Constraining Geohazards to the Past: Impact Assessment of Submarine Mass Movements on Seabed Developments

S. Thomas, J. Hooper, and M. Clare

Abstract This paper presents a conceptual review of submarine mass movements and associated hazards such as run-out and turbidity currents, and their implications for the planning of exploration and development activities. Submarine mass movements are placed in the context of ground models and geohazard scenarios from which conditioning factors and trigger mechanisms can be assessed and event magnitudes estimated. The approach to dating these events in order to derive a frequency is discussed with reference to radiometric, biostratigraphic and Optically Stimulated Luminescence techniques that have been successfully deployed in recent projects. The need for good stratigraphic control, both seismostratigraphic and lithological, is emphasized. Based on the ground model and geohazard scenarios, ground movement at different locations within the mass movement system can be inferred. This understanding along with predicted soil conditions derived from the ground model and evolutionary history of the site allows the potential consequences on well conductors, facilities and flowlines to be assessed and the need for geohazard design and mitigation evaluated. These findings indicate the constraints on possible exploration and development activities.

Keywords Geohazard assessment • mass movement • seabed development • ground model • integrated study • geohazard design • mitigation • geohazard core logging

1 Introduction

Varnes (1978) presented a synthesis of onshore landslide classification, recognition, avoidance, and control that made a significant step forward from previously published work and built on a wealth of new data available from site investigations.
and academic research. Today we find ourselves in a similar position in the offshore environment, with a relatively recently acquired arsenal of 2D and 3D seismic surveys, high-resolution seafloor images, deepwater cores, in-situ tests, and an enhanced knowledge of mass movement processes (e.g., Lee et al. 1993; Mulder and Cochinat 1996) and conditioning factors (e.g., Masson et al. 2006). With an increased interest in deeper water projects, it is necessary for the offshore industry to identify hazards that are known to, or have the potential to, exist within a given environment and to understand their potential for impact on exploration or development activities. Traditionally when planning for submarine developments, routes or locations have been sought that avoid known geohazards. When exploring deepwater prospects it may be necessary to determine not whether the hazard can be avoided, but rather which route or location will suffer the least impact.

1.1 Submarine Mass Movements – What Are the Hazards?

The classification promoted by Mulder and Cochinat (1996) defines mass movements in terms of their occurrence as either mass slides or gravity flows. Such a division differentiates those processes that are the direct effects of mass slide activity (e.g., creep, translation, rotation, and avalanche) from those that may have evolved downslope from the point of failure (e.g., mass flows and turbidites). While this classification scheme is static, the dynamic interrelationship between mass movements has been well developed in recent publications such as Masson et al. (2006). The scheme of Mulder and Cochinat (1996) has been implemented by the authors to facilitate understanding of the adverse impact that submarine mass slides and their run-out may have on developments and to guide geohazard assessment (Table 1).

Two typical types of offshore structures are considered in Table 1 – vertical foundations (which may include, but not be limited to, piles, conductors, and caissons) and seabed-laid or shallow-buried installations (such as pipelines, flowlines, and cables). Recent work undertaken by the authors has shown that the latter may suffer in particular from geohazard impact as they can span a considerable length across many geohazard-prone areas, offering little resistance to significant mass movement events. It should be borne in mind that small gravity-based or shallow-skirted structures are not included in Table 1, but may be important components in a field development. While not a comprehensive study, Table 1 details the difference in potential geohazard impact dependent upon the location of a structure relative to mass movement. For instance, a piled foundation at the crest of a rotational failure may be subjected to vertical compression (downdrag), however a similar structure at the base of the same failure would undergo vertical extension (uplift). For simple modeling purposes, structures such as pipelines may be considered as horizontal piles; therefore the direction of applied lateral force will control the nature of deformation. Pipeline compression typically results from a parallel movement at the toe of a translational slide, whilst a perpendicular force may create dragging. In addition to these impacts, the nature of run-out will determine whether a flow has potential for loading, scour, or subsequent burial of the structure.
1.2 The Geohazard Assessment Process

Geohazard assessment is required not only to predict those geological processes that may pose significant threat to a development, but to place them in a spatial and temporal context through an understanding of the evolutionary history of the site. This should allow for those geohazards with negligible, or no potential for occurrence to be eliminated, thus reducing the risk profile to the development. Table 2 details some of the tools available to modern geohazard assessment including both traditional and innovative technologies, but these tools should not be considered in isolation from each other. Integration of all available data, along with a geohazard-focused data acquisition program, is essential for a fit-for-purpose review and assessment.

For a determination of actual geohazards the authors find that multiple data acquisition is essential, promoting that as well as obtaining standard geotechnical
samples there is a need for long core samples to be taken specifically for the purposes of detailed geohazard core logging. Where cores have been subsampled for geotechnical testing, often significant sections of the stratigraphic record are removed, thereby allowing for whole event deposits to be missed, adding uncertainty to derivations of event frequencies and magnitudes. Experience of the authors has proven that reliance solely upon geophysical data may often overestimate event magnitudes, as multiple stacked mass movement deposits may appear as one large seismic unit on sub-bottom profiles, where individual deposits are below the limits of separability on seismic records. Therefore use of the term mass movement complex is promoted herein to describe seismostratigraphically mapped features, and mass movement deposit is reserved for those individual units identified from lithostratigraphic core logging.

The process of data integration should be an iterative process, identifying requirements and locations for further data acquisition at every step of the assessment. Figure 1 summarizes a geohazard assessment, from a regional-scale desk study, through a site-specific survey and investigation and finally to a deliverable. It is this deliverable that will directly inform a risk assessment (which may be qualitative, semi-quantitative, or quantitative), providing information for engineering design and/or mitigation. The key outputs of this process are a geohazard inventory and a ground model that are updated throughout the assessment process and form the discussion in the next section.

### Table 2  Some of the tools and techniques available for a modern marine geohazard assessment, detailing typical outputs from each method of data acquisition or analysis

<table>
<thead>
<tr>
<th>Geohazard assessment tool</th>
<th>Geohazard assessment output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath bathymetry</td>
<td>Geomorphological mapping to identify areas of potential mass movement</td>
</tr>
<tr>
<td>Ultra high resolution CHIRP data acquired from Autonomous Underwater Vehicle (AUV)</td>
<td>Lateral and vertical extents of mass movement deposits</td>
</tr>
<tr>
<td>Geographic Information System (GIS)</td>
<td>Soil province/terrain unit mapping; interrogation of spatial data; provision of data for quantitative slope stability analyses</td>
</tr>
<tr>
<td>Geotechnical testing</td>
<td>Soil properties such as step changes in undrained shear strength; identification of soil type for engineering purposes</td>
</tr>
<tr>
<td>Detailed geohazard core logging</td>
<td>Facies-driven classification; understanding of sedimentology; identification of type and magnitude of events; guides geochronological sub-sampling</td>
</tr>
<tr>
<td>Geochronological analysis</td>
<td>Determination of event frequency; correlation with conditioning/triggering factors</td>
</tr>
<tr>
<td>Mineralogical testing</td>
<td>Data may guide interpretation of sediment provenance/behavior</td>
</tr>
</tbody>
</table>
Fig. 1 A conceptual geohazard assessment process detailing how the various stages guide and update a geohazard inventory and ground model as development-specific and time-specific data become available. The final stages of assessment provide data that feed directly into front-end engineering design (FEED), modeling impact studies, and risk assessment. All images property of Fugro GeoConsulting Limited.
2 Three-Dimensional Geohazard Visualization

A ground model includes a three-dimensional visualization of geohazards at a development detailing their geomorphological, bathymetrical, and geological context. By considering all geohazards in a spatial framework, a focused study can be conducted that is specific to the proposed offshore development. Figure 2 details a conceptual ground model for a typical deepwater development comprising a spar platform with spread moorings, manifolds, flowlines, and an export pipeline. The impacts of potential geohazards are varied and often significantly controlled by the seafloor topography. A geohazard inventory should be compiled concurrently with the synthesis of a ground model that aims to list all those geological processes that may have adverse consequences for the development. As the process of assessment continues, it is possible to update and populate the inventory with more specific information including spatial extents, potential for activity, frequency, magnitude, impact, evaluation, mitigation measures required, and an assessment of risk.

In order to progress the assessment to the evaluation of specific impacts, and any mitigation required, a development layout plan or route corridor is required to identify those geohazards that could potentially impact wells, facilities, or infrastructure. A *geohazard scenario* differs from the ground model in that it represents a higher-resolution study, focusing on either an individual geohazard or a specific geohazard-prone area within the development. For example, this may take the form of one scenario for direct mass slide impact, one for turbidity current activity, and another for contourite development. A *terrain systems* approach may be applied to

![Figure 2](image-url)  
*Fig. 2* A conceptual ground model illustrating a terrain system approach for geohazard assessment. Annotations are as follows: 1 – Creep; 2 – translational slide; 3 – rotational slide; 4 – debris avalanche; 5 – debris flow; 6 – liquefied/fluidized flow; 7 – high density turbidity current; 8 – low density turbidity current; 9 – hyperpycnal flow; 10 – along contour flow; 11 – laminar flow
demarcate areas particularly susceptible to different geohazards within a large development, and their predicted spatial relationship to events (Mackenzie et al. 2009). Terrain units or provinces may be identified using the approach introduced by Campbell (1984) which involves a systematic and interactive synthesis of regional geological, seismic and ground-truth data. Further to this integration, and an appreciation of a combined dataset, it is possible to make preliminary suggestions as to conditioning and/or triggering factors for mass movement.

2.1 Benefits of Visualizing Geohazards

There are many benefits provided by a ground model approach, but primarily derive from forcing the assessor to review all conceivable geohazards in a spatial context and with specific relation to the proposed development. Downslope evolution of mass movement processes is considered, particularly with respect to direction and location of impact on seabed structures. The ground model provides a means to focus attention on relevant geohazards and, while initially developed as a conceptual model, it gains sophistication with inputs provided from different geohazard assessment tools. Simply by considering them in spatial context it may be possible to eliminate certain geohazards from the inventory due to falsification with evidence or lack of credibility for their occurrence. That being said, consideration of spatial controls is often not enough to significantly refine a geohazard risk profile. Geological processes must therefore be placed in a temporal context which is determined by means of a resolute seismostratigraphy calibrated with a custom-designed geohazard core logging-derived lithostratigraphy, and geochronological analyses. It is important to bear in mind that the seafloor environment does not typically suffer from denudation in the same way as onshore sites and apparently ‘fresh’ features indicative of submarine mass movement may in fact represent failure that occurred several thousand or tens of thousands of years ago.

3 Determination of Event Frequency – Application of Geochronological Techniques

The principle of uniformitarianism holds that the present is the key to the past and vice versa. With this in mind, determination of those past events that occurred in similar environmental conditions to that of the present day is key to geohazard assessment. Likewise, geohazards can be considered as unlikely where their conditioning and triggering factors can be constrained to past environmental conditions or events. Acquiring accurate dates for emplacement of submarine mass movement deposits is fraught with obstacles. It is necessary for a successful geohazard assessment to deploy a suite of complimentary dating techniques so that any inaccuracies can be minimized. Spurious dates could lead to the identification of an incorrect
conditioning factor (e.g., sea level rise vs. fall) or miss a direct trigger altogether, such as an earthquake or volcanic caldera collapse. Thus the need for a focused and informed sampling and testing strategy is suggested combining biostratigraphic, radiometric and luminescence dating techniques on appropriate materials whose stratigraphic position and geological significance is clearly understood. This section details some of the most useful geochronological techniques that may be employed, but is by no means an exhaustive review of available methods.

3.1 Radiometric Dating Techniques

The most reliable method for constraining emplacement dates during the last 45 ka is by $^{14}$C dating of pelagic sediment immediately above the mass movement deposit (Owen et al. 2007). In order to provide the most accurate result this technique should be coupled with a biostratigraphic analysis which identifies the contemporaneous assemblage of carbonate-shelled organisms (such as planktonic foraminifera). This is necessary as a result of mixing that may occur at seabed, due to bottom current activity for example or in the sediment column by burrowing benthic organisms (Loubere et al. 1995). The effects of bioturbation can be pronounced in certain environments, skewing the apparent age of the shells selected, and hence the inferred age of the sediment. Identification of a microfossil assemblage may also provide information about former ocean surface water temperatures and availability of oxygen at the sea floor which can be built into the environmental component of the ground model, informing discussion of potential conditioning factors. If the stratigraphic sequence is relatively complete, and sufficient samples are investigated biostratigraphically, then a climate change profile can be developed which can function as a proxy, but less resolute, dating method through the known climatostratigraphy. $^{87}$Sr/$^{86}$Sr dating is another radiometric technique which is suited to older sediments (in excess of 500 ka – McArthur et al. 2001) and, in conjunction with $^{14}$C, has been employed successfully on several recent geohazard assessments performed by the authors. Limitations of $^{87}$Sr/$^{86}$Sr are similar to those of $^{14}$C, but also may be affected by non-marine Sr ratios such as may be provided by fluvial systems (McArthur et al. 2001).

3.2 Optically Stimulated Luminescence Dating

Optically Stimulated Luminescence (OSL) dating is a relatively new dating technique applied to marine sediments which attempts to determine age of emplacement by measuring the time since quartz grains contained within a deposit were last exposed to sunlight (Aitken 1992). OSL may be used on sediments as old as 250 ka and is therefore a useful technique to provide data between the upper limits of $^{14}$C and the lower practical limits of $^{87}$Sr/$^{86}$Sr. A minimum practical limit for this technique
appears to be about 1,000 years (Aitken 1992). The limitations of the technique are similar to radiometric techniques. Success also requires delivery to the testing laboratory of intact sediment samples that have been protected from re-exposure to sunlight. Experience of the authors with this technique in the marine environment has yielded reasonable success, with correlatable dates from OSL and 14C techniques typically varying less than 12% (based on currently unpublished Fugro results).

3.3 A Geohazard-Focused Geochronological Approach

Combination of the above techniques and others, such as $^{210}$Pb and $^{137}$Cs dating in very young sediments (about 150 to <50 years BP), will allow for a higher degree of confidence to be placed in the dates determined and in the interpretations made in the geohazard assessment. A successfully targeted geochronological testing program will be predicated on the stratigraphy, with key laterally continuous seismic horizons targeted in order to provide an age-calibrated seismostratigraphic framework for the development area. A good understanding of the lithostratigraphy, and sedimentological features should also be developed prior to any geochronological testing. This avoids the negative effects that may be caused by sampling from bioturbated horizons, reworked sediments or any other post-depositional diagenetic processes.

4 Assessment of Ground Movement

There is significant data in the public realm (e.g., Owen et al. 2007) providing evidence that submarine mass movement activity is more active during periods of relative sea level lowstand and transition, certainly at high and mid latitudes. The experience of the authors is primarily derived from passive margin settings and it has been observed that in such settings climatic changes have provided the conditioning for episodes of submarine mass movements (based on currently unpublished Fugro results). Therefore, mass movements in periods of relatively high sea levels, such as at the present day, can be inferred in many instances to have a reduced likelihood for occurrence or can be constrained to the geological past entirely.

Through a synthesis of data acquired from all available sources (Table 2) it is possible to conduct an integrated study of specific failures and characterize them according to the criteria defined in Table 3. The parameters listed provide data that can be directly input to slope stability analyses (e.g., MacKenzie et al. 2009), risk assessment and impact modelling studies (e.g., Niedoroda et al. 2000; Bruschi et al. 2006; Parker et al. 2008), and include geomorphological, geological, geotechnical, and geochronological data. Such characterization will indicate whether failure is of significant size to impact a development, whether it has potential to occur, and at what orientation the development or structure will be impacted. This will allow for
Table 3: A conceptual slope failure characterization detailing outputs from various geohazard assessment tools. It should be noted that the information above, while credible, is not based on any specific locality.

<table>
<thead>
<tr>
<th>Measured from GIS and Seismic Data including Bathymetry and Sub-bottom Profiles</th>
<th>Interpretation assisted by Detailed Geohazard Logging</th>
<th>Derived from Detailed Geohazard Logging and Geotechnical Testing</th>
<th>Derived from Geotechnical Data</th>
<th>Geochron. Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain System</td>
<td>Location of Headwall Scarp</td>
<td>Depth to Failure Surface (m)</td>
<td>Slope Angle (°)</td>
<td>Displacement (m)</td>
</tr>
<tr>
<td>Slope System 1</td>
<td>2.00km Marker Post</td>
<td>75m</td>
<td>10.0 - 12.0°</td>
<td>35m</td>
</tr>
<tr>
<td>Slope System 2</td>
<td>3.00km Marker Post</td>
<td>15m</td>
<td>17.5-20.0°</td>
<td>30m</td>
</tr>
<tr>
<td>Slope System 3</td>
<td>25.00km Marker Post</td>
<td>5m - 12m</td>
<td>7.5-12.0°</td>
<td>20m</td>
</tr>
<tr>
<td>Slope System 4</td>
<td>40.00km Marker Post</td>
<td>3m - 6m</td>
<td>5.5-10.0°</td>
<td>12m</td>
</tr>
</tbody>
</table>
an evaluation to be made as to whether the geohazard can be eliminated from further consideration, mitigated against, requires further assessment, or presents such a high risk that it must be avoided or accepted by the development.

5 Conclusions and Way Forward

When considering submarine developments, especially in geohazard prone areas such as in deeper water, Locat and Lee (2002) asked the questions: where did and where will mass movement occur; how frequently will it occur; what are the triggering mechanisms; what is the area of influence; and can a previous failure be reactivated? The phrasing of the questions may vary, but the answers provide the framework for a geohazard assessment. For the purposes of planning, design, installation, and operation of a deepwater development a geohazard assessment should encompass the following tasks:

- Comprehensive desk study establishing a ground model and geohazard inventory, such as that proposed by Clayton and Power (2002). These documents become an auditable record of the process of geohazard assessment undertaken in the effective planning of seabed developments.
- Identification and mapping of geohazards from regional geophysical and geological information within both the public and private domains. This provides essential information to develop scopes of work for optimized and fit-for-purpose geophysical and geotechnical data acquisition.
- Ongoing revision of the geohazard inventory and ground model based on updated knowledge so they evolve from conceptual to development-specific models.
- Use of GIS for data organization, regional analyses and slope stability assessment (e.g., Mackenzie et al. 2009).
- Essential data collection and evaluation tools to be used in future geohazards site investigations should be chosen from the following.
- Region-wide multibeam bathymetry for geomorphological analysis of the seafloor.
- Ultra high-resolution surveys using AUV with CHIRP for early identification and mapping of shallow mass movement deposits.
- Long piston cores for sampling of geohazards identified in the ground model. To be used for comprehensive lithological and geotechnical analyses.
- Supplementary box cores to ensure that recovery of the youngest sediments where piston coring of recent mass movements may disperse these sediments on impact.
- Seabed Cone Penetration Tests (CPT) used to geotechnically evaluate mass movement complexes. Geotechnical information calibrates seismostratigraphic units and increases the sophistication of the ground model in terms of its usefulness for conceptual foundation engineering studies.
It may be impossible to entirely preclude the potential for mass movement to occur at a seabed development; however, by using the tools above, and following the assessment procedure detailed in this paper, it may be possible to constrain such a hazard to the geological past, and significantly reduce the level of risk posed to the development during its engineering lifetime.

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References