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Seafloor instabilities and sediment deformation processes: The need for integrated, multi-disciplinary investigations

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ABSTRACT

In this paper, we present the current practice of investigations of seafloor instabilities and deformation processes, based on extensive research conducted over the last years, which sets the scene for future research activities in this field. The mapping of the continental margins and coastal areas with ever increasing resolution systematically reveals evidence of instabilities and deformation processes, both active and palaeo-features. In order to properly assess the hazards and risks related to these features, an integrated and multi-disciplinary approach is essential, but challenging. Such an approach consists of combining field data (geophysics, geology, sedimentology, geochemistry and geotechnical data) with numerical simulations constrained by results from laboratory data. As such, it is of paramount importance to build a common knowledge base and understanding that unify these disciplines into more complete and conceptual models constrained by all the data.

We review the status of this integrated approach adapted to palaeo-landslides (e.g., Storegga, Ana, Vesterålen) and recent deformations (Finneidfjord, Nice, Gulf of Guinea), allowing to identify gaps in our knowledge at these sites. By reviewing these case studies, one can conclude that each case remains highly site-specific in which both the regional and local geological–tectonic settings have a distinct effect of the type of instability or deformation taking place (or that can take place). Our knowledge on the actual triggers remains poorly constrained, and there is even ambiguity for historic landslides (e.g., Finneidfjord). Also our knowledge of the preconditioning factors is incomplete. There is a general lack of geotechnical data, both in situ and from laboratory, and therefore, modelling the dynamics (e.g., rheology) of the instabilities relies on a number of assumptions rather than facts. In addition, excess pore pressure and its evolution is one of the key parameters driving instabilities. Despite this fact, in situ (excess) pore pressure is rarely measured or monitored. Much work remains to be done to relate and integrate geotechnical data with geophysics, e.g., through inversion and rock physical models, in order to obtain additional quantitative information from the sub-surface, but also with respect to partial saturation (free gas, hydrate) and pore pressure behaviour, or lithologies.

It is of critical importance to be able to identify the different processes which can lead to hazardous situations which include establishing recurrence intervals (timing and frequencies, through event recognition and age control) and magnitudes, so that proper mitigation measures can be developed. In this perspective, the smaller-scale instabilities deserve much attention, as there are many instances where such features had far-reaching consequences for society (e.g., Nice, Finneidfjord). In that perspective, human interferences (e.g., exploitation, drilling, blasting, loading) must be one of the factors that should be taken into consideration.

1. Introduction

1.1. Outline of this paper

The structure of this manuscript is different from a typical journal paper. Following a general introduction to our current knowledge of submarine instabilities and deformation features (Fig. 1), we present the state-of-the-art with respect to data and analysis methods required for a multi-disciplinary investigation of offshore geohazards, including suggestions for improvements. A significant part of the paper discusses results from carefully selected but generally well-known case studies (for location of these sites, see Fig. 2), all the scene of extensive and longer-term research activities. In our selection criteria, we considered the type of sediment instability or deformation, its present or recent level of activity, our current knowledge about the controlling parameters as well as the variety of the data collected. None of these investigations is complete, and therefore, it allows for a gap analysis of our present-day knowledge of instabilities and deformation processes, shedding light on parameters or processes that are as of yet not well understood, are

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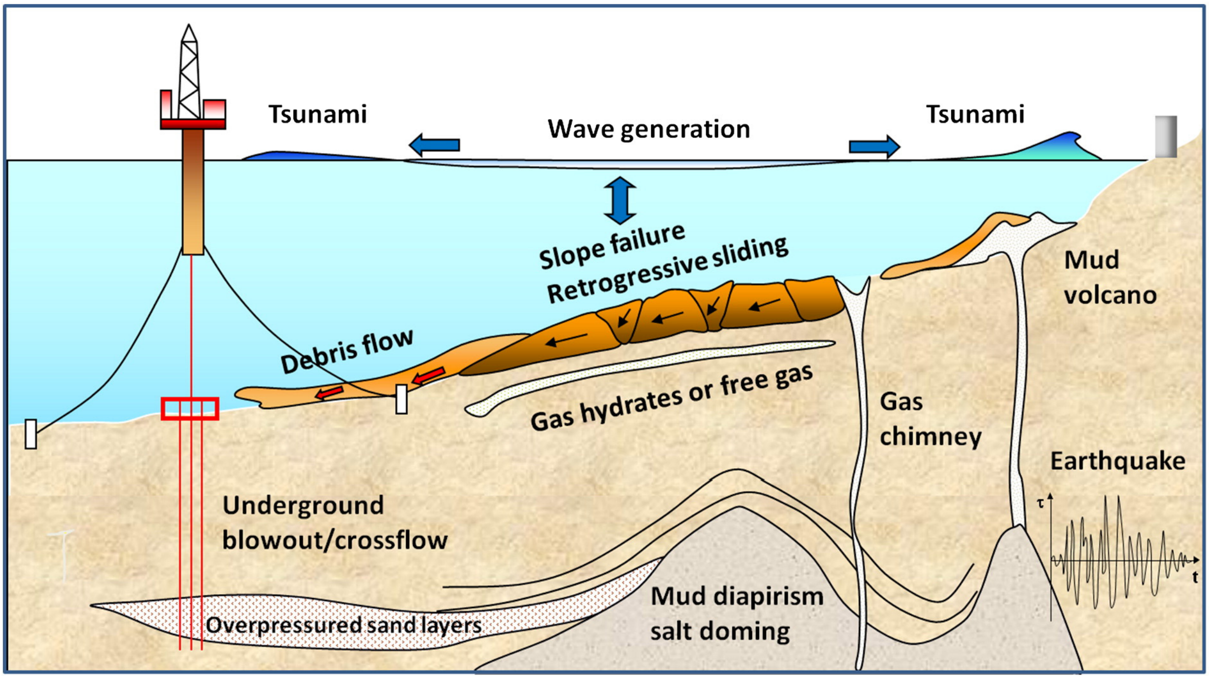

Fig. 1. Various geohazards may occur along the continental slopes. These include slope failures, impact of debris on infrastructure, dissociation of hydrates, shallow gas pockets, overpressure (shallow water flows), fluid escape features (gas chimneys, mud volcanoes), diapirism, and seismicity. Submarine slope failures can also generate highly destructive tsunamis.

difficult to quantify properly, or assess. As such, lessons learned from these sites should be used to improve the current practice in this field, from survey planning over data acquisition, defining suitable laboratory programmes, numerical simulations and – importantly – integration of the multi-disciplinary data set.

We do not present a complete overview of all these case studies, but rather their unique or specific character in terms of the investigations performed from the authors' involvement. As such, we have all inside information necessary to evaluate the cases, from data acquisition to the integration of the results, and it is our aim to do so in an objective and unbiased way. Ultimately, we put the information into a larger perspective, with recommendations for further research and development, with implications for site investigations, deep water engineering applications, in situ testing, and data integration.

Nevertheless, our case studies are not representative for all instabilities worldwide. We emphasize that investigations on instabilities will retain a site-specific character where all possible factors need to be addressed. A few examples of causative or preconditioning factors not addressed in this paper are permafrost and freeze–thaw cycles, large sediment input at deltas, large tidal fluctuations, static and cyclic liquefaction, or creep. Other types of instabilities, like rock falls, lie beyond the scope of this work.

1.2. Offshore geohazards

Geohazards are defined as *a geological condition which represents – or has the potential to develop further into – a situation leading to damage or uncontrolled risk*. Submarine landsliding is one of the most critical of offshore geohazards. Other examples include shallow sediment deformation phenomena (e.g., mud diapirism, gas chimneys, pockmarks, gas hydrates), but also shallow water flows, shallow gas accumulations, and seismicity (Fig. 1). Specific threats to society are the disappearance of valuable land near the shorelines, devastation of coastal areas by landslide-generated tsunamis and the destruction of seafloor installations (e.g., communication cables, pipelines, templates). Assessing and mitigating offshore geohazards also imply estimating of risks, where probabilities associated with the different scenarios are difficult to quantify (Vanneste et al., 2011a). This becomes of primary importance as exploration and field development has developed rapidly in areas where geohazards may pose a risk since the 1990s, considering that both natural causes and human interferences may provide the ultimate trigger for instability.

The results from large-scale national and international geosurvey efforts (e.g., *MAREANO*, Norway; *MaGIC*, Italy; *ZEE* project, Spain; *UNCLOS*, USA; *NEREIDA*, Canada) – in addition to the site surveying and reservoir imaging done by the offshore industry – to map the continental margins in ever increasing resolution, clearly indicate that recent mass movements with a variety of dimensions are common features on the seabed. More data were collected in the framework of dedicated slope stability investigation programmes, e.g., *COSTA*. In this paper, we discriminate between mass movements or slope instabilities on the one hand side and more local sediment deformation processes on the other side, as these phenomena may require different investigation methods due to their spatial extent. Having said this, all types of geohazard investigation imply the use of multiple disciplines across the geosciences, particularly geology, geophysics, geotechnics and geochemistry, but also numerical modelling/simulations and risk assessment.

1.3. Submarine landslides—Go with the flow

Submarine landslides occur worldwide in a large variety of geological–tectonic environments, for example open ocean settings on passive margins e.g., Grand Banks (Piper et al., 1999), Storegga (Bugge et al., 1988; Solheim et al., 2005a), Hinlopen-Yermak (Vanneste et al., 2006; Vanneste et al., 2011b), Big'95 (Lastras et al., 2004a), on active margins (Goldfinger et al., 2000; Cochonat et al., 2002), in volcanic areas and island flanks (Moore et al., 1989; Masson et al., 1998), but also in lakes (Bøe et al., 2004; Strasser et al., 2007; Vardy et al., 2010) and fjords (Longva et al., 2003; Levesque et al., 2006; L'Heureux, 2009; Vanneste et al., 2013). Most – if not all – of the submarine landslides develop in a common pattern, irrespective of the landslide type (slump, slide, debris flow, etc.) (Canals et al., 2004); nevertheless, from the pre-failure, failure to the post-failure stage, each deformation phase and

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