotic effect	Salt diapirs	Soil softening and collapse compromised wellbore stability	Hill et al. (2015)
Release of gas	Hydrate-bearing sediment	Submarine mud volcanoes	Bhaumik et al. (2013), Zhang and Wright (2017)
Gas hydrate dissociation	Hydrate-bearing sediment	Shallow water flow	Zhang et al. (2018a), Zhang et al. (2018b)
Salt migration through frozen horizons	Interaction of frozen hydrate saturated sediments with salt solutions	Decomposition of intra-permafrost gas hydrates and permafrost thawing	Chuvilin et al. (2019)
Fractures caused by earthquake		Gas emission	Tsang-Hin-Sun et al. (2019)
Deeper fluid pressures	Deep-seated faults extending close to the seabed, potentially connecting deeper-fluid pressurised sediments to the shallow stratigraphy	Overpressure in shallow structures	Chiocci and Ridente (2011), Cox et al. (2020)
Slide or erosive event		Other slide or erosive event	Yamada, Yamashita, and Yamamoto (2010), Chiocci and Casalbore (2017), Sammartini et al. (2021)

(Digby 2012; McConnell, Zhang, and Boswell 2012; Best et al. 2013; Wegner and Campbell 2014; Li et al. 2021a). Next, laboratory testing is complicated, due to the large instability of the samples extracted. During sampling, little variations of in-situ pressures and temperature conditions imply sample deterioration, leading to unrepresentative tests results (Long et al. 2005; Mienert et al. 2005; Power, Galavazi, and Wood 2005; Hester and Brewer 2009; Schultheiss, Aumann, and Humphrey 2010), and synthesis of hydrate-bearing cores in the laboratory or in situ testing are used instead (Ghiassian and Grozic 2013; Lee et al. 2013; Collett et al. 2015; Smith, Priest, and Hayley 2018; Taleb, Garziglia, and Sultan 2018). Foremost, gas hydrate accumulations' stability is compromised by little variations in temperature, induced by, for instance, other gas hydrate seeps (Glasby 2003) or human activities (Kvalstad, Nadim, and Arbitz 2001). To exacerbate the situation, thermodynamic stability models are not well developed for methane hydrate-bearing sediment systems (Collett et al. 2015); it is also unclear whether or not existing models can accurately predict the long-term geomechanical response of hydrate-bearing soil (Miyazaki, Tenma, and Yamaguchi, 2017). From all the above, the literature here mentions substantial uncertainty regarding the gas hydrate location and its temporal and spatial variation quantities, along with its stability. In a geohazard analysis, such uncertainty could be assessed by judging the accuracy of existing models or the lack of them, this being the main uncertainty issue when it comes to analysing risks associated with gas hydrates.

Some geohazard analyses require the stability of gas hydrate or pore pressure models, which in turn are based on models representing the spatial features and structures in the seabed and below. These features and structures have in some cases been formed by historic and cumulative erosional and depositional processes, including compaction. Compaction in nature is dependent on initial porosity, composition, and effective stress. Compaction is a process which also depends on time, temperature, and solid volume loss. According to the literature, this process is hard to model, and enormous uncertainty in its estimation can significantly affect the assessments of, for instance, pore pressures or the calculation of sediment layer thickness. Therefore, the degree of compaction as such is considered a great unknown variable (Giles, Indrelid, and James 1998). Due to the potential inaccuracy of existing models or the lack of them, a geohazard analyst should flag for attention this major uncertainty and assess the models' pedigree, to advance more informed risk assessments.

3.3. Consequences (C)

The literature available in the set analysed is particularly focused on the effects of geohazards on the infrastructure built on the seabed, such as wells, platforms, manifolds, and pipelines. Emphasis is put on the impacts on drilling infrastructure such as blow outs, loss of the adjacent soil to wells, settlements, uncontrolled water and gas flows, water and gas leakage from the well-bore casing and damage to the well-bore casing, loss of wells, and loss of platform foundations (e.g., Glasby 2003; McConnell, Zhang, and Boswell 2012; Hill et al. 2015). Rupture, excessive deformation and differential settlement, scouring, development of unsupported spans, removal of backfill of pipelines, plus burial, collapse or large displacements of installations are the effects considered (Kvalstad 2007; Devine and Haneberg 2016). Most of the effects are analysed by models dealing with the interactions between geohazards and the infrastructure. As to these interactions, several sources report modelling problems. Table 2 summarises some of the issues found. Note, however, that traditional models are being optimised into three-dimensional coupled models, using, for instance, Eulerian-Lagrangian and non-linear finite elements techniques, in conjunction with new constitutive soil models, to more accurately capture the interactions and address some of the issues (e.g., Pike, Kenny, and Hawlader 2014; Paulin and Caines 2016; Pike and Kenny 2016; White et al. 2016). From Table 2, identified typical uncertain variables linked to geohazard consequences are associated with deformation of the coupled materials (soil, ice, water, infrastructure) and loads and stresses. In their estimation, the input variables, such as the transition of mechanical properties between soils and fluids and the resistance properties of the soils as such, propagate significant uncertainty. Based on this, care should be taken by analysts to check for data availability and reliability, agreement of specialists, assumptions' reasonability, irrespective of whether or not probabilistic assessments coupled to simulations can be conducted, in an attempt to limit uncertainty.

3.4. Uncertainty measures (Q)

Frequently, in the literature analysed, uncertainty is understood as lack of information or knowledge, but the term is also used interchangeably to mean randomness. Sometimes, uncertainty is measured using probabilities. When uncertainty is measured using probabilities, frequentist probabilities are often used. In relation to this, Haneberg (2015) mentioned that, in the field of geohazards, probabilities can originate from informed expert judgement, by counting the number of events in the geological record in an area and over a particular epoch, on the basis of the frequency of trigger events, or even by simulations in a probabilistic analysis. In practice, combinations of these methods are used, e.g., probabilities may be modified, using expert judgement, to take into account recent or future changes in site-specific conditions and triggering factors. In this respect, we should note that frequentist probabilities are of limited use because these assume that variables vary in large populations of identical settings, a condition which can hardly be justified for few variables, due to both the often one-off nature of many geohazards features and the impossibility of repeated verification or validation of data by, e.g., field failure tests. Considering the usual constraints in data and the limitation in modelling, as well as the nature of geohazard events, alternatively, a more meaningful and practical approach can be used to measure uncertainty, namely, the use of

Table 2. Issues related to the interactions between geohazards and infrastructure.

Type of infrastructure	Issue	Mentioned by
All types	Choosing geotechnical materials' characteristic values for the analysis	Lacasse and Nadim (2011), Randolph and Gourvenec (2011), Lacasse et al. (2019)
	Deformations around piles, penetrometers, anchors and pipelines, during run-out of submarine slides, required new numerical modelling techniques considering large deformation coupled to suitable soil models that account for the changing strength, including the effects of remoulding and reconsolidation	White, Boylan, and Levy (2013)
Anchors	Lack of agreement among specialists to model anchoring for offshore structures	Eltaher, Rajapaksa, and Chang (2003), Evans, Usher and Moore (2007)
Piles	The frequent use of potentially unsuitable models for the analysis of piles	Eltaher, Rajapaksa, and Chang (2003)
	Ultimate axial capacity estimated by various experts ranged over more than a factor of two	Gilbert and Puskar (2005)
	Suboptimal empirical design methods for laterally loaded piles in offshore sloping seabed, leading to over-conservatism	Jang (2015)
Pipelines	Rate of shear on which drag forces depend as an overlooked factor for debris flow impact on pipelines' foundation	Zakeri (2008)
	Determining sand-wave depth to ensure that pipelines are installed beneath the active migrating sedimentary bedform	Bransby et al. (2010)
	Analysing pipeline condition following flow events	Kumar, McShane, and McDonald (2010)
	Unrealistic assumptions such as considering lateral soil resistance to be uniformly distributed in pipeline design	Yuan et al. (2012)
	Disparate results in analysing drag forces on submarines pipelines due to diversity of models	Yuan et al. (2012)
	Traditional foundation design does not account for significant torsional moment induced by the connection of a number of pipes	Bruschi et al. (2014)
	Simple structural beam-spring models which are not sufficient to account for the highly complex three-dimensional soil/structure interaction effects, load-transfer effects, and failure mechanisms to analyse pipeline integrity	Pike, Kenny, and Hawlader (2014)
	Models for strudel scour, upheaval buckling, friction between inner and outer pipes of a pipe-in-pipe system within the bundle, improved pipe-soil interaction for the bundle had not been developed to reduce conservatism	Georghiou et al. (2015)
	Selecting the appropriate ice keel attack angle which should be used in the analysis of pipelines	Kenny et al. (2007), Pike and Kenny (2016)
	Lack of continuity between the geotechnical variables that characterise the intact seabed and the material models and variables that are used in a simulation of the slide run-out and the slide-pipeline loading when analysing landslide-debris flow problems	Boylan et al. (2009), Zhu and Randolph (2010), White et al. (2016)
	Over-simplistic uncoupled analyses made when using the Mohr-Coulomb material and Winkler model for seismic fault line displacement and ice gouging analysis, leading to overconservative design of pipelines	Odina and Tan (2009), Pike and Kenny (2016)
	Determining the design directions of strike by flows on pipelines and the potential of lift, partial burial, and impact loading	Bonnell and Mullee (2000), Bruschi et al. (2006), Malgesini et al. (2018)
	Deformation overestimation in ice–seabed interaction processes in decoupled approaches	Odina and Tan (2009), Azimi and Shiri (2021)

knowledge-based (also referred to as judgemental or subjective) probabilities (Aven 2019). A knowledge-based probability is understood as an expression of the degree of belief in the occurrence of, for instance, *RS*, *A*, or *C*, by a person assigning the probability, conditional on the available knowledge *K*. Since *K* includes data, the probability of *RS*, *A*, or *C* is conditional on the available input data used by the analyst at the time of the assessment (Flage, Aven, and Berner 2018). The probability of *RS*, *A*, or *C* is also conditional on the models chosen by the analyst for the prediction of *RS*, *A*, or *C*, as well as conditional on the associated modelling assumptions made by that analyst. Here, we note that *K* also consists of observations, justifications, rationales, and claims or arguments, and these aspects are to be considered. In total, to describe uncertainty about *RS*, *A*, or *C*, probabilities are assigned, based on *K*, and then these are linked to an overall judgement of the strength of the corresponding knowledge, *K*. Structured methods exist to assign probabilities and conduct the assessment of *K* (see e.g., Aven 2019). Since models form the available background knowledge *K*, we also draw attention to the fact that simulations by models in conventional probabilistic analysis can also inform these knowledge-based probability assignments.

Regarding the updating or revision of probabilities measuring uncertainty in variables in an assessment, we note that few sources show how such updating can be achieved as new information becomes available. Updating or revising probabilities is important for improving predictions, for the early identification of events, and for informing decision-making reliably and timely. It is particularly essential when the new evidence is controversial in comparison with the existing information (Sättele, Bründl, and Straub 2015). Existing approaches to updating annual probabilities of geohazard events are limited (e.g., Nadim, Kvalstad, and Guttormsen 2005; Gilbert, Habibi, and Nadim 2016): the use of the Bayesian framework in conjunction with the observational method, an exhaustive monitoring approach to inform design (Lacasse et al. 2019), and the Bayesian updating of mechanical variables for slope stability analysis (e.g., Das, Varela, and Medina-Cetina 2019) and for determining the value of information provided by new soil borings (e.g., Gilbert and Puskar 2005).

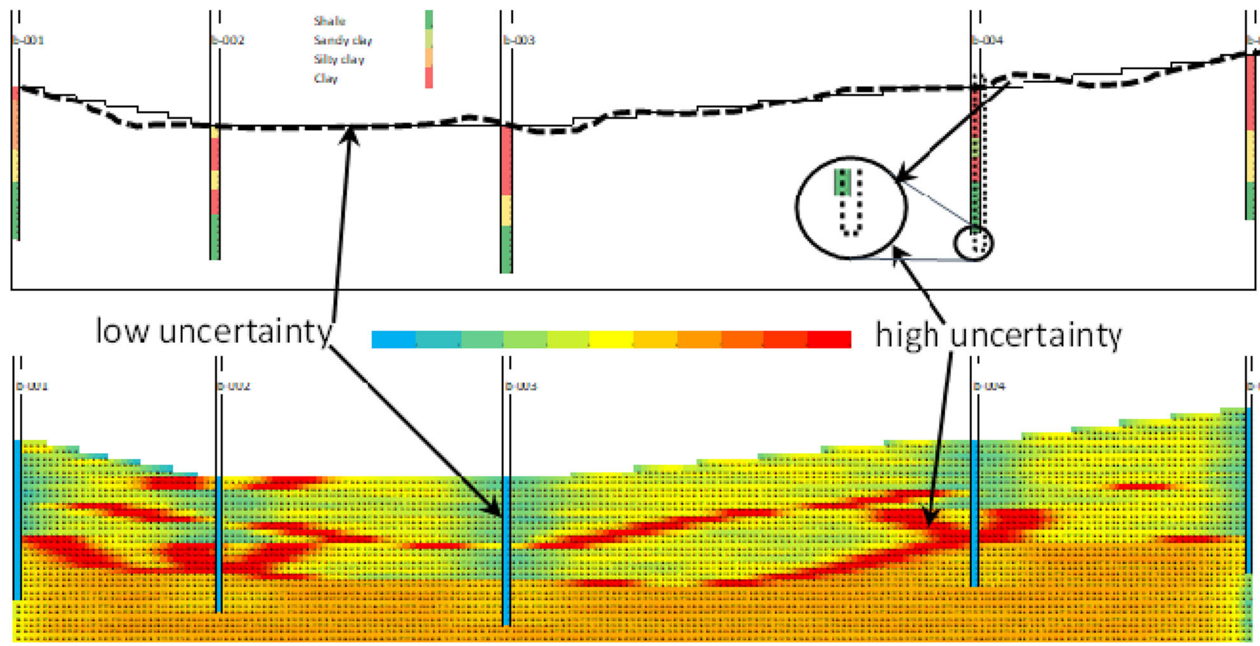

Figure 3. Inaccuracies and errors in bathymetric data, generating uncertainty about the structure of the ground.

3.5. Knowledge supporting the assessments (K)

3.5.1. Data

The variation over space and time of features, processes, and soil properties on and below the seabed is a well-known issue, addressed by a number of publications in the set analysed, e.g., Kvalstad, Nadim, and Arbitz (2001). However, reference is also made to the fact that geohazard ground investigations can only provide very limited data (Kvalstad 2007; Gilbert, Lacasse, and Nadim 2014; Talling et al. 2014; Devine et al. 2016). This characteristic reflects uncertainty in relevant variables regarding geohazard assessments. Some causes are analysed in the following.

To develop ground models involving features and processes occurring on the seabed and subsoil, seismic reflection imagery is the technique most used to capture data. Although this technology has advanced enormously since its inception in the 1990s (Long, Bulat, and Stoker 2004), increased imagery resolution and the use of other geophysics tests, such as electric conductivity tests, along with coring and cone penetrometer tests, are required to avoid misinterpreting geohazard features and to reduce inaccuracies (McConnell 2004; Savazzi et al. 2015; Andrew Buckley and Cottee 2017; Cox et al. 2020). The integration of geophysical, geological, and geotechnical survey data has been also used to improve accuracy (e.g., Medina-Cetina, Son, and Moradi 2019). Appendix B to this paper shows some of the potential features and processes which are yet difficult to map and, according to the literature, might generate uncertainty.

There are more factors driving uncertainty in relevant input variables. High resolution technologies such as autonomous underwater vehicles and remotely operated vehicles to capture bathymetric information are reported by, among others, Orange et al. (2003), Wynn et al. (2014), Contet and Unterseh (2015), Martin et al. (2015), Clare et al. (2019), Carlton et al. (2019), and Kopp et al. (2021). Yet the processing and interpretation of bathymetric data includes filtering, smoothing, and discretising procedures, which potentially can degrade information (Dyer 2011; Haneberg 2015; Arogunmati and Moocarme 2019; Clare et al. 2019). Although 3 D seismic imagery methods exist to achieve a non-negligible accuracy of one-metre resolution in sub-bottom profiling (Digby 2012; Lebedeva-Ivanova et al. 2018), the gathering and processing of data at this resolution is still highly time- and memory-demanding and requires considerable optimisation (Marsset et al. 2010; Xiao et al. 2016; Monrigal, de Jong, and Duarte 2017; Lebedeva-Ivanova et al. 2018). 3 D seismic imagery processing is based on the Bayesian inversion, an approach which is highly resource-demanding and still requires human manipulation and interpretation (McConnell 2004; Mosher, Bigg, and LaPierre 2006; Dyer 2011; Digby 2012; Schwenk et al. 2016; Provenzano, Vardy, and Henstock 2018; Arogunmati and Moocarme 2019; Cox et al. 2020; Zhang et al. 2021), thus increasing inaccuracies, as shown by Haneberg (2015). Next, errors during surveys result in horizontal positioning inaccuracies, therefore affecting layer thickness estimation or features' identification. See Figure 3. (Urlaub, Talling, and Masson 2013; Talling et al. 2014; Clare, Talling, and Hunt 2015; Haneberg 2015; Allin et al. 2016; Clare et al. 2017; Pope, Talling, and Carter 2017; Allin et al. 2018).

In the case of landslide run-out estimation, past fluid flow sources' identification, or the mapping of previous turbidity current pathways, the geohazard analysis relies on datasets and information on past events. Yet, this information base can only provide information on what occurred in the past and little on the processes to occur (Clare et al. 2017). Typically, to address this, scaled-down laboratory experiments (e.g., Boylan et al. 2009; Randolph and Gourvenec 2011; Malgesini et al. 2018; Rui and Yin 2019) or models are used; however, their calibration (Randolph and

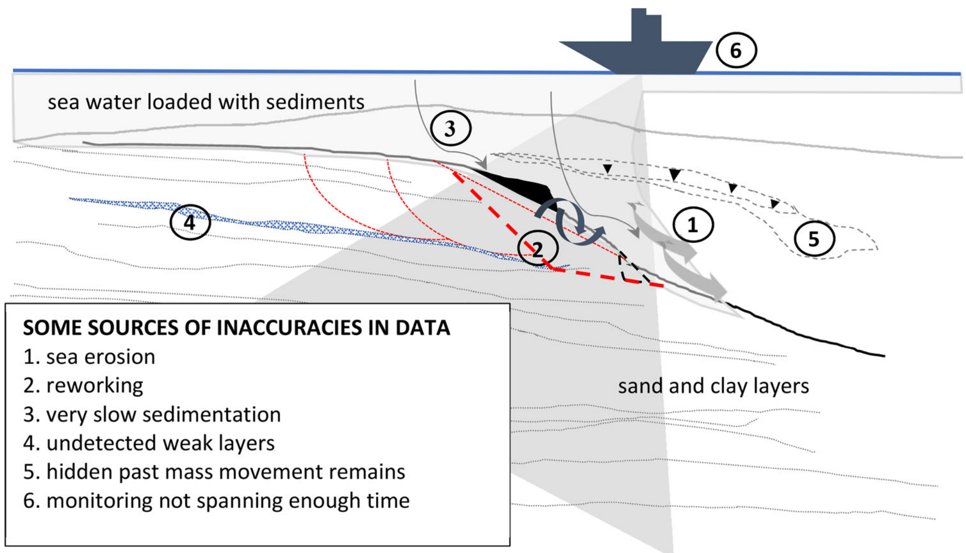

Figure 4. Some sources of inaccuracies in data, generating uncertainty about the structure of the ground.

Gourvenec 2011; Li et al. 2021b) and validation are challenging (Clare et al. 2017). For example, important modelling input data, such as depositional records, are usually incomplete and unreliable, due to sea erosion, reworking, very slow sedimentation, or bioturbation (e.g. Bonnell and Mullee 2000; Niedoroda et al. 2003; Solheim et al. 2005; Maslin et al. 2010; Chiocci and Ridente; 2011; Chiocci, Cattaneo, and Urgeles 2011; Johnson et al. 2011; Urlaub, Talling, and Masson 2013; Talling et al. 2014; Clare et al. 2017; Allin et al. 2018; Stacey et al. 2019), leading to a situation in which there is no certainty on the former structure of the ground. Next, repeat surveys or monitoring rarely span enough time to recognise recurrence rates for dynamic geologic processes such as sediment transport or iceberg scour. Figure 4 summarises the issues (Mosher 2011; Chiocci, Cattaneo, and Urgeles 2011; Kopp et al. 2021).

As discussed in the previous section, the uncertain variables for earthquakes' analysis are those associated with their magnitude, frequency, intensity, and duration. Their uncertainty is mainly due to near-source strong motion data, and strong motion data are likely to be unrecorded (Fenton et al. 2002; Angell and Hanson 2005); it is also sometimes difficult to select representative time history records or interpret data about the seismic sources (e.g., Gilbert and Puskar 2005; Dash et al. 2007). This situation forces specialists to base their estimates not only on the existing records but on the observed strain or stress rates and geological and tectonic controls, to complement available data, a process which incorporates uncertainty in the earthquake key variables and depends strongly on assumptions (Aspinall 2013; Iacoletti, Cremen, and Galasso 2021).

In total, the input data issues above generate a cascade of uncertainties in relevant variables describing geohazards, which, additionally, are difficult to quantify, mainly due to complications in conducting field verifications (Hamilton et al. 2004; Haneberg 2015; Clare et al. 2017; Zhang and Wright 2017). We, note, however, that the introduction of standardised methods for capturing data (Clare et al. 2019), together with improved accuracy provided by the use of autonomous underwater vehicles and remotely operated vehicles (e.g., Wynn et al. 2014; Kopp et al. 2021), have the potential to improve the knowledge of variables relevant to geohazards. Next, to address the issues in interpretation, Arogunmati and Moocarme (2019) have shown the use of convolutional neural networks. The authors reported improved and automatic detection of features of faults and salt, based on seismic imagery, a task prone to bias if conducted by humans alone. The further development of some elements provided by Wellmann and Regenauer-Lieb (2012) could also be considered in new research undertakings, to inform on the accuracy of geological models on a spatial basis. These authors have used information entropy and simulation tools. The proposed research should take into account the issue raised by Haneberg (2015), who states that comprehensively analysing the majority of the uncertain variables in an assessment is almost impracticable.

A general remark is that uncertainties in input variables relevant to marine geohazards are not often reported in the publications examined. Furthermore, rarely, authors proposed the need to identify those uncertain variables (e.g., Angell and Hanson 2005; Huisman et al. 2019). Some attempts to explicitly and formally recognise uncertainty in relevant input variables are reported in the literature. By identifying data gaps, Smith et al. (2002) informed data acquisition efforts. Hanson et al. (2005) provided information on uncertainty related to the location of volcanic sources, while Mannaerts et al. (2005) produced a map in which the probability of encountering sand packages for an exploration unit is displayed. In relation to the timing and frequency of landslides and turbidity currents, Urlaub, Talling, and Masson (2013), Clare, Talling, and Hunt (2015), and Allin et al. (2016) reported uncertainties associated with sediments' thickness. Carlton et al. (2019) conducted gap analyses to determine follow-up activities and additional data acquisition, and to revise design criteria for a sea crossing in Norway.

3.5.2. Models

In the literature scrutinised, in general, geohazard assessments are supported by models. In geohazard assessments, we consider that models are mainly used for understanding the performance and risks related to an activity (system), predict its output, and assess relevant risks. The models link the activity output to some quantities and events on a more detailed activity (system) level (Aven 2019). An inventory of geohazard models is provided by Kvalstad, Nadim, and Arbitz (2001). The inventory includes models for slope stability, pore pressure, strain softening, in situ stress conditions, sedimentation and consolidation, gas hydrate stability, mud and debris flow run-out, turbidity currents, the response of pipelines and structures to slides, erosion under pipeline by flows, and the design of anchors and piles. Case analyses are reported by, e.g., Bonnell and Mullee (2000). Modelling analysis considerations have been provided by Eltaher, Rajapaksa, and Chang (2003). In addition to the limitations reported in Table 2, we discuss further modelling limitations as follows. Angell et al. (2003) noted that there are problems in selecting appropriate models and model variables, e.g., for the fault displacement hazard characterisation. We also note that calibration of geohazard models is a difficult task, and the associated issues below are not addressed in the marine geohazard literature. Given the usual condition of very limited and unverifiable data in assessments, it is very difficult to meet data requirements for the ideal parameterisation of models, as that suggested by Betz (2017). Parameterising models is further challenged by the potential dependency among parameters, as well as between parameters and initial and boundary conditions (see, e.g., Albert, Callies, and von Toussaint 2022; Degen et al. 2022). When models are somewhat calibrated, the credibility of predictions, namely, that of those model outputs not observed in the calibration data, can also be questioned (e.g., unobserved extreme velocities in marine turbidity currents, as mentioned by Bruschi et al. (2006)). To help calibrating models, we can consider using back analysis, structural models, and Bayesian networks (Hund and Schroeder 2020; Albert, Callies, and von Toussaint 2022). With considerable data, these ideal methods can support the specification of a joint distribution of model parameters. However, under the usual circumstance of lack of information, establishing such joint distributions is challenging and requires, in many instances, that an analyst encodes a set of assumptions (e.g., prior distributions, data likelihoods, independency, linear relationships, normality, the stationarity of the variables and parameters considered); see, e.g., Albert, Callies, and von Toussaint (2022). More promising options to address the parametrisation problem are surrogate models, in conjunction with fast sensing technologies, allowing for real-time model updates (e.g., Cardenas 2019; Azimi and Shiri 2021; van den Eijnden, Schweckendiek, and Hicks 2021; Wang et al. 2021; Tran and Kim 2022; Rammay, Alyaev, and Elsheikh 2022) and parameters' reduction (e.g., Fröhlich et al. 2022), although these approaches do require considerable data. Yet, like many models, the credibility of surrogate model outputs not observed in the training data is to be examined.

The modelling of flows such as debris flows or turbidity currents captures considerable attention in the literature. It often relies on numerical models solving systems of differential equations which describe the motion of viscous fluid substances, e.g., Navier–Stokes equations (see, e.g., Bonnell and Mullee 2000; Elverhøi et al. 2002; Chow, Li, and Koh 2019). The input of those equations are normally initial and boundary conditions, which should reflect the conditions constraining each particular flow being analysed. Boundary conditions would be, e.g., the rate of upstream flow or sediment concentration generated by other erosional processes (e.g., Bonnell and Mullee 2000). Specifying these boundary conditions is challenging for marine flows. Typically, these conditions are uncertain, due to inaccuracies in seafloor and subsoil investigations (e.g., Pope, Talling, and Carter 2017; Malgesini et al. 2018). These inaccuracies are exacerbated by the effect of historic erosional and depositional processes, which rework the sedimentary records, as mentioned earlier. Next and foremost, these boundary conditions change over space and time (Elverhøi et al. 2002). Under these circumstances, a possible situation is that boundary conditions would not be those assumed. This problematic issue also holds for the modelling of landslides and sediment mobility and scour, where boundary conditions are required to be set (Angell et al. 2005; Randolph and Gourvenec 2011; Bruschi et al. 2014; Urlaub et al. 2015). The impact of the uncertainty linked to boundary conditions as such is a largely overlooked subject in the literature studied. Among the few, Chow, Li, and Koh (2019) considered the use of periodic boundary conditions in the simulation of submarine landslides and mudflows. Due to the changing nature of boundary conditions, modelling based on simulations in conjunction with hindcasting approaches (e.g., Randolph and Gourvenec 2011; Dimmock, Mackenzie, and Mills 2012; Yuan et al. 2012; Beven 2016; White et al. 2016; Malgesini et al. 2018; Sun et al. 2021) would help quantify uncertainty impacts, albeit in a limited and resource-demanding fashion.

The issue of stationarity has drawn some attention in the literature analysed. Typically, in geohazard assessments, data stationarity (i.e., no long-term change in the mean and variance of the time series) is assumed. Considering the observed changes in, for instance, the periglacial belt, the assumption of data stationary can be questioned (Arenson and Jakob 2015). Moreover, addressing non-stationarity makes conventional statistical testing of models' input data more difficult (Beven 2012). Non-stationarity generates uncertainty in variables relevant to geohazards. Non-stationary uncertain variables are, e.g., the soil and fluid mechanical properties which may degrade over the long term. This demands alternative approaches in geohazard risk assessment. In the literature analysed, this issue has only been addressed in a somewhat conceptual fashion by Read (2018).

In line with the calibration problem, we have also seen that, in many cases, models cannot be validated, due to the already mentioned data constraints. In other instances, the issue is the incomplete model response, which refers to a model not having a solution for some combinations of the input variables (van den Eijnden, Schweckendiek, and Hicks 2021). This particularly represents uncertainty in the form of model output uncertainty and warrants the consideration of alternatives to validation (Aven 2019). Unfortunately, for these situations, little guidance has been provided for judging a particular model's pedigree or its sufficiency to support the assessments (e.g., Hanson et al. 2005). We also should note that, in the literature scrutinised, the credibility of models used to support geohazard assessments generates reservations, since exhaustive investigations of how model outputs and predictions are sensitive to the choice of model parameters, data likelihoods and initial and boundary conditions are virtually not conducted. To address these points, Aven (2016) has provided a potential framework to be used and further developed in geohazard assessments. This author has also reviewed different methods to evaluate models which can be customised and set in place in geohazard assessments. In hydrology and hydraulics, Wagener, Reinecke, and Pianosi (2022) have also illustrated the possibility of alternative models' evaluation, based on physical consistency checks for predicted unobserved outputs, to avoid physically implausible representations of the system, whereas Lu and Lermusiaux (2021) have discussed the potential of model learning, an approach which does not need any prior information about laws' functional forms but requires local verification of conservation laws in the data.

As shown in Table 1, geohazards are highly interactive events. In general, such interactions are reflected in links among seafloor tectonics, erosional and depositional processes, compaction, gas, fluid and heat migration, stresses and temperature fields, and salinity concentrations and their mobility. These are features and processes occurring on and below the seabed. In spite of this, a multi-hazard modelling approach to their coupled analysis has not been reported in the publications analysed. What is more, enhanced physical modelling means, to numerically express the changes over space and time and in a fashion which couples the geohazard features and processes, need to be in place. This endeavour has been partly envisioned by Culshaw (2005), Angell and Hanson (2005), Nadim (2006), Hough et al. (2011), Lacasse and Nadim (2011), Bruschi et al. (2014), and Griffiths (2016). It has been also suggested that, in such enhanced ground modelling, the uncertainty involved could be displayed on a point-by-point basis and numerically (Brumund 2011). In the literature examined and regardless of the enormous advances in the field, these changing processes are mostly reported in a descriptive and regional way and sometimes very schematically, as by Kvalstad, Nadim, and Arbitz (2001), Chiocci and Ridente (2011), Hough et al. (2011), and Allin et al. (2018). For example, underground fluid and gas flows are basically captured by seismic reflection imagery, e.g., Fenton et al. (2002). Conceptual mappings are usually obtained to display erosional and depositional processes (e.g., Hough et al. 2011; Allin et al. 2018). Yet, the probability of failure of slopes has been partly informed by geomorphology analysis (Dimmock et al. 2012). Exceptionally, coupled analysis, involving gas hydrates' dissociation processes and slope stability analysis, is reported by Nixon and Grozic (2007), Liu et al. (2011), Urlaub et al. (2015), Handwerger, Rempel, and Skarbek (2017), and Li et al. (2021a). A coupled stress and fluid flow model for a landslide model has been reported by Urlaub et al. (2015). These latter authors assessed the sensitivity of overpressure generation and slope stability with respect to different sedimentation rates and patterns, sediment consolidation properties, and stratigraphic layer configurations. Enhanced ground models are therefore regarded as essential to reduce the geohazard uncertainty. These new models would help to research future scenarios, including those due to ocean warming. It has been conjectured that, as occurred in the past (e.g., Elverhøi et al. 2002; Slowey et al. 2003; Bryn et al. 2005; Long et al. 2005; Mienert et al. 2005; Kvalstad 2007; Mienert et al. 2010; Collett et al. 2015; Kremer et al. 2017; Newton and Huuse 2017; Allin et al. 2018) and is occurring today (e.g., Glasby 2003; Bruschi et al. 2014; Wei et al. 2014; Kelner et al. 2016; Paulin and Caines 2016; Chiocci and Casalbore 2017; Pope, Talling and Carter 2017; Harrison et al. 2018; Everett et al. 2021), significant changes in sub-bottom fluid flow, erosion, depositional processes and sea currents' regime are expected in the oceans, including the Arctic (Glasby 2003; Maslin et al. 2010; Mienert et al. 2010; Chiocci, Cattaneo, and Urgeles 2011; Geissler et al. 2016; Allin et al. 2016; Dou et al. 2016; Griffiths 2016; Clare et al. 2017; Kremer et al. 2017; Newton and Huuse 2017; O'Leary, Garrigus, and Krzewinski 2018; Nikiforov et al. 2019; Paull et al. 2022). To address this complicated issue, still under development, approaches which can model jointly, and on a spatial basis, physical processes in the form of surrogates and data becoming available from intensive monitoring might be useful (e.g., Zhang et al. 2018c; Wang et al. 2019, Depina, Oguz and Thakur 2020; Bastías Espejo et al. 2021; Korup 2021; Lu and Lermusiaux 2021). Regarding the required modelling input data, Wynn et al. (2014), Campbell, Kinnear, and Thame (2015), Gafurov and Klochkov (2015), Unterseh and Letaief (2017), Nali et al. (2019), Tayber et al. (2019), and Kopp et al. (2021) have also shown the potential of autonomous and remotely operated underwater vehicles and other techniques to improve the acquisition of data by intensively and even regionally monitoring temperature, salinity, gas and fluid flows, soil deformation, active structures in the ground, e.g., faults and fractures, erosional and depositional processes, and sea currents' variables.

In the examined set of publications, there are exhaustive contributions on how to conduct geohazard assessments for different purposes (e.g., Kvalstad, Nadim, and Arbitz 2001; Fenton et al. 2002; Jeanjean, Hill, and Taylor 2003; Lacasse 2004; Gilbert and Puskar 2005; Hanson et al. 2005; Kvalstad 2007; Power, Galavazi, and Wood 2005; Nadim 2006; Lacasse and Nadim 2011; Haneberg 2015; Devine et al. 2016; Read 2018; Lacasse et al. 2019; Berger et al. 2020), as well as thorough studies reporting on geohazards-infrastructure interaction modelling supporting design (e.g., Eltaher, Rajapaksa, and Chang 2003; Kenny et al. 2007; Bruschi et al. 2014; Paulin and Caines 2016; Sancio and Al-Sharif 2016;

White et al. 2016; Malgesini et al. 2018). However, the long-term integrity of infrastructure on the seabed, considering jointly geohazards and future scenarios including those due to ocean warming, is an underreported and therefore unknown issue, which requires increased investigation.

In addressing other former modelling limitations, much has been achieved using the finite element and finite difference methods (Malgesini et al. 2018). Note, however, that some of the suggested models entail strong simplifications (e.g., Milkov and Sassen 2000; Nixon and Grozic 2007; Odina and Tan 2009; Chatzidakis, Tsompanakis, and Psarropoulos 2020), whereas other models reported are complicated and data-demanding (e.g., Odina and Tan 2009; White, Boylan, and Levy 2013; White et al. 2016; Malgesini et al. 2018; Li et al. 2021b). However, guidance is lacking for determining the circumstances under which an analyst can confidently use a simplified model and when the specialist can deploy a more complicated version of it.

Geohazard assessments have also been enriched using probabilistic analysis to quantify uncertainty. We have noted that, in the literature analysed, uncertainty is often measured using probabilities. Using models, uncertainty quantification helps determine how likely the responses of a system are when some variables in the system are not known (Saouma and Hariri-Ardebili 2021). A system's response can be calculated analytically, numerically, or by random sampling. In the sampling procedure, specified distributions of the input variables are sampled, the respective outputs of the model are recorded, and then the process is repeated as many times as may be required for the desired accuracy. Finally, the distribution of the outputs can be used to calculate probability-based metrics, like an expectation or the probabilities of critical events. Given the high-dimensional and spatial nature of hazards and associated variables, sampling methods are frequently used because they result in a less expensive and more tractable uncertainty quantification, in comparison with analytical and numerical methods. See, e.g., Fenton et al. (2002), Dimmock, Mackenzie, and Mills (2012), Haneberg (2015), White et al. (2016), Omar et al. (2020), and Wang et al. (2021). These authors have demonstrated that, using probabilistic analysis, more informed assessments can be carried out. Probabilistic analysis has helped to calibrate models (e.g., Malgesini et al. 2018; Li et al. 2021b). Probabilistic approaches are also seen as an alternative to physical testing programmes, which are often time-consuming and costly. Probabilistic analysis provides an effective approach to inform soil investigation (Lacasse 2004; Gilbert and Puskar 2005; Hanson et al. 2005) and to examine a wide range of variables and design scenarios (Gilbert and Puskar 2005; Kenny et al. 2007; Kumar, McShane, and McDonald 2010). In addition, Lacasse et al. (2019) mentioned that disclosing uncertainty through a probabilistic analysis will usually promote a debate that should lead to more robust decisions. Despite all this, some reservations can be formulated. It is evident from this review that probabilistic analysis does not exhaustively consider the majority of uncertain variables, as those identified in this paper. As seen, analysts may fail to specify, e.g., important input variables, such as those related to trigger factors. Consequently, geohazard events can also be ignored. What is more, as already shown in previous sections, the quantification of those uncertainties is sometimes challenging. For instance, it is not clear how prior knowledge of input variables in the form of probability distributions should be selected in a structured fashion. The fact that model responses' uncertainty is conditional on the choice of model components, such as parameters, initial and boundary conditions, and input variables, should also be recalled. Thus, given the usual data restrictions, if only some of these model components can be constrained by data, the modelling will only reflect some aspects of the uncertainty involved. Paradoxically, fully parameterised models could potentially be accurate at reproducing data from past events, but even these may turn out to be inadequate for unobserved outputs. This particularly calls for alternative analysis about, for example, the relative influence of modelling choices and assumptions, since they provide improved insights into uncertainty quantification.

An additional reservation is that, even when probabilistic modelling is conducted, at each realisation, soil properties are averaged over each soil deposit (e.g., Nixon and Grozic 2007; Morgan and Baise 2011), which might mean unreliable quantifications of, for instance, probability of failure, a key uncertain quantity in landslide hazard analysis. This raises questions about the need to optimise such analyses, using, for example, random field theory, as has been done in the onshore geohazards field (e.g., Griffiths, Huang, and Fenton 2009).

3.5.3. Assumptions

Some publications provided explicit information on the use of assumptions, but these are rarely reported as either tested or evaluated, with evaluation only occurring indirectly when a modelling approach is validated with field data. We have seen that, in many instances, models cannot be validated. In consequence, the associated assumptions are not tested. Along with this, an approach to make, analyse, and evaluate assumptions is missing in the reviewed literature. Yet, a few directions in this respect are provided by the observational method (e.g., Lacasse et al. 2019). Based on either logic trees or conditional trees, some other approaches to explicitly analysing assumptions' effects have been developed for seismic hazard analysis and water management (Kulkarni, Youngs and Coppersmith 1984; Fenton et al. 2002; Beven and Alcock 2012). Optimised approaches need to address the following challenges. In some cases, it is largely difficult or impossible to verify some of the assumptions, e.g., normal compaction assumption to estimate pore pressure (Zhang et al. 2018b). Current practice can hardly afford to test all the assumptions made, in a timely fashion. In these cases, apparently conservative assumptions are made (e.g., Milkov and Sassen 2000; Citta et al. 2003; Eltaher, Rajapaksa, and Chang 2003; Audibert et al. 2004; Nadim, Kvalstad, and Guttormsen 2005; Bruschi et al. 2006; Nadim 2006; Kvalstad 2007; Johnson et al. 2011; Bruschi et al. 2014; Nash, Burnett, and Parry 2014; Haneberg 2015; Lacasse et al. 2019; Ruppel and Waite 2020; Li et al. 2021b), but, in the majority of cases, the extent to which the assumptions made implied robust situations is not explicitly analysed or clear. There are some cases in which assumptions are based merely on statistical associations and either have no causal support or are physically inconsistent (Steger et al. 2021).

In concluding this section, relevant questions can be formulated. How do the identified uncertain geohazard variables compare with one another? Which of these uncertain variables should science or projects focus on first? To what extent are the associated assumptions made robust? Based on the revised literature, the answer to these questions remains elusive and leads us to a major uncertainty, which is not knowing which variables matter most. Nonetheless, the use of sensitivity analysis can clarify this. The use of sensitivity analysis, SA, tools has been suggested or reported in the literature examined (e.g., Nadim, Krunic, and Philippe 2003; Best et al. 2004; Lacasse 2004; Hanson et al. 2005; Nadim, Kvalstad, and Guttormsen 2005; Solheim et al. 2005; Bruschi et al. 2006; Kenny et al. 2007; Nixon and Grozic 2007; Kumar, McShane, and McDonald 2010; Lacasse and Nadim 2011; Yuan et al. 2012; Hill et al. 2015; Rodríguez-Ochoa et al. 2015; Paulin and Caines 2016; Liu et al. 2018; Malgesini et al. 2018; Barbieri et al. 2019; Azimi and Shiri 2021). To improve modelling or predictions, sensitivity analysis helps identify the most important variables which further research should focus on (Saltelli 2002; Hanson et al. 2005; Borgonovo and Plischke 2016). Next, sensitivity analysis functionalities support the prioritisation of monitoring activities and risk assessment efforts (Hough et al. 2011), which, in turn, will potentially contribute to the early identification of marine geohazard events. As long as measurements or accurate predictions of sensitive factors are made, SA is believed to allow trigger factors and associated geohazard events to be identified. SA has aided the design optimisation of structures on the seabed (Eltaher, Rajapaksa, and Chang 2003; Liu et al. 2018) and helps assumptions to be evaluated for robustness (Beven et al. 2018). Hence, using SA, uncertain variables can be identified, analysed, classified, and prioritised according to their importance, to ultimately inform risk analysis and decision-making, and orientate scientific research efforts. However, we acknowledge that, in some cases, uncertainty is difficult to quantify, which makes it hard to use SA. Complementary methods, with alternative ways to characterise uncertainty, require further research. To address this point, we can consider the assumption deviation assessment approach (Aven 2013) that assesses which assumptions could be wrong, how an assumption might be wrong, and the quantification of the impact of a deviation of the assumption. The assumption deviation assessment approach analyses additional features beyond SA. The major and distinctive features of the assumption deviation assessment approach are the evaluation of the credibility of the knowledge *K* supporting the assumptions made, together with the questioning of the justifications supporting the potential for deviations. Such an approach is believed to be more insightful to establish the credibility of predictions, as well as to identify unknown, at the time of the assessments, triggering mechanisms linked to future geohazard events.

3.6. Specifying RS’, A’, and C’

In the proposed framework to define and describe geohazard risk, see Section 2 and Figure 2, we have made a distinction between the specified or identified risk sources, events, and consequences, *RS*’, *A*’, *C*’, and the risk sources, events, and consequences that actually occur, *RS*, *A*, *C*. This implies an acknowledgement that, in a risk assessment, it is possible that not all elements in *RS*, *A*, or *C* are contained in *RS*’, *A*’, or *C*’, respectively, e.g., as seen in this review, during many assessments, triggering factors which could bring a soil mass to failure could remain unknown to analysts. As pointed out by one of the reviewers of this paper, this raises the question of how to specify *RS*’, *A*’, or *C*’ to provide more confidence that all elements in *RS*, *A*, or *C* are contained in *RS*’, *A*’, or *C*’. Another reviewer critically questioned how the proposed review and framework can help assess the uncertainty of hazard events linked to compound and even undistinguishable risk sources. Unfortunately, in the literature reviewed, these questions are not explicitly tackled. Here, we aim to show how some aspects of the proposed framework and the output of this review will help in addressing the reviewers’ questions. In order to do this, we summarise here some details in the form of steps which can be considered to specify *RS*’, *A*’, or *C*’. Many of the steps relate to the examination of strength of knowledge, *K*, supporting the assessments, which was introduced in Section 2.

- In the examination of strength of knowledge, a distinctive aspect of the framework to define and describe risk, a potential output is the characterisation of sources of uncertainty in an assessment. Identifying sources of uncertainty in an assessment appears to be a basic starting step. The examination of the sources of uncertainty will, for instance, help make the choice for a set of specific models, including key variables and, in turn, define the scope of probabilistic assessments and uncertainty quantification. We have shown that, using the customised framework to define and describe geohazard risk, this review has thoroughly examined the sources of uncertainty linked to marine geohazards and, therefore, is considered to provide important input to any geohazard assessment. Recall that sources of uncertainty are described in the subsections, *Data, Models, Assumptions*, within the subsection, *Knowledge K*. The examination of sources of uncertainty is also essential input to the following steps, which are helpful to specify *RS*’, *A*’, or *C*’.
- Selecting credible models, based on the examination of *K*. Specifically, the judgement of the quality in predictions can inform the selection of models. Selected models can, for instance, help identify which geohazard events, *A*’, can be linked to trigger and conditioning factors, *RS*’, verified or believed likely in the future. Using models, uncertainty quantification about chosen variables can also be conducted by conventional probabilistic analysis.

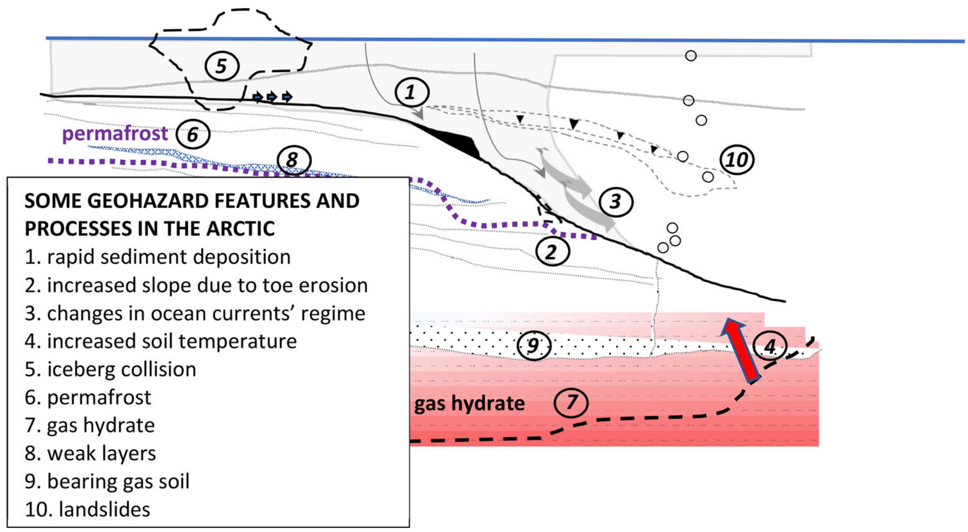

Figure 5. Some marine geohazard features and processes in the Arctic.

Further, we have learnt from literature that credible predictions can also be provided by those models yielding physical consistency. The reservations regarding models' used in geohazard assessments have also been exposed in this review and can be considered when choosing credible models.

- The examination of the strength of *K* considers the reporting and scrutinising of assumptions, including modelling assumptions. In the framework, assumptions are considered part of the supporting knowledge, *K*. Emphasis is on the potential of deviations in assumptions' assessment, introduced earlier and as shown in Aven (2019, 248-249). Notably, in our research, this particular assessment has been very helpful in differentiating compounded risk sources, *RS*', alongside *A*' or *C*'. We recall that, in this review, we have provided considerations regarding the assumptions made in geohazard assessments. Taking into account these considerations as a basis for the examination of assumptions will allow analysts to judge the credibility of predictions and, accordingly, to assess the uncertainty of the variables involved.
- Conventional practice suggests analysts use the models chosen and sensitivity analysis to identify and monitor *RS*'. We can consider, for example, the intensive monitoring of sensitive variables, such as e.g., *pore pressure*, *soil deformation*, and *fracturing*, analysed here as input variables linked to highly uncertain geohazard events such as *landslides* or *flows*. These sensitive variables can be identified by conducting sensitivity analysis. This will potentially contribute to an early identification of trigger factors, *RS*, and associated geohazard events in *A*, in so far as the sensitive variables are monitored and found likely to produce a generalised failure of the slope in the form of, e.g., landslides or flows.
- In the assessment of the strength of the knowledge, *K*, supporting the assessments, other steps are the examination of the amount and relevancy of data or information and the degree of agreement among experts regarding their judgements about, for instance, changes in ground conditions (conditioning factors) in the future or the quality of a chosen model.

Enacting these steps in a geohazard assessment could potentially enable a more systematic specification and differentiation of *RS*', namely the specification of trigger and conditioning factors. Once *RS*' are specified, credible modelling predictions, together with uncertainty quantification by probabilistic analysis, as well as the monitoring of sensitive variables, will provide an increased basis to specify *RS*', *A*', or *C*'. In so far as all these steps can be undertaken in an assessment, this will ultimately contribute to early detection of relevant elements in *RS*, *A*, or *C*. Successful experiences using the strength of knowledge examination approach have been reported in Aven (2019, 246-252).

4. Arctic geohazards

Exploration and development activities include those in the Arctic (Gulas et al. 2017), which are also exposed to geohazards such as slope failures, fluid expulsion features, and faulting (Devine and Haneberg 2016, e.g., Glasby 2003; Deering et al. 2019). Figure 5 shows some more potential geohazard features and processes in the Arctic. The associated uncertain variables have already been discussed in the previous section. Yet, there are some geohazards specific to the Arctic. Ice gouging, permafrost thawing and erosion, strudel scour, and frost heave are the most frequent Arctic geohazards considered by the literature analysed (Kenny et al. 2007; Solomon et al. 2008; Odina and Tan 2009; Loktev et al. 2012; Ravet et al. 2013; Bruschi et al. 2014; White et al. 2014; Georghiou et al. 2015; Devine and Haneberg 2016; Dou et al. 2016; Linch and Dowdeswell 2016; Paulin and Caines 2016; Pike and Kenny 2016; Loktev, Tokarev, and Chuvilin 2017; O'Leary, Garrigus, and Krzewinski 2018; Chuvilin et al. 2019; Nikiforov et al. 2019; Azimi and Shiri 2021). Unfortunately, these sources did not explicitly identify the uncertain key variables relevant to geohazard assessments. Based on these publications, in the following, we infer some of these variables.

Ice gouging occurs when some ice bodies may have sufficient draft; under environmental driving forces, the ice keel may penetrate the seabed and create gouges or furrows that can be metres deep, tens of metres wide, and hundreds of metres long (Kenny et al. 2007). From the publications of White et al. (2014) and Loktev, Tokarev, and Chuvilin (2017), the direction, displacement, timing, and velocity are the inferred variables involving large uncertainty.

Permafrost thawing and erosion is an active process, leading to degradation of the soil affected by temperature changes and flows, creating chaotic and non-continuous permafrost structure (Loktev et al. 2012; Paull et al. 2022). Loktev et al. (2012), Ravet et al. (2013), Dou et al. (2016), Loktev, Tokarev, and Chuvilin (2017), and Paull et al. (2022) suggested that location, extension, migration pathways, and temporal and spatial variation are the variables about which there is often significant uncertainty.

Strudel drainage and associated seabed scour occurs when water overflowing onto a surface of ice has completely drained off the ice surface and scours the seabed surface, leaving a radial pattern of channels that lead to a hole (Solomon et al. 2008). Based on the publications of Solomon et al. (2008) and Georghiou et al. (2015), the location and timing of these processes would be the key uncertain variables.

Frost heave is a form of soil swelling caused by ice in the ground as it grows towards the seabed surface (Bruschi et al. 2014). Location, extension, and temporal and spatial variation would represent the uncertain variables.

As mentioned earlier by Taylor et al. (2008), in comparison with overseas publications, less is reported in the literature examined about Arctic geohazard assessments. Further, basic input information, such as the extent of permafrost in northern environments, has been subject to poor mapping (O'Leary, Garrigus, and Krzewinski 2018; Paull et al. 2022). Few publications have addressed the issues related to permafrost stability analysis (e.g., Chuvilin et al. 2019; Everett et al. 2021), and no study has inquired about the potential effects of sub-bottom permafrost thaw, which can trigger changes in sub-bottom gas and fluid flow, erosion, and sea currents' regime, as somewhat conjectured by Kvalstad, Nadim, and Arbitz (2001), Glasby (2003), Dou et al. (2016), O'Leary, Garrigus, and Krzewinski (2018), and Nikiforov et al. (2019). A major concern, however, is that the influence of ocean warming on the occurrence of geohazards in the Arctic has not yet been investigated. Hence, large uncertainty remains about the future geohazard events in the Arctic. But, as previously discussed, this is not a problem peculiar to the Arctic; it occurs for overseas regions. Note, however, that existing knowledge gained overseas could still be useful in researching future scenarios in the Arctic. For example, studies conducted in different places in the world on slope instabilities and thaw settlement by permafrost degradation (e.g., Arenson and Jakob 2015; Simpson et al. 2016; Etzelmüller et al. 2021; Ni et al. 2021); highly intensive erosive and sedimentation processes, such as occur in large delta and glacial zones and shorelines (e.g., Slowey et al. 2003; Kvalstad 2007; Bruschi et al. 2014; Wei et al. 2014; Allin et al. 2016; Kelner et al. 2016; Chiocci and Casalbore 2017; Newton and Huuse 2017; Harrison et al. 2018); gas hydrate stability, which might be sensitive to seasonal temperature variations (Glasby 2003; Ruppel and Waite 2020); and deep waters (Bruschi et al. 2006; Nadim 2006) are potential inputs. Enhanced ground modelling, as discussed in the previous section, should also contribute to the analysis of future scenarios for the Arctic.

From the science perspective, addressing Arctic uncertainties regarding geohazards requires increased ground investigation and the development of coupled models, involving sub-bottom fluid flow, erosion and depositional processes, and sea currents' regime interactions. Regardless of whether or not this is achieved in a specific setting, geohazard analysts would need to strive to evaluate specific uncertainties, by assessing the reasonability of the assumptions made, the amount and relevancy of data or information, the degree of agreement among experts, and the extent to which the phenomena involved are understood and accurate models exist for risk-managing activities in the Arctic.

5. Further discussion and conclusion

We have reviewed the literature related to marine geohazards, to identify marine geohazards' uncertain variables, along with their uncertainty causes and issues. This has been achieved using a modern framework to define and characterise risk. Variables of interest with large uncertainty were found for the risk sources, geohazard events, and their consequences. The issues generating this uncertainty in data, models, and assumptions were also analysed. From this, some important findings can be further discussed, and conclusions can be drawn.

The probability-consequence approach is the dominant method to characterise risk. However, this approach contributes poorly to any geohazard risk assessment. This is particularly true under conditions of weakly constrained uncertainty, which some marine geohazard analyses might involve. As demonstrated, a more exhaustive and meaningful definition and description of geohazard risk is given by defining risk by the set (*RS, A, C, U*) and describing risk by the set (*RS', A', C', Q, K*).

We can also distinguish specific contributions to risk assessments, which are summarised in the following:

- a customised framework to define and describe risk in the marine geohazards field. This framework uses the elements of a recently developed general framework (Aven 2019), see Fig. 2. With this framework, we believe clarifications were made regarding the meaning of uncertainty. This framework should stimulate assessments to be more informative. Note that the customised framework has also been developed from the marine geohazards' specifics revealed by the literature studied;

- the review provided some key variables of interest to marine geohazard assessments. An analyst with this information can focus attention on these variables, to evaluate their uncertainties in each specific setting being analysed;
- this review also reported variables of interest with large uncertainty, that is those whose uncertainty is poorly constrained due to issues in gathering, processing, and verifying data, as well as in calibrating, validating, and testing models. Based on this information, an analyst would have more elements for prioritising the examination of the knowledge, *K*, supporting the quantification of these large uncertainty variables and possibly assessing them as critical;
- based on literature outside the marine geohazards field, we also give recommendations on how to better specify *RS*', *A*', and *C*'. Mostly, the recommendations are oriented to an exhaustive investigation of sources of uncertainty, the use of models grounded on the physics of the process analysed, and, more importantly, making explicit assumptions and assessing the impact of their deviations in conjunction with the examination of the strength of knowledge, *K*, supporting the assessments.

Uncertainty in variables relevant to marine geohazards is not often reported in the publications examined. Among the potential causes is that uncertainty in the variables identified is difficult to quantify. Another factor might be that many authors in the set of publications analysed failed to acknowledge that geohazard assessments are conditional on current knowledge, *K*. Based on this observation, analysts in the field should seriously consider a more structured reporting of the uncertainties involved in their analysis, to inform uncertainty reduction, provide more scientific grounds to the research outputs, promote robust decision-making, and more optimally orientate research efforts.

When uncertainty is measured in terms of probabilities, sometimes it is unclear whether they correspond to conditional probabilities. Most of the probabilities are conditional and should capture the local specifics associated with a given geohazard and account for the vulnerability of the infrastructure of interest, in relation to impact by the geohazard. This consideration, however, also has more important implications when it comes to making inferences, testing hypotheses, or concluding on causal relationships between risk sources and geohazard events. In any geohazard assessment, the conditional nature of probability needs to be further assessed when testing hypotheses under conditions of scarce data. This is not straightforward, however, and entails a scientific challenge, which needs to be addressed by alternative methods to statistics.

Among the large uncertain variables found, we fail to identify those which matter most, and this is a major uncertainty. The limited use of sensitivity analysis, SA, in the published research hindered this endeavour. A few authors in the publications analysed have seen and reported the benefits of SA. However, we acknowledge that, in some cases, uncertainty is difficult to quantify, which makes SA hard to use. Fortunately, literature from other fields has provided additional and more informative options to measure and analyse uncertainty (see Aven 2019). The options available consist of assessing the impact of assumptions' deviations, together with a thorough examination of the supporting knowledge, *K*. Nevertheless, these options ought to be customised and, in some cases, optimised and further developed, to improve geohazard assessments.

Alongside the identification of relevant geohazard variables, whose quantities are typically uncertain, and based on an exhaustive scrutiny of knowledge, *K*, we have made other discoveries, described in the following.

Ground models are essential in geohazard assessments; however, they are yet somewhat highly limited by the identified current issues in gathering, processing, and verifying data, as well as in calibrating, validating, and testing models. Next, supporting models to investigate future geohazard scenarios associated with ocean warming are highly underdeveloped.

Probabilistic assessments have proved helpful to support assessments. Yet, we have made it evident that current probabilistic analysis does not exhaustively account for the majority of uncertain variables. Therefore, usually the modelling only reflects some aspects of the uncertainty involved. Further, it is not clear how geohazard boundary conditions should be considered and how prior knowledge of input variables in the form of probability distributions should be selected in a structured fashion. Furthermore, a customary analysis about the influence of assumptions made for these probabilistic assessments is desirable.

Marine geohazards might be highly interactive; however, based on the analysis of the support of the hypothesised interactions and their conditional nature, doubts are raised as to current limitations in modelling these interactions, whether conventional statistics are meaningful to conduct scientific inference, and regarding the credibility of regional studies.

Regarding the Arctic environment, clearly, less is known about geohazards in this setting, in comparison with overseas, but much of the experience overseas is helpful in dealing with the specifics in the Arctic. From the science standpoint, addressing Arctic uncertainties related to geohazards requires increased ground investigation and the development of coupled models, involving sub-bottom gas and fluid flows, erosion and depositional processes, and sea currents' regime interactions.

As to limitations of this work, potentially relevant publications were not examined, due to misclassification during indexing processes conducted by the bibliographic database. However, we believe that most of these unexamined publications have been referred to and quoted in the sources analysed by us. Note that the sources also included reviews and discussed findings in comparison with antecedent literature, and these were also analysed for this research. This means that these unexamined contributions form, in any case, the existing body of knowledge substantiating this research.

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Notes on contributor

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Data are available on request. Requests can be sent to the corresponding author.

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Appendix A. Other geohazards

In Table A-1, some other geohazard-related features and processes mentioned in the literature are displayed. These correspond to items for which uncertain key input variables relevant to marine geohazard assessments were somewhat not clearly identified. However, we register some inferred variables, whose quantities are likely to be uncertain. To conduct particular geohazard assessments, further investigation into these features and processes is required, to evaluate their local importance, taking into account the assessment of their uncertainties, as previously shown. In Table A-1, the literature sources are attached.

Appendix B. Geohazard features and processes which are difficult to map

Table B-1 shows some of the potential features and processes which are difficult to map and, according to the literature, might generate uncertainty. Sources have been incorporated into the table.

Table A-1. Other geohazard-related features and processes mentioned in the literature reviewed.

Item	Key uncertain variables	Mentioned by
Asphalt volcanoes	Location, migration pathways	Serié et al. (2017)
Brittle and sensitive soils	Location, resistance and deformation properties	Randolph and Gourvenec (2011), Bruschi et al. (2014)
Contourite deposits	Extension, displacement	Ruano et al. (2014), Cattaneo et al. (2017)
Deep-seated faults and folds	Location, displacement, and displacement recurrence	Angell et al. (2003), Jeanjean, Hill, and Taylor (2003), Hanson et al. (2005), Dash et al. (2007), Chiocci and Ridente (2011)
Fault networks, polygonal faulting	Location, extension, associated fluid migration pathways	Younes et al. (2005), Berndt et al. (2012b)
Footprints		Nancy et al. (2014)
Hardground	Location	Wood and Hamilton (2002)
Highly reworked soils	Location, resistance and deformation properties	Paulin and Caines (2016)
Ice calving	Location, extension	Everett et al. (2021)
Ice jam	Location, extension	Lagadec, Boucher, and Germain (2015)
Iceberg scour	Location, extension	Solomon et al. (2008), Odina and Tan (2009)
Large migrating sedimentary bedform	Location, extension	Bransby et al. (2010), Chiocci and Ridente (2011), Bruschi et al. (2014)
Lateral variation in soil properties	Location, extension	Wood and Hamilton (2002)
Liquefaction	Location, resistance and deformation properties	Jeanjean, Hill, and Thomson (2003), Randolph and Gourvenec (2011), Sancio and Al-Sharif (2016), Harrison et al. (2018)
Methane-driven oceanic eruptions	Location, extension	Zhang (2003)
Morainic mound	Location, extension, resistance and deformation properties	Long (2001)
Mud volcanoes	Location, migration pathways, temporal and spatial variation	Chiocci and Ridente (2011), Benjamin and Huuse (2017), Zhang and Wright (2017), Ivanov et al. (2020)
Natural oil seeps	Location, migration pathways, temporal and spatial variation	Anka, Berndt, and Gay (2012), Ivanov et al. (2020)
Oozes	Location, extension, resistance and deformation properties	Newton and Huuse (2017)
Pingos	Location, migration pathways, temporal and spatial variation	Loktev et al. (2012), Collett et al. (2015), Loktev, Tokarev, and Chuvilin (2017), Serié et al. (2017)
Polygonal faulted clays with high levels of smectite	Location, extension	Cox et al. (2020)
Remoulded soils	Location, resistance and deformation properties	Bruschi et al. (2014), Paulin and Caines (2016)
Reservoir compaction / seafloor subsidence	Temporal and spatial variation	Cook et al. (2002), Jeanjean, Hill, and Thomson (2003), Mel'nikov and Kalashnik (2011)
Salt diapirism and flow	Location, migration pathways, temporal and spatial variation, velocity	Angell et al. (2003), Jeanjean (2003), Orange et al. (2003), Jeanjean, Hill, and Thomson (2003), Johnson et al. (2011), Randolph and Gourvenec (2011), Chuvilin et al. (2019)
Sediment waves (underground)	Location	Putans (2013)
Soil erosion due to permafrost thaw	Location, extension, migration pathways, temporal and spatial variation	Loktev et al. (2012), Ravet et al. (2013)
Stamukha	Extent, displacement, timing, and velocity	White et al. (2014), Loktev, Tokarev, and Chuvilin (2017)
Structured and reactive clay	Location, resistance and deformation properties	Barwise et al. (2015), Hill et al. (2015)
Strudel scour	Location, timing	Solomon et al. (2008), Georghiou et al. (2015)
Uncompacted horizons	Location, resistance and deformation properties	Cox et al. (2020)
Volcano	Location (sources), migration pathways, frequency, velocity, height, extent	Hanson et al. (2005), Staudigel and Clague (2010), Romano et al. (2019)
Weak layers	Location, extension, resistance and deformation properties	Nadim (2006), Hunt et al. (2013), Rodríguez-Ochoa et al. (2015), Rodríguez-Ochoa, Nadim, and Hicks (2015)

Table B-1. Geohazard features and processes which are difficult to map.

Geohazard feature	Mentioned by
Canyons and grooves	Chiocci and Ridente (2011), Martin et al. (2015)
Carbonate facies	Al-Maghlouth, Szafian, and Bell (2017)
Deep sediments	Berger et al. (2020)
Gas hydrate accumulations	Digby (2012), McConnell, Zhang, and Boswell (2012), Best et al. (2013), Wegner and Campbell (2014), Madof (2018), Li et al. (2021a)
Gas migration	McConnell (2004)
Glaciogenic deposits	Andrew Buckley and Cottee (2017)
Individual wedges in fault systems and complex faulting	McConnell (2004), Ruano et al. (2014), Arogunmati and Moocarme (2019)
Landslide mechanisms of failure	Kvalstad, Nadim, and Arbitz (2001)
Permafrost	Loktev et al. (2012), Dou et al. (2016), Loktev, Tokarev, and Chuvilin (2017)
Pressurised sediments	Herron and Sayers (2006), Kvalstad (2007), Mapelli et al. (2015), Andrew Buckley and Cottee (2017), Tingay (2018), Zhang et al. (2018a)
Salt pockets and migration	McConnell (2004), Herron and Sayers (2006), Johnson et al. (2011)
Sediment waves underground	Putans (2013)
Shallow water flow	Citta et al. (2003), McConnell (2004)
Small slumps, slides, pockmarks and seeps < 5 m	Kvalstad (2007)
Unconsolidated shallow sediments in depths < 300 m	Gherasim et al. (2015)
Underground gas and fluid flow features and paths	Gettrust, Grossweiler, and Wood (2003), Zhang (2003), McConnell, Zhang, and Boswell (2012), Chen (2016), Andrew Buckley and Cottee (2017), Loktev, Tokarev, and Chuvilin (2017), Serié et al. (2017), , Cox et al. (2020), Li et al. (2021a)
Weak layers	Rodríguez-Ochoa et al. (2015)

Appendix C. Keywords used in the excerpts' searching process

Unlike other exhaustive reviews based only on the analysis of abstracts, this review went further and analysed the body of the papers. This was achieved with the help of data mining tools provided by the software, Orange 3.27.1. Specifically, in the accessed documents' text, excerpts of interest were captured, by manually extracting the text context of keywords associated with the word "uncertainty," which are automatically highlighted throughout the text by the software's filters. The associated keywords are, for example, the word "assumption" and derivations of it, such as "assumed." The filter used is reported here (see below). In the filter, the symbol "|" limits the search to a certain chain of characters. For instance, in searching the word "assumption" and related words, we set in the filter "assum|"; the machine highlights every chain "assum" in the text, and every related word such as "assumed" or "assumption" can be recognised in the text. Then the associated excerpt is extracted. Note that the software is able to highlight all the queried words set in a filter at once. Further note that the full list of useful keywords has been a product of a learning process. New keywords were identified from the excerpts as they were captured. This learning process ceased approximately when examining the 45th publication. After this instance, no new meaningful keyword was identified.

account | accura | addition | address | agree | ambigu | appear | assum | belie | bias | caveat | certain | challeng | clar | clear | concern | conclusive | confi | conflict | conjectu | consider | consisten | constrain | contrary | contrast | controver | debat | deviat | differen | difficult | discrepan | discuss | disput | doub | down | drawback | enhanc | enigma | equivo | estimat | evidence | evident | expect | explain | explor | fail | feel | foreseen | gap | however | hypothe | ignor | impl | improv | interpretation | investigat | issue | known | lack | learn | limit | little | miss | need | negl | nevertheless | obscur | overlook | pitfall | poor | possible | precis | problem | prov | question | rare | recogni | reliab | rema | report | require | research | seem | short | simpl | specul | suggest | suspicio | thought | underst | weak |