OGP

Geohazards from seafloor instability and mass flow

Report No. 425
December 2009

International Association of Oil & Gas Producers

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Acknowledgements

Draft written by Tore J. Kvalstad, Norwegian Geotechnical Institute.
Subsequently modified and completed by the OGP Offshore Structures Committe.

Abstract

Seafloor instability geohazards were first recognised in our industry in 1969 following Hurricane Camille. Since the 1990s, oil & gas exploration and field development has developed rapidly in offshore areas where geohazards may pose risks. The objective of this report is to give a possible systematic overview of a methodology applied to assess these risks, with focus on seabed instability and submarine mass flow effects such as may be found on the continental slopes and in ultra-deep waters worldwide. Other forms of geohazard such as anticline formations, active shallow faulting, salt and mud diapirs and mud volcanoes are encountered by the industry, with experience and knowledge of these phenomena increasing each year. The methodology of this report can be adapted and applied to a variety of offshore geohazards.

Oil & gas industry activities on the continental slopes and in ultra-deep waters tend to be concentrated in areas where the sediment thickness is high and where pore water overpressure may exist. The major differences compared with the continental shelf areas are the increased seabed inclination over extensive distances and the deepwater pressure and temperature conditions. Overpressured sediments and slope inclination lead to increased likelihood of instability at the seabed and at depth. Very large slide scars and mass flow deposits have been observed.

The assessment of geohazards required the integration of geotechnical and geological disciplines. Site characterization with respect to stratigraphy, shallow faulting, fluid pressure conditions, stress conditions and soil strength can be applied both for assessment of seabed stability and for well design.

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1 Introduction

Geohazard definition

ISO 17776 defines a hazard as a "potential source of harm". Geohazards in the context of offshore petroleum activities can thus be defined as local and/or regional site and soil conditions having a potential of developing into a failure event that could cause loss of life or damage to health, environment or assets. The event-triggering sources can be ongoing geological processes or human induced changes caused by the field operator or by 3rd party activities.

Large scale geological processes

Large scale geological processes are increasingly important to understand and incorporate in petroleum exploration, but also in geohazard evaluations. Plate tectonics and cyclic sea level changes of more than 100m caused by the major glaciations during the past 900,000 years control the development of continental shelves on a global basis and margins and thus many of the important factors relevant for offshore geohazard evaluations.

Regional geological conditions and processes

These control the sedimentation rate and thickness as well as the type of sediments. The major river deltas of the world (Ganges-Bramaputhra, Nile, Amazon, Mississippi, *etc*) and the glacial fans on the margins along the North Atlantic and Arctic Seas are areas where the average sedimentation rate during the last million years has been very high (Figure 1). Rapid deposition may lead to high excess pore fluid pressures (*ie* above hydrostatic pressure). This may result in underconsolidated soils with reduced shear strength, overpressured strata with potential for shallow water flow and generation of fluid escape features from deeper strata towards the seabed.

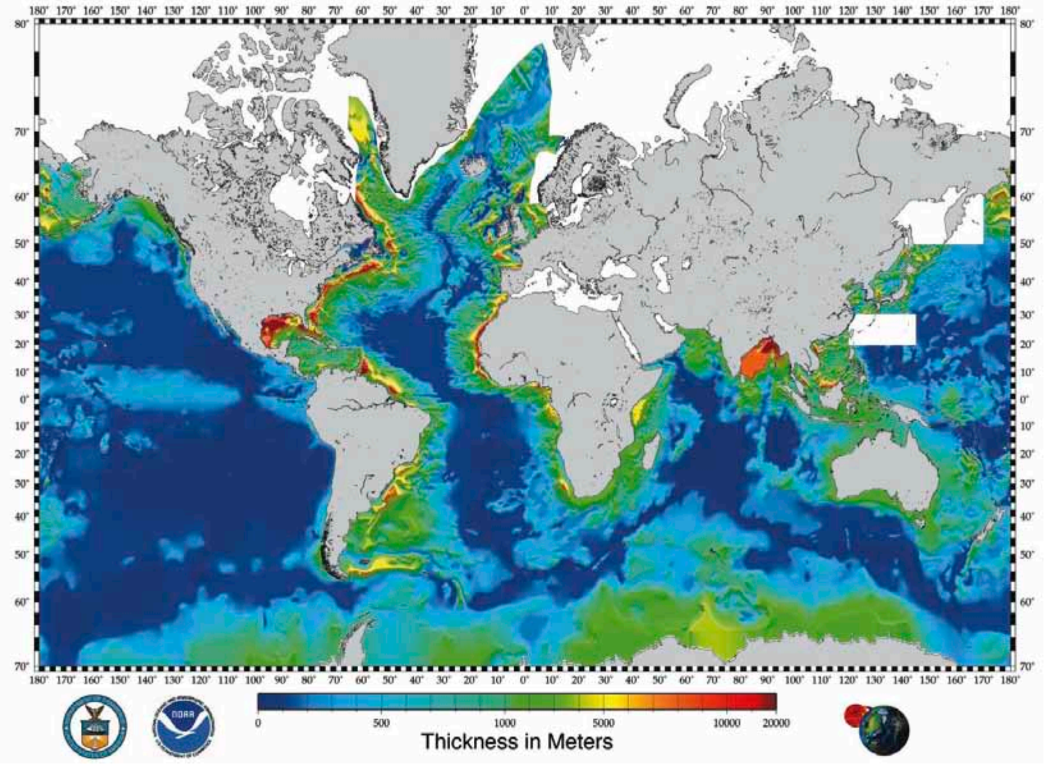


Figure 1 – Sediment thickness and oil reserves A) Total Sediment Thickness in the Oceans (Ref. Divins, NGDC)

Oil & gas activities

The major part of the offshore activity is located in the areas where the sediment thickness is high. Exploration and field development have since the 1990s developed rapidly on the continental slopes and in ultra deep waters world wide. The major changes compared with the continental shelves are the increased seabed inclination over extensive distances and the deep-water pressure and temperature conditions. Methane gas hydrate can exist below 300 to 500m water depth and represents a potential hazard related to sea bed instability, wells and foundation structures that is not yet fully understood.

Further, the oil & gas reservoirs in these areas are often related to anticlines and diapiric structures generated by the pressure difference between the weight of the thick shelf/upper slope sediment column and the continental rise/slope thinner sediment column. The seabed inclination is affected by the relatively slow and gradual deformation of these structures, often with active faults extending to seabed.

Seabed instabilities

Seabed instabilities ranging from smaller slumps to enormous retrogressive (back-stepping) underwater slides have been mapped as slide scars and mass transport deposits (MTDs) on slope inclinations less than 1 to 3° in glaciated margins and on the major river deltas. Several of the major events are of late glacial to Holocene age (*ie* less than 15,000 years old). The damage potential of such events ranges from local effects on pipelines and subsea structures to complete loss of all installations on one or several licences and ultimately to 3rd party losses related to slide induced generation of tsunamis.

Geohazard risk

Geohazard risk is the sum of the products of probability of geohazard failure events and damage consequence, and is an integral part of the total project risk. Geohazard risk should thus be treated according to existing regulations and international standards applying accepted risk analysis methodology. Geohazard events can generally not be treated on a statistical basis applying solely historical data. The nature of geohazards is site and time dependent, and assessment of failure probability and frequency should be based on geomechanical modelling taking into account the uncertainty in the modelling of site conditions, soil parameters, ongoing geological processes, loads and applied analysis methods. In this information paper an attempt has been made to give a systematic overview of the geohazard risk assessment components required for quantitative risk analysis based on NGI's project experience and ongoing research and development. Other methodologies have been proposed in the literature. Numerous reports and documents have been written on the formal methodologies that can be applied in risk assessment in general, and this will not be covered in any detail in this document.

2 Framework for risk assessment

2.1 Industry standards

In the Norwegian offshore sector, risk assessment should be conducted in accordance with NORSOK Standard Z-013, *Risk and Emergency Preparedness Analysis* (http://www.standard.no/pagefiles/955/Z-013.pdf). The main tasks of a risk analysis according to this code are shown in Figure 1.1. The ISO 17776:2000E (ISO, 2000) standard and API RP 14J (API, 2001b) also provides description of the principal tools and techniques that are commonly used for the identification and assessment associated with offshore oil & gas production installations. The NORSOK standard presents requirements to planning, execution and use of risk analyses associated with exploration drilling, exploitation, production and transport of petroleum resources as well as all installations and vessels that take part in the activity. The standard does not specifically address risk analysis related to site specific geohazards. The scope of each main task illustrated in Figure 3, will in a geohazard context have to be defined for each specific project.

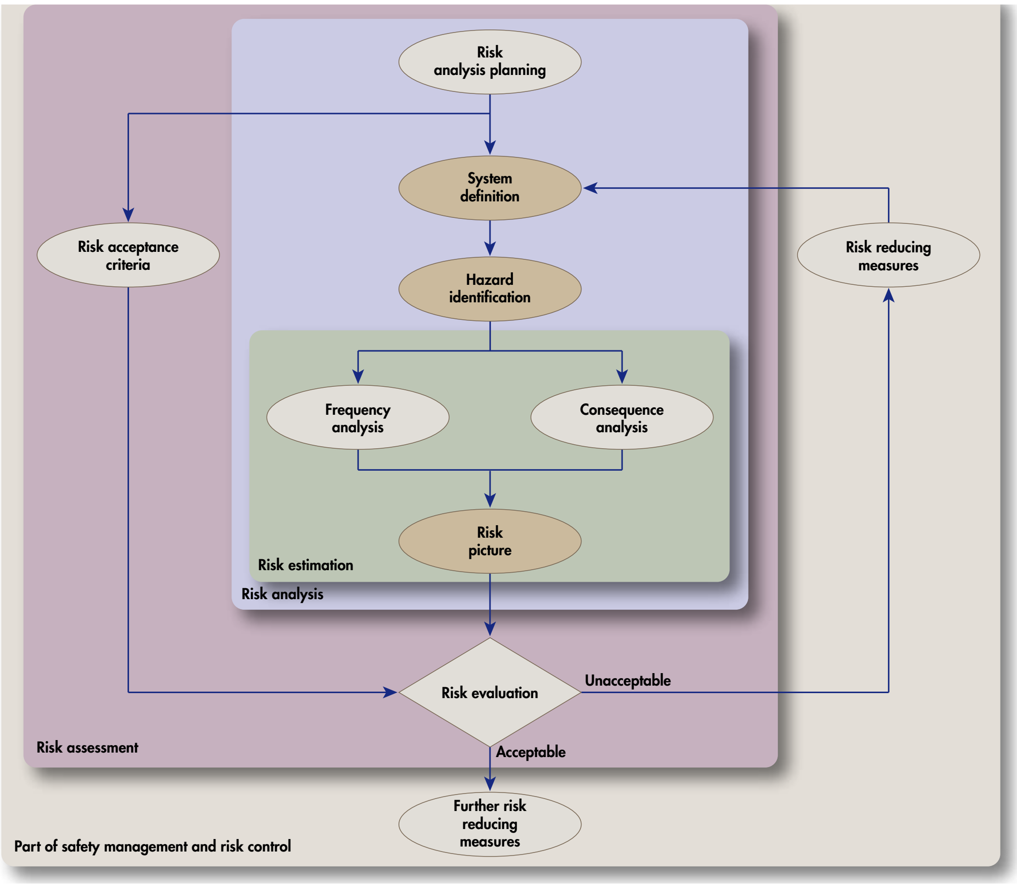


Figure 3 – Risk analysis framework (after NORSOK Z-013)

2.2 Geohazard risk assessment work tasks

Assessment of geohazard risk usually requires the following steps, which can be used as a guide for geohazard risk assessment:

a) System definition. The areal extent of a geohazard system needs to cover the field installations and pipeline corridor areas with surrounding areas potentially influenced by field development and production activities. In addition, the influence zone of natural hazards needs to be evaluated. On the continental slopes the system might need to be extended to include large areas upslope and/or downslope of the field installations. In case of tsunami hazards, even the surrounding coastlines needs to be included. In the vertical direction, the geohazard system should cover soil and pore pressure conditions that might have a significant influence on the stability of seabed, foundations and wells.

b) Hazard identification (HAZID). The HAZID describes potential failure scenarios that may affect human life, environment and assets caused by relevant triggering sources and possible damage or consequence. The HAZID should be performed by an experienced interdisciplinary group composed of experienced geologists/geophysicists, geotechnical engineers, and all other relevant engineering specialists dependent on the types of hazards and consequences involved.

c) Risk estimation. The failure scenarios identified in the HAZID can be considered as systems of geomechanical failure modes, triggering sources (initiating events) and related failure consequences. Quantitative risk analysis (QRA) requires estimates of the frequency (typically as annual probability) of occurrence of triggered events and assessment of the associated consequences.

The resulting geohazard risk estimate will then be included in the overall project risk estimate and be compared with established risk acceptance criteria typically as F-N curves relating the frequency (F) or annual probability of loss which could be expressed as number of fatalities (N), economic or environmental. Establishment of the risk acceptance criteria is the responsibility of the field operator. Typically the acceptance criteria are classified according to consequences for people, assets, and environment. An example of a workflow diagram showing the main work task of a geohazard risk assessment study is shown in Figure 4.

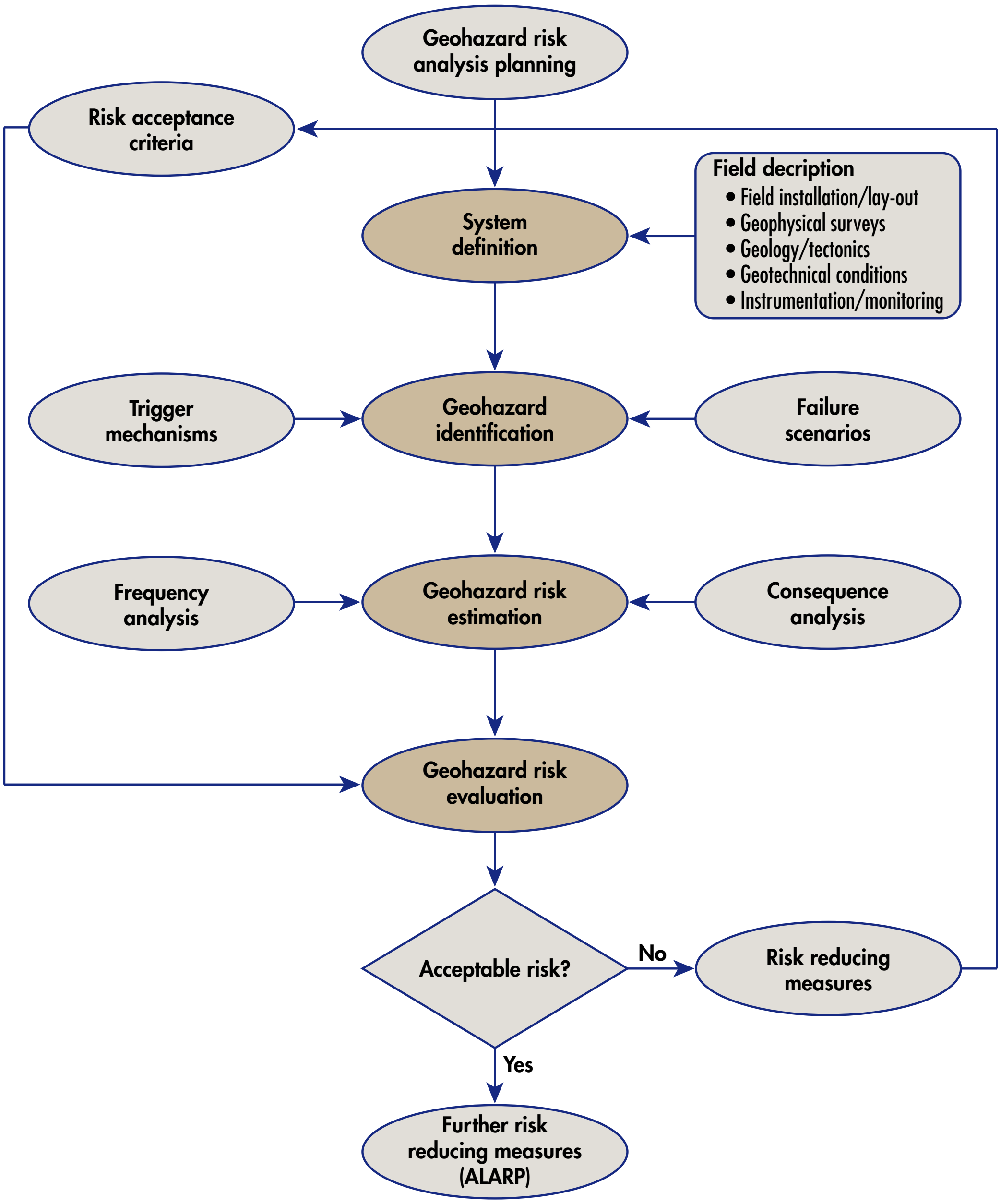
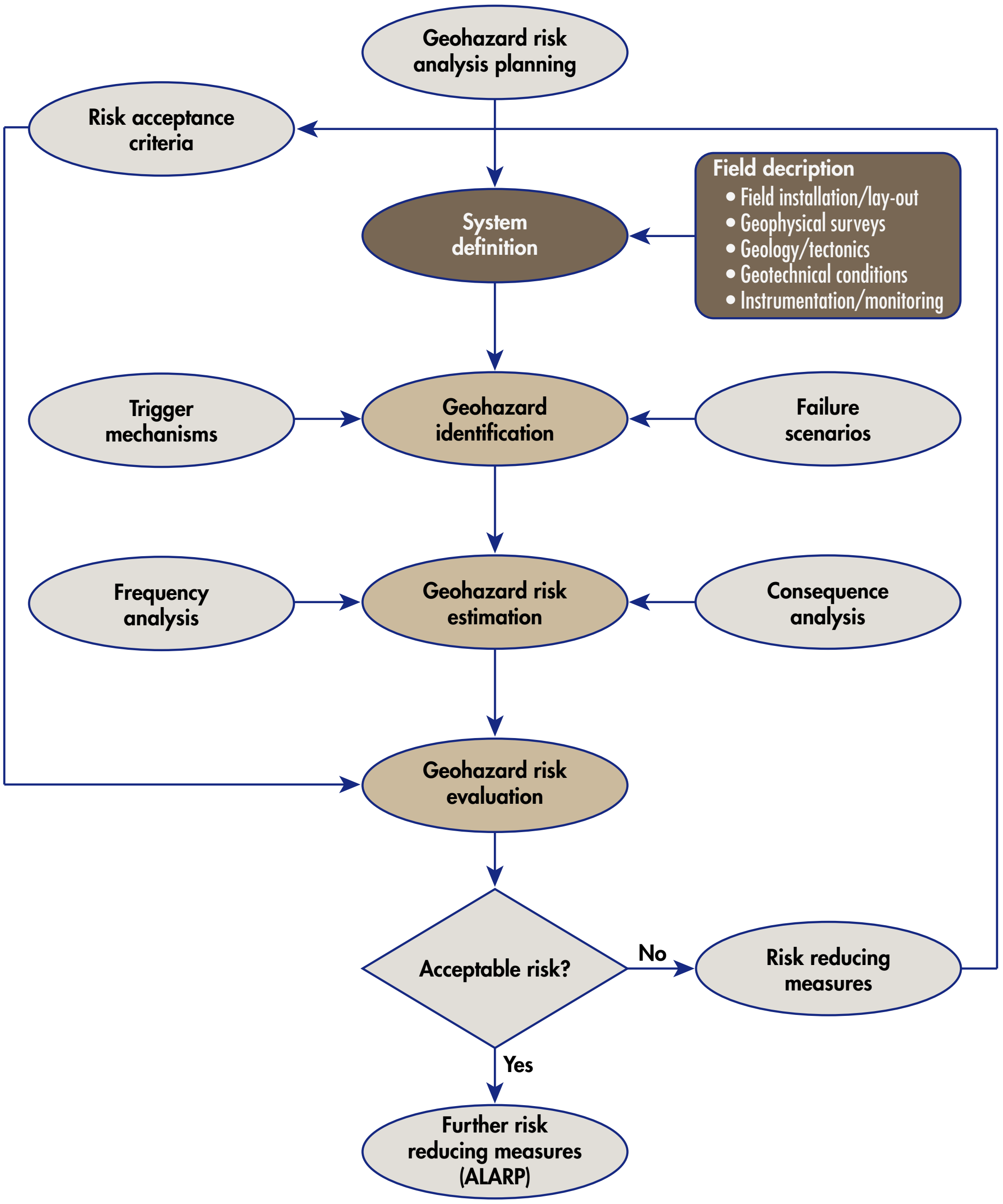


Figure 4 – Example of a geohazard risk analysis framework

3 System definition



3.1 Components of the system

A geohazard risk system may include the following:

a) local and regional geological and geotechnical site conditions (*ie* the presently existing geomechanical system)

b) ongoing local and regional geological processes and human activities that may change these conditions from a stable or labile situation into an unstable situation (*ie* the triggering of geohazard events)

c) location, extent and vulnerability of values (human life, environment and facilities) that potentially could be exposed to geohazard events either directly or by an escalation of the event.

The system definition in the early phases of a study may be based on limited information. Gathering of existing local and regional background information about geography, geology, tectonics and historic hazard information from published literature, local authorities and institutions should be combined with information from previous investigations and projects in the area (Figure 5a).

Existing background information

Geological setting

Geographical location, maps
Global bathymetry (ETOPO2, etc.)
Sediment thickness maps
Active or passive plate boundaries and hotspots
Glacial or river fed margin
Submarine canyon systems
Salt sheets/diapirs, clay diapirs, mud volcanoes
Volcano catalogue
Slide database

Historic hazard information

Earthquake catalogue
Tsunami catalogue
Changes in rivers and deltas, human influence

Previous investigations

Neighbour projects
Research projects, DSDP/ODP/IODP, EU projects

Geotechnical contractors/operator, geotechnical databases

Figure 5a – Example of data collection for definition of system properties

This may be combined with data from the project specific investigations, during exploration and field development planning, covering geophysical data, logs from exploration wells, seismic hazard assessment, geotechnical/geological boreholes for ground truthing and assessment of soil parameters as well as plans for production wells and field lay-out (Figure 5b).

Project input information

Geophysical input

Swath bathymetry
SBP and SSS data
3D seismic data
2D UHR seismic data
EM waves
Shear waves

Exploration drilling & sampling

Drilling logs

Well logs

Seismic hazard assessment

PGA vs. recurrence period
Recommended time histories

Geotechnical field investigation

Drilling & sampling quality, disturbance
In-situ testing, CPT, vane, piezopr.
In-situ piezometers
Borehole logging

Geotechnical laboratory testing

Classification testing
Compaction and permeability
Soil strength, triax/DSS/ring shear intact & remoulded

Geological testing

Minerology
Age determination

Production wells and field layout

Well design
Subsea structures and foundations
Infield and export pipelines
Platform foundations and risers

Figure 5b – Example of data collection for definition of system properties

This information can then be evaluated and further processed to quantitative geological, geomorphological and geotechnical models of the system from seabed to reservoir depth. In this way seabed and sub-seabed features, ongoing geological processes and soil conditions that may influence the stability of wells, seabed and foundations can be mapped and quantified (Figure 6). The interpretations require tools and methodologies ranging from seismic processing systems to geotechnical finite element analysis of compaction and pore pressure conditions. The amount of data increases during project development and require effective visualisation tools.

The interpretation and evaluation of available data will inherently include uncertainties which are dependent on the penetration depth of the investigation tools and the density and resolution of the sampled data as well as positioning accuracy.

Data interpretation and evaluation

Seabed and seabed features

Gradients/slope inclination
Slide scars, slumps, depris flows
Protruding mud volcanoes and salt diapirs
Pock marks, fluid esc. features
Debris, wrecks, hard-ground, corals

Subsurface features

Subsurface channels
Deep faults
Palaeo slides
Debris flows
Sand layers/pockets, potential SWF zones
Shallow gas
Salt diapirs
Gas hydrates

Geological models

Stratigraphic model
Chronostratigraphy

Reservoir models

Reservoir compaction model

Geotechnical models

Sediment compaction model
Excess pore pressure distribution
Effective stress distribution
Site response model
Strength model for slope instability
Strength model for foundation design
Strength model for conductors/casings

Figure 6 – Example of system definition: interpretation of collected data

3.2 Bathymetry and seabed features

Global or large scale maps may give a first impression of the location relative to major geographic/geological features like major rivers and their drainage area, deltas and deep-sea fans, extension of continental shelves and slopes. In frontier areas there is normally a lack of detailed bathymetric data. The publicly available databases ETOPO2 with a 2' grid (Smith and Sandwell, 1994) and GEBCO with a 1' grid (GEBCO, 2003) are based on satellite altimetry data calibrated against ship track bathymetry, and can be used for plotting maps for selected areas in an early phase of a project.

3D seismic surveys can provide substantially improved details of the local bathymetry within the surveyed area. Today's bathymetric surveys are normally carried out as swath bathymetry using multi-beam echosounder systems, mounted on ships. The accuracy decreases with increasing water depth due to beam spreading and increased footprint. However multi-beam echosounders mounted on underwater vehicles (towed or autonomous) may deliver nearly photo sharp information about the seabed bathymetry in deep water areas (Figures 7a & 7b). Experience from recent and ongoing geohazard studies show that detailed bathymetric mapping of the investigated system is invalu-

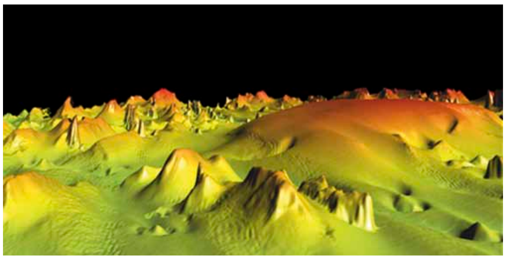


Figure 7a – Detailed AUV multibeam bathymetry in the Storegga Slide area showing the gradual infill of marine clay between and over the slide debris from the Storegga Slide (from Norsk Hydro)

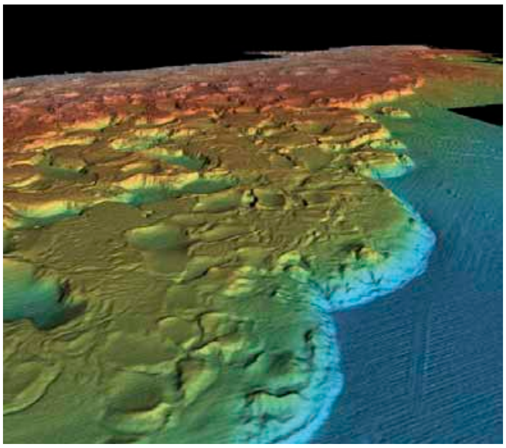


Figure 7b – The Sigsbee Escarpment and the uneven terrain behind formed by salt diapirism in the Gulf Of Mexico (from NGDC/NOAA)

able in the evaluation of the geohazard risk and for the planning of risk analysis and site investigations. Autonomous underwater vehicles (AUVs) can now operate to 4500m water depth (Kongsberg, 2006). See also George et al. (2002) for a detailed description of the AUV surveys for Atlantis and Mad Dog fields at the Sigsbee escarpment in the GOM.

Side scan sonar (SSS) surveys provide information about seafloor morphology and reflectivity (backscatter), and are useful for identification of seabed hard ground, pock marks and active gas seeps, as well as debris like ship wrecks, lost fishing gear, anchor cables, drill pipe, *etc*.

3.3 Seismic profiling.

Towed streamer seismic surveys may give a good penetration depth and cover large areas effectively. However the vertical resolution is a function of the seismic wave length. Typically a 3D survey for exploration purposes may have a penetration depth of about 5km and resolution of about 12m in the upper hundred meters of sediments, while an ultra high resolution (UHR) 2D survey may penetrate less than 1000m and have a vertical resolution of about 4 to 5m. This will allow identification of larger features and slide areas as well high amplitude reflections (bright spots) indicating free gas. However, smaller slumps, slides, pockmarks and seeps that may represent a hazard for subsea structures and pipelines may not be identified clearly. Bottom towed autonomous underwater vehicles (AUV) for ultra-ultrahigh resolution have a restricted penetration ability and may possibly penetrate 50 to 100m below seabed, but have vertical resolution of about 0.5m. A comparison of resolution is shown in Figure 8.

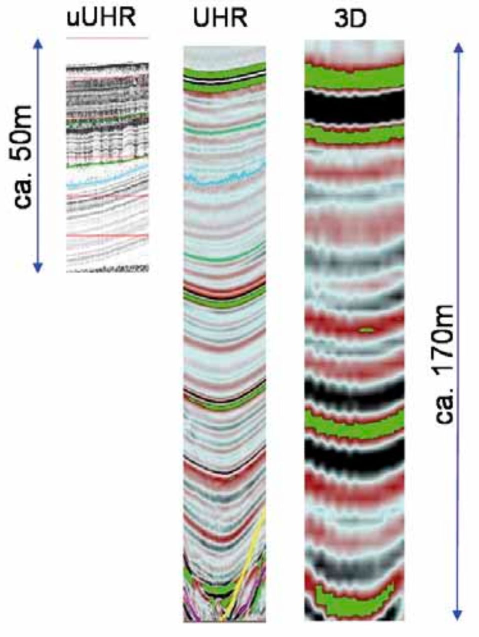


Figure 8 – Comparison of resolution

Seismic profiling allows identification of palaeo slide activity. Buried MTDs and slide scars show the preferred glide planes and dating of the infill sediments on top of the MTDs may reveal cyclicity of slide activity that could be related to sea level and climate variations. The very rough surface of slide debris blocks will lead to large variations in the local deposition rate as the unevenness of the debris is gradually levelled out. This may cause differential compaction leading to local "cracking" of the surface, shallow faulting and considerable variation in the seabed gradient in the cover materials.

Salt and mud diapirs, mud volcanoes, deep-seated faults and faults to the surface can be identified. Combined with dating of the major seismic horizons the displacement rate of active faults can be estimated.

Gassy soils

Gassy soils will have a low compression modulus and tend to absorb the wave energy from compression waves (P-waves). This leads to gas blanking on the seismic profiles and makes the identification of seismic horizons difficult. Shear waves are not affected significantly by free gas, and the use of seismic shear waves is a possible way to overcome gas blanking. Shear wave generators have been developed and it is expected that equipment and techniques for a more streamlined application of shear wave seismics will develop during the next few years.

Gas hydrates (GH)

Gas hydrates are ice-like crystals of gas molecules encaged in an ice crystal structure of water molecules. Gas hydrates are stable above a certain pressure and below a certain temperature. Methane, CH_4, is the most common natural gas in sediments and thus the most common hydrate former, but other natural gases like CO_2 and higher order alkanes like ethane and butane may also form hydrates. Figure 9 shows a stability diagram for methane hydrate at a water depth of 1000m. The green curve is the phase shift line between stable hydrate and dissociated hydrate = water and methane. The purple line is the temperature distribution vs. depth below seabed with a seawater temperature of 2°C at seabed and with a geothermal gradient of 5°C/100m. This gives a hydrate stability zone down to about 245m below seabed. The red line shows a temperature distribution typical for the Mediterranean, with sea bed temperature of about 14°C. In this case the temperature is too high to form methane hydrate at 1000 m water depth.

At the base of the gas hydrate stability zone (GHSZ) free gas may form when methane hydrate dissociates. As the depth of the base of the GHSZ depends on the pore water pressure and temperature, the base of the GHSZ can be seen as a reflector following the variations of the seabed, but diving deeper with increasing water depth. This reflector is called a Bottom Simulating Reflector (BSR) and can be an indicator of gas hydrate in the sediments above the BSR. However, a BSR is not a proof that GH exist. GH in sufficient concentration may partly cement the sediments, and this may affect the P-wave and S-wave velocity. Attempts have been made to quantify the GH saturation level based on observed velocity changes, however the uncertainty is considered to be considerable, and direct measurement by sampling is recommended.

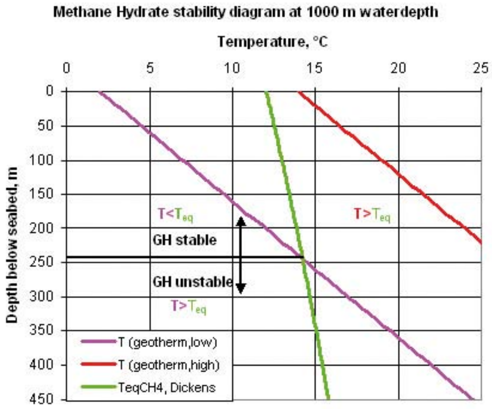


Figure 9 – Example of methane gas hydrate stability diagram in 1000m water depth and for two different temperature distributions

3.4 Geotechnical/geological site investigations

General advice for planning and execution of offshore and nearshore soil investigations for foundation design of platforms, anchors foundations have been developed (ISSMGE, 2005, Fugro NV (2001). The focus of geohazard soil investigations should be directed towards providing data that can help to explain observed instabilities and anomalies and be used in a quantitative assessment of the geohazard risk of the present situation and how it is influenced by field development activities. The seismic stratigraphy is based on interpretation of P- (and S-) waves and will in a new area be affected by uncertainty with respect to nature and properties of the different strata. In order to reduce the uncertainty and to assess quantitatively the properties of the strata, soil sampling and testing are required. Geotechnical/geological coring from seabed can cover the upper 5 to 30m and in situ tests like field vane and cone penetration tests may reach depths of 50m in soft soils. Drilling of boreholes from specially equipped vessels allows soil samples to be taken and downhole field testing like cone penetration tests (CPTs) and field vane tests to be carried out. The limiting water depth of commercial geotechnical drilling vessels is presently at 3000 m. The borehole depth may vary from a few tens of meters to several hundred meters dependent on the identified objective, but also on the vessel's equipment. Soil samples are tested for classification and geological interpretation. Simple classification and index tests will provide density, porosity and grain size distribution. More advanced laboratory tests are required for parameters like preconsolidation stress, compressibility and permeability as well as information about the soil stiffness, peak and residual/remoulded strength parameters. Wire line logging of the boreholes will cover gaps in the field tests and sampling records and provide a more continuous set of data.

In areas where there is uncertainty connected to the pore pressure conditions and excess pore pressure might be expected, field test may be performed under the correct in situ stress conditions, while reconsolidated laboratory test may be carried out at too high stress levels based on measured unit weights and water contents and assuming hydrostatic conditions.

Pore water salinity

Pore water salinity and clay mineralogy may influence material behaviour considerably and should be included in the laboratory test program. It is thus important that laboratory testing is performed under controlled salinity conditions. Freshwater smectites have a very low residual friction angle and high porosity and are not representative for smectites with normal seawater salinity.

Temperature distribution

In areas where gas hydrate may exist, measurement of temperature distribution vs. depth, *ie* water temperature at seabed level and the thermal gradient, is required for assessment of the hydrate stability zone and potential effects of heat flow from wells and flowlines/pipelines. Determination of thermal properties of the sediments might be required.

Pressure coring

Pressure coring is required to preserve samples containing gas hydrate. This is not standard for geotechnical site investigations. Equipment has been developed in connection with the ODP/IODP scientific investigations of gas hydrate locations like Blake Ridge and the Hydrate Ridge. However, monitoring of sample temperature immediately after sampling and chlorinity distribution of the pore water may give a good indication. If gas hydrate is present, considerable sample cracking and disturbance due to gas expansion and uneven water content distribution should also be expected when the samples undergo pressure relief of more than 30 bar.

Age determination

In areas with rapid sedimentation high pore pressures may develop. Analyses for prediction of pore pressure and effective stress conditions require quantitative data on sediment accumulation rate. The most important time period to consider in this connection is the Quaternary, *ie* the past 1.8 million years. This is a period with fluctuating sea levels caused by the repeated waxing and waning of northern hemisphere glaciers in conjunction with climatic cyclicity. The most important methods within this time frame are:

- Historical sources for the past ~3,500 years.
- 14C, radiocarbon dating for the period 300 to about 50,000 years BP.
- Amino acid ratios in fossils. The technique can be used in fossiliferous sediments from a few thousand to about 400,000 years old.
- Optically stimulated luminescence (OSL) dating is a method of determining how long ago minerals like quarts and feldspar were last exposed to daylight. Ages can be determined typically from a few hundred years to more than 100,000 years and possibly towards 400,000 years. The accuracy obtainable under optimum conditions is about 5%.
- Correlation to well dated standard records such as the marine oxygen isotope record or the palaeo-magnetic time scale. These correlation methods rely on almost continuous sediment recovery and can be used from very young records to ones a few hundred million years old.

Pore pressure measurements

It is important to know the in situ pore pressure conditions for assessment of slide risk and sea bed stability and also for planning and execution of laboratory test programs. Direct measurement of the pore fluid pressure is possible with different kinds of piezometer devices. However, the disturbance caused by inserting the piezometer device into the soil generates a change in pore pressure conditions. In fine grained soils typical for deepwater offshore conditions, dissipation of the disturbance takes time dependent on the size of the disturbed zone and specially designed thin piezoprobes have been developed to reduce the time required for dissipation. Still, more than 6 hours – and often considerably longer times – are required to get reliable measurements of the in situ pore pressure.

The hourly cost of a geotechnical drilling vessel is high and alternative solutions with push in piezometers and piezometers installed in boreholes were applied in the Ormen Lange project (Strout and Tjelta, 2005).

Recently multilevel piezometers have been developed (Figure 10). These instruments are equipped with data loggers that can record pressure over long time and dissipation time is thus not a problem. The data loggers can be picked up by ROVs in a later survey of the area. Further, these instruments use differential pressure transducers which improve the resolution and accuracy in deep water conditions considerably.

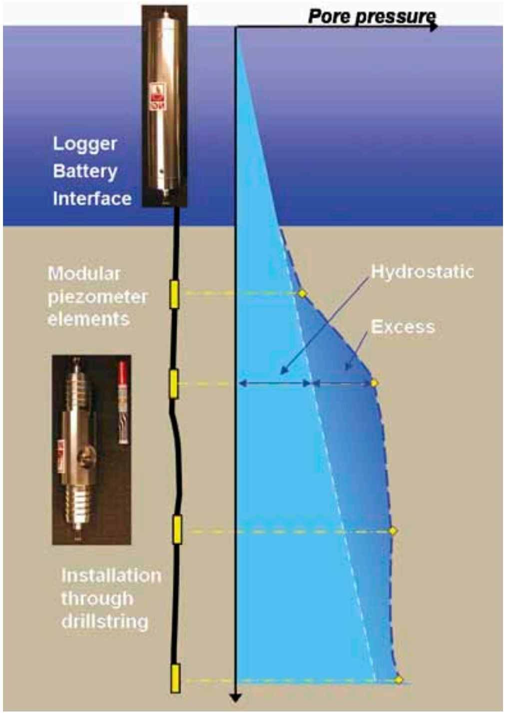


Figure 10 – Multilevel piezometer concept

Residual and remoulded strength

The observed large scale slide events on glacial margins and in river deltas on slope angles less than 3° can only be explained by progressive and retrogressive failure models combined with excess pore pressure. Marine, hemipelagic clays, are strain-softening materials (Figure 11), which may lose a considerable part of the peak undrained shear strength when exposed to large shear strains; so called sensitive clays. The remolded strength can be as low as ⅙ to ⅓ of the peak strength and is a central parameter in progressive and retrogressive slide processes. The loss in strength is caused by increased pore pressure due to reorientation of mineral structure towards a denser configuration (contractive behaviour).

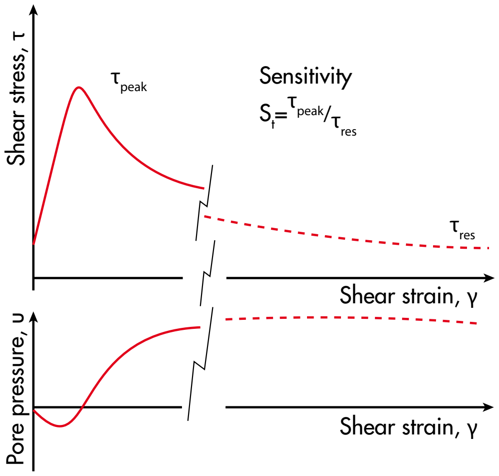


Figure 11 – Stress-strain and pore pressure vs. shear strain showing strain-softening behaviour of marine clay subjected to shear straining.

The remoulded strength is considered to be a lower bound value of the undrained strength, and a sufficient number of tests should be carried out to define this strength parameter. Sleeve friction, fs, from CPTs (or a fraction of about ⅔ of fs) and remoulded field vane test data may be considered as well. However, sleeve friction may produce uncertain results and should be used cautiously and is generally not the preferred method. Also the remoulded strength should be normalised vs. overburden stress.

Integration of seismic stratigraphy and geotechnical/geological borehole profiles

Boreholes are 1D and must be tied to the seismic stratigraphy from 2D and 3D surveys. Tie-lines between geotechnical boreholes and exploration wells are required for extrapolation of geotechnical/geological information from boreholes to the surrounding area, alternatively the boreholes should be placed at crossing points of seismic lines. Still information about sediment properties such as P-wave velocity, is needed for proper correlation, since seismic data are recorded in time and not in true depth in meters. Generation of synthetic seismograms is an important tool in seismic-borehole correlations.

Normalisation of soil parameters

As the elevation and thickness of the identified strata may vary considerably over the area investigated, normalisation of soil parameters is normally required to enable extrapolation of information from boreholes to the overall area. Effective overburden stress has a significant influence on compression behaviour, permeability and strength of soils and is the preferred normalisation parameter. In areas where the sediments have been unloaded due to loss of overburden, *ie* the sediments are overconsolidated, the overconsolidation ratio should be added as a second normalisation parameter (SHANSEP approach, Ladd and Foott, 1974). Normalisation of deformation and strength parameters will also enable a statistical treatment of data over large area and overburden depths.

Strength anistropy

Strength anisotropy is an important factor in analysis of slope stability. The compressive undrained strength is generally higher than the direct simple shear strength and the extension strength is even lower. The anisotropy seems to be higher for low plasticity clays than for highly plasticity clays.

Stress dependency

Stress dependency should be evaluated and included in the evaluation of strength parameters. At shallow depth, i.e. low consolidation stress, the normalised strength is higher than at greater depths below seabed.

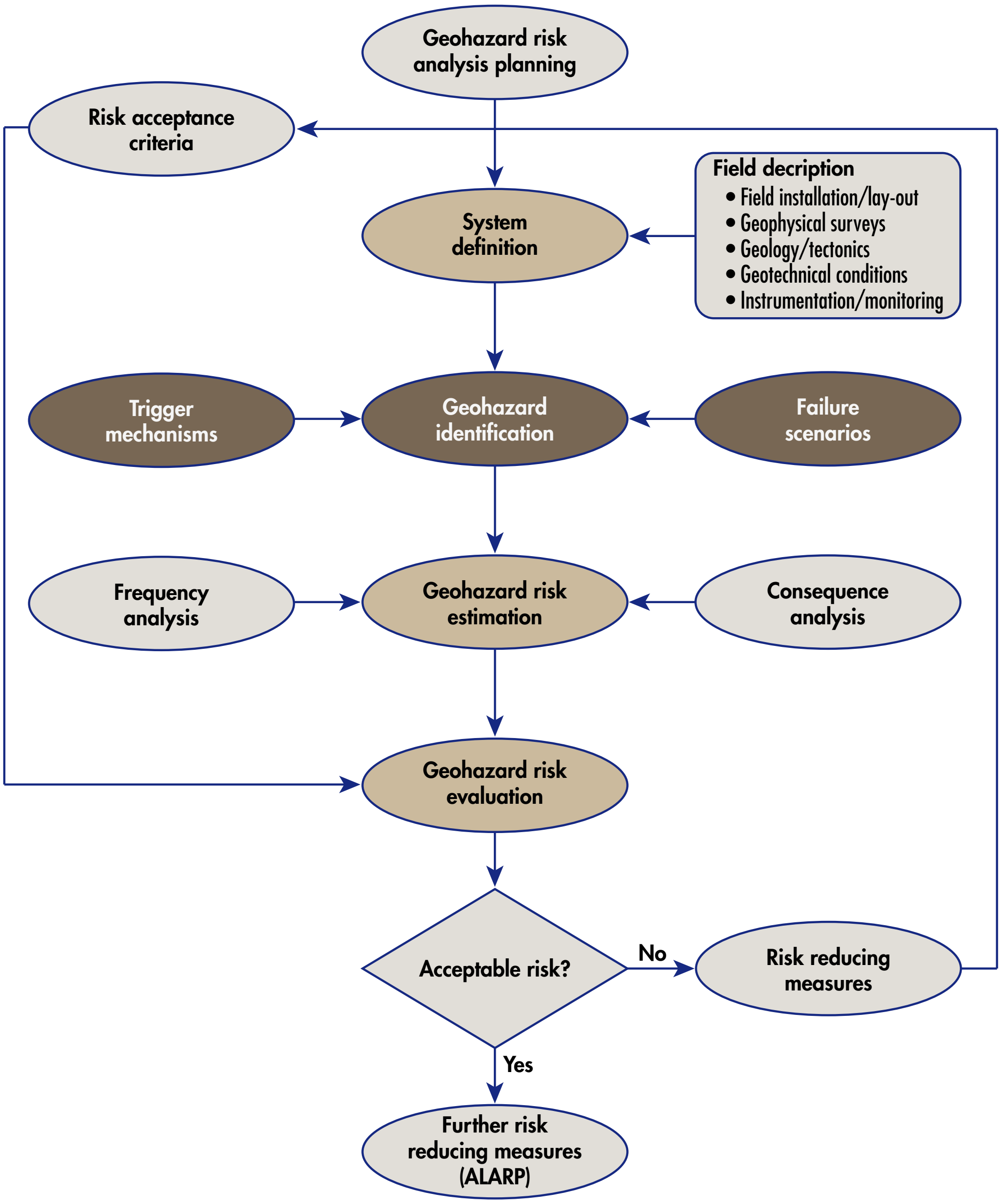
Strain rate effects

Strain rate effects have a significant influence on undrained strength and should be accounted for. The difference between the applied strain rate in laboratory tests (a few percent per hour) and the strain rates in situ under nearly static loading conditions and under wave loading and earthquake loading varies considerably.

Comparison with available databases

Soil investigations in connection with geohazard assessment will often have to cover extensive areas. To reduce the uncertainty, it is recommended to compare normalised stiffness and strength data with available soil databases. This also applies to classification and index data in order to identify anomalous material types and stress conditions.

4 Geohazard identification – HAZID



4.1 General

The identification of geohazards will require an evaluation of existing site conditions and assessment of the present or planned situation with respect to local and regional seabed stability and stability of wells, subsea structures, pipelines and platform foundations/anchor. The HAZID is a systematic search for natural and human-induced processes and activities, i.e. triggering sources, which have a potential for transforming stable conditions to unstable conditions with harmful consequences (Figure 12). An expert team of experienced geologist, geophysicist, geomorphologist and geotechnical engineers with ability to communicate across discipline borders is thus required to identify relevant failure scenarios and associated triggering mechanisms. The HAZID team should be assisted by drilling and/or facilities engineers and guided by a risk analysis expert in order to systemize and rank the scenarios and triggers in a way that allows QRA to be performed.

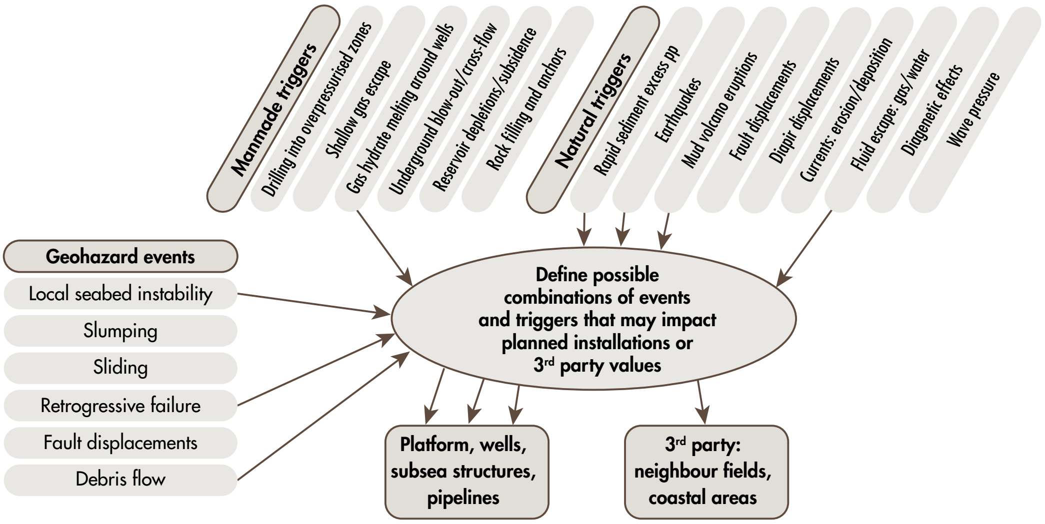


Figure 12 – Failure Scenario Identification through Systematic Combination of Geohazard Events and Triggers that may affect Installations or 3rd Party Assets.

4.2 Failure scenarios

Geohazard failure scenarios are basically envisions of potential geomechanical failure modes that may involve or affect field installations or 3rd party assets based on the available information and the knowledge, experience and intuition of the HAZID team. Geomechanical modelling of the failure scenarios is required to evaluate the likelihood of occurrence and criticality in order to rank the different failure scenarios.

Local seabed instability

This category of failure scenarios are related to unacceptably large displacements causing damage or production restrictions to equipment installed on or into the seabed soils; typically reduction of vertical, lateral or rotational bearing capacity of mat supports, piles, wells or pipelines/flowlines.

Local seabed deformations under or towards installations may occur due to changes in

- Bathymetry and seabed gradients (sedimentation, erosion)
- Pore pressure conditions/fluid flow
- Soil strength - softening under straining and cyclic loading
- Generation of fluid/gas flow under or close to foundations
- Temperature increase around wells, manifold structures and pipelines causing gas hydrate melting followed by gas bubble expansion, fracturing and free water that will reduce the shear strength of the soil (Figure 13).
- Cratering caused by blow-outs/uncontrolled gas and shallow water flow

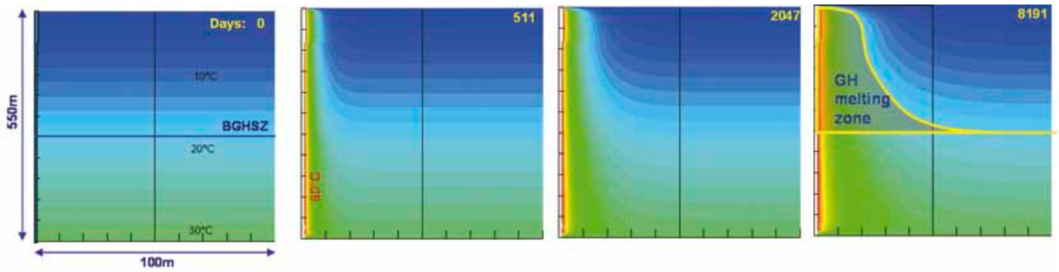
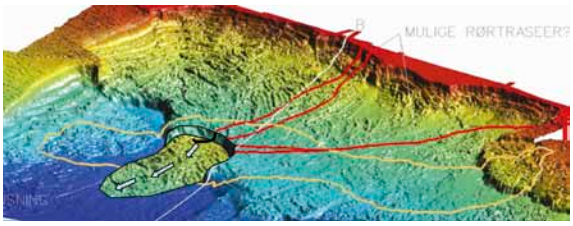


Figure 13 – Heat flow simulation around 4-well cluster at 80°C showing the increase in temperature and the potential zone of methane gas hydrate dissociation from production start to 22.5 years (8191 days).

Mass transport initiated within field development area

This category comprises slumping and local sliding that affects installations either as loss of foundation area or as debris impact. Areas with increased gradient, caused by submarine channels, uneven deposition or erosion, escarpments from previous slide events and active faulting, are more critical than the surrounding areas. Sea bed instability can be initiated by gradual over-steepening or by other triggers like earthquakes and human induced changes in pore pressure and loading conditions like heavy subsea installations, rockfill supports and trenching for pipelines and anchor forces (Figure 14). Sensitive clays may lead to progressive failure and development of long compression zones in the toe area and tendencies to retrogression behind the crest.



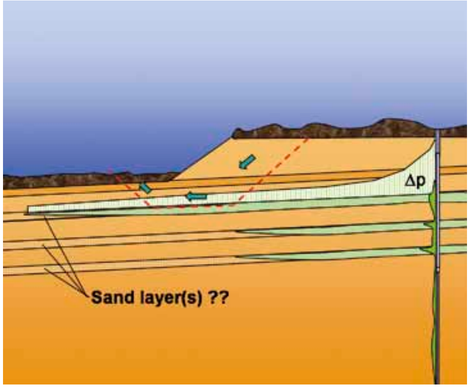


Figure 14 – Ormen Lange field failure scenario: large scale failure of lower headwall of the Storegga slide caused by crossflow into possible sand layer causing total loss of subsea installations and wells.

Mass transport into field development area

In areas with long continuous slopes, the run out distance of submarine slides can be very long. Upslope slide events may develop to debris flows (Figure 15) or generate extensive compression zones. When running into or crossing over parts of a field development area or pipeline corridor there is a high potential for damage to structures and pipelines and total or partial burial of equipment. These slides can be triggered by wave pressure in the shelf edge area, earthquakes, over-steepening from deposition, erosion faulting and human activities in licenses located upslope.

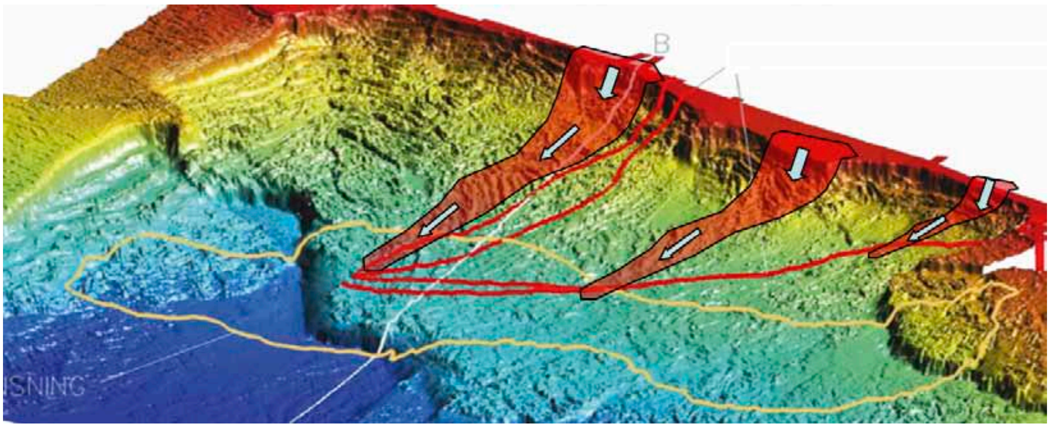


Figure 15 – Ormen Lange field failure scenario: failure of upper headwall of the Storegga slide hitting pipelines and field installations.

Retrogressive sliding events

Retrogressive slides may escalate to enormous slide events. These slides may be triggered as a smaller slide event in the lower part of a delta or continental slope. Progressive failure combined with high mobility of the debris may generate retrogressive (back-stepping) processes over tens of kilometres. These slides have also a tendency to spread laterally as can be observed in the Storegga slide area (Figure 16).

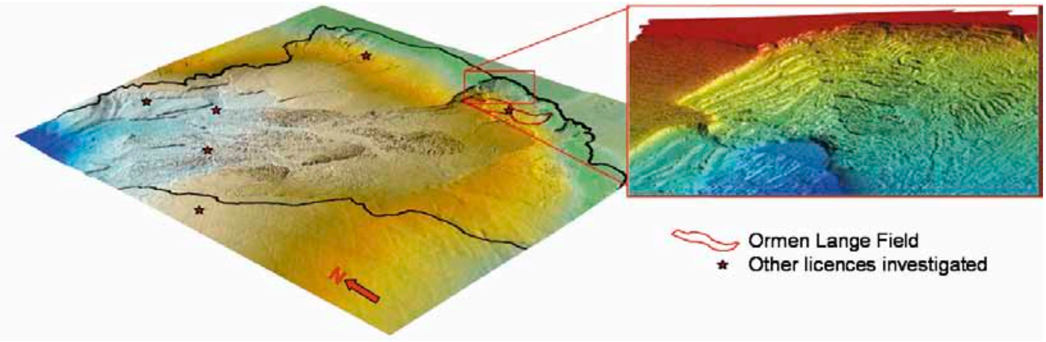


Figure 16 – Storegga slide scar with the Ormen Lange gas field and locations of other investigated licences.

4.3 HAZID team objective:

The HAZID team should ask and answer the following questions:

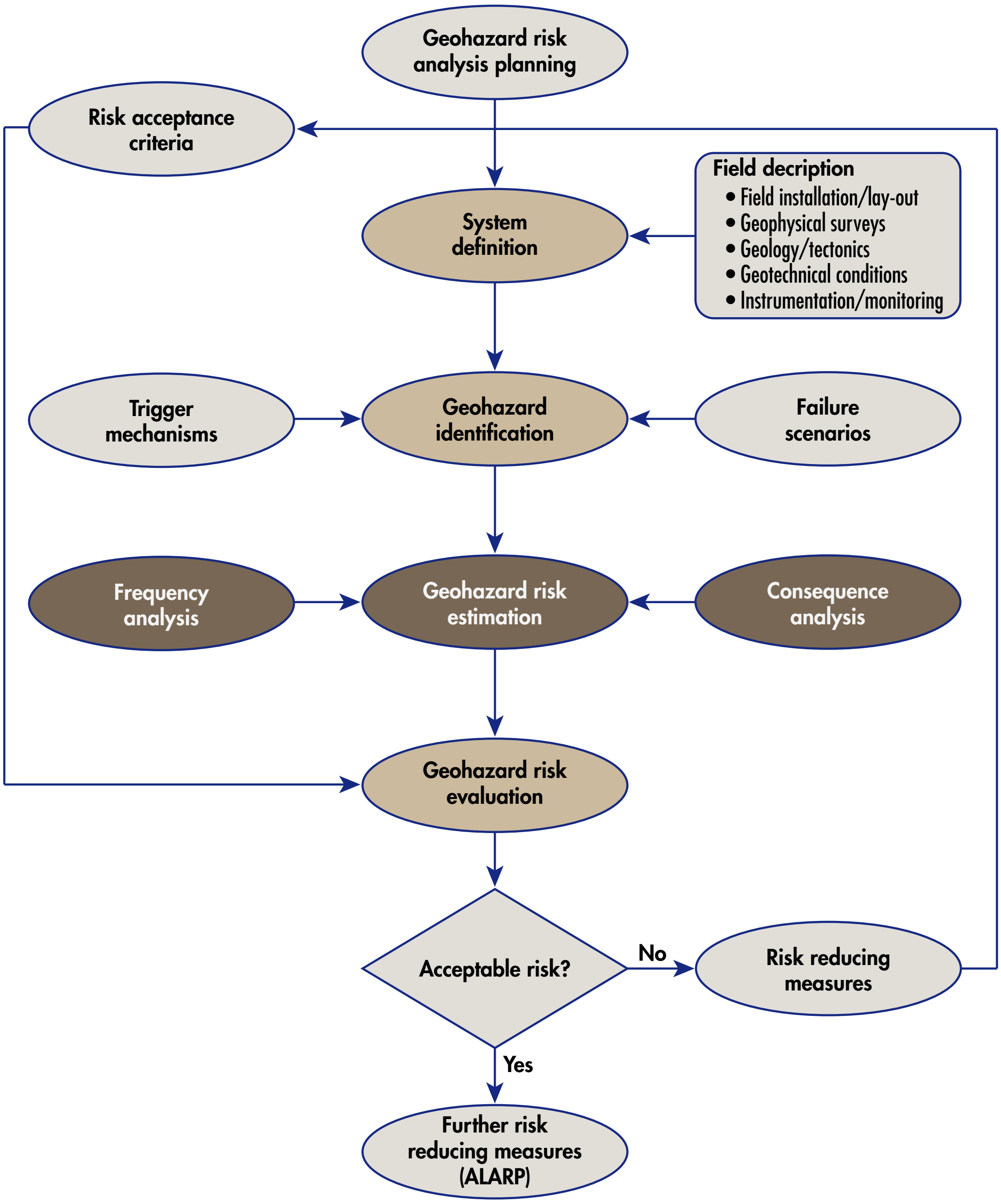
- Can we explain what can be observed in the area from available information i.e. infer the past? Can anomalies, slides, slumps etc. be linked to
  - geological processes and climate conditions?
  - past soil stress, strength and pore pressure conditions?
  - natural trigger mechanisms?
- What are the potential natural hazards today and in the near future (field life)?
  - ongoing geological and climate processes changing the conditions?
  - uncertainty in soil and pore pressure conditions?
  - natural triggers?
- Can planned activities related to exploration, field development and production within the licence area change conditions and represent hazards?
- Can licence installations be affected and damaged by identified hazards?
- Can 3rd parties be affected by field activities in the licence?

A representative set of past, present and near future failure scenarios should be described and selected for further evaluation:

- to explain the observed instabilities and anomalies in the area and gain confidence in the understanding of the geological processes, site condition and soil/pore pressure conditions.
- to asses to likelihood/probability of future geohazard events, quantify the associated consequences and evaluate the geohazard risk.

The HAZID team should advise on missing/required information for the geohazard risk evaluation and communicate their findings to the field development project.

5 Geohazard risk estimation



5.1 Frequency analysis

5.1.1 Modelling approximations and simplifications

Risk estimation requires evaluation of the probable frequency of hazardous events and the associated consequences for each identified failure scenario. Data on submarine geohazard events are scarce and statistics are generally not available. Evaluation of event frequency has thus in most cases to be based on a combination of field observations, dating of earlier events and geotechnical analyses of the failure scenarios. Ideally, complete mechanical models of the scenarios should be analysed with full interaction between soils, structures, environmental and geological processes and load effects including uncertainties in the parameters of the models in 4 dimensions (x, y, z, and time). This is not feasible with today's modelling capabilities (and will probably never be achieved). The risk analyses have to be split into separate sequences with considerable simplifications and approximations within each sequence, as well as in the interfaces between the sequences.

5.1.2 Deterministic analyses

Deterministic analyses of failure scenarios will normally be the starting point (Figure 17). The analyses deliver traditional factors of safety. By varying the soil parameters as well as the magnitude of loads (triggers) and combinations of triggers, an impression of the likelihood of failure and the sensitivity of the failure scenario to uncertainties in input parameters can be established. This allows screening of the scenarios and identification of the parameters that have a major impact on failure probability.

Geotechnical analyses of failure scenarios, back-calculation of observed failures

Effective stress and pore pressure conditions

Sedimentation/compaction BASIN

Excess pore pressure prediction (BASIN)

Strength decrease due to earthquakes

Site response AMPLE, SHAKE

Liquefaction evaluation in sands

Degradation of soil strength in clay

Slope stability, failure initiation

Infinite slope stability

Slope stability (SLOPE/W PLAXIS)

Critical seabed gradients, areas affected

Escalation to retrogressive sliding

Progressive failure due to strain softening PLAXIS/BIFURC

Retrogressive slide: slide size, velocity, run-out, areas affected (CFX,tri-bock, BING)

Figure 17 – Overview of geotechnical analyses involved in deterministic assessment of seabed stability

Prediction/analysis of effective stress and pore pressure conditions

Modelling and analysis tools exist for prediction of pore pressure conditions. Finite element (FE) codes for analysis of sedimentation and compaction process are available. Most of the available program codes have been developed for basin modelling of source rocks, hydrocarbon formation and migration, traps and reservoirs. They may thus have restrictions on the material models and modelling of near seabed areas with slide events and unloading reloading processes, but several may still be applied for evaluation of compaction and pore pressure effects (Wangen, 1993). Special purpose programs for compaction/pore pressure analysis have been developed (*eg* NGI, 2001) and also commercial geotechnical FE codes with ability to model staged excavation/construction processes may be applied (*eg* ABAQUS, PLAXIS).

The input required is the best estimate of chronostratigraphy based on seismic profiling and age determination/estimation, and the stress dependent compressibility and permeability properties of sediments. The output is the time dependent accumulation and compaction of the sediment column with effective stress and excess pore pressure development.

In situ pore pressure measurements with piezometers are recommended to confirm or invalidate predicted overpressures.

Earthquake site response and strength degradation

Linear and non-linear elasto-plastic FE software is available for 1D time domain analysis in horizontal and sloping terrain (e.g., NGI, 1991). The analyses allow evaluation of amplification of the bedrock input acceleration and estimation of strain and displacement time histories in the overburden. Linear-elastic -ideal plastic FE analyses tools can also be applied in 2D simulations of earthquake effects. In sloping terrain earthquake vibrations may lead to accumulation of downslope displacement of the overburden. The associated accumulation of shear strain and increase in pore pressure may lead to reduction of the shear strength of the soil during and after earthquake loading. 1D and 2D FE analyses deliver estimates of the cyclic and accumulated shear strains and will, combined with data from relevant cyclic load tests, allow assessment of the "post-earthquake" strength as a function of terrain slope, acceleration time history and peak ground acceleration (PGA).

Slope stability analysis

In long slopes, infinite slope analysis may give a quick indication of the factor of safety against sliding under static gravity loading and how it is affected by excess pore pressure and slope inclination. However, ideal plastic behaviour is assumed, and effect of local unevenness or steepening, strain softening and earthquake effects cannot be evaluated.

Limit equilibrium

The limit equilibrium approach using the method of slices is still the most widely used method for assessment of slope stability of escarpments. This method is also based on ideal plastic behaviour but allows variable terrain, stratigraphy and soil strength models to be incorporated. Static surface loads can be applied simulating the effect of triggers like rockfills, anchor, trenching, etc. Most advanced software have now automatic or semi-automatic search for the critical slip surface, and this allows easy evaluation of the sensitivity of the factor of safety to variations in the input parameters. Several commercial program codes are available. Pseudo-static earthquake loading is normally included as an option. This is not a physically accurate modelling of a dynamic process and is not the preferred method.

FE analysis

FE analysis has found wide use in slope stability analysis. Geotechnical and general purpose FE codes are available and have been verified against rigorous plastic solutions of slope stability. The advantage with FE analysis is automatic detection of critical slip surfaces/failure modes and calculation of strains and displacements. Modern pre- and postprocessors have reduced the modelling efforts and computer time considerably. A large number of material models is available and coupled stress-strain and flow analyses are possible (ref. section on pore pressure analysis above).

Strain softening

Strain -softening, which probably is the most central component of material behaviour in evaluation of submarine slope stability, is not a standard feature in geotechnical FE software. A few geotechnical FE codes like PLAXIS and BIFURC have robust solution algorithms and allow user defined strain softening material models also including strength anisotropy (Andresen, 2001). Other codes like FLAC may have comparable models, and general purpose FE codes like ABAQUS may also handle this for static loading conditions.

Analysis of progressive failure

With strain-softening material models incorporated, progressive failure can be modelled and evaluated. This was a central element in the demonstration of failure models for explanation of the Storegga slide (and thus for any other major submarine slide on low slope angles). Local overstressing beyond peak strength, forms strain concentration and leads to a local decrease in resistance towards residual strength that requires stress redistribution. If the drop in strength is sufficient and the brittleness of the material is high, the strain concentrations zones will spread and form a shear band involving increasingly larger areas in the strain softening process.

If the failure initiation is in the upper part of a local slope, the shear band may progress downslope along the bedding planes of the sediments. A slide block will form and start to move downslope, generating passive failure in the toe area with a gradual development of a compression zone.

If the failure initiation is initiated by slumping in a locally steeper part in the lower part of a slope, the unloading of the slump escarpment will lead to elastic expansion of the material behind the escarpment. A shear band may progress upslope along the bedding planes of the sediments as shown in Figure 18. A triangular wedge is pushed out, on the softened base layer by the weight of the material behind the escarpment. Inclined shear bands develop, forming a graben structure, which sinks down behind the frontal wedge.

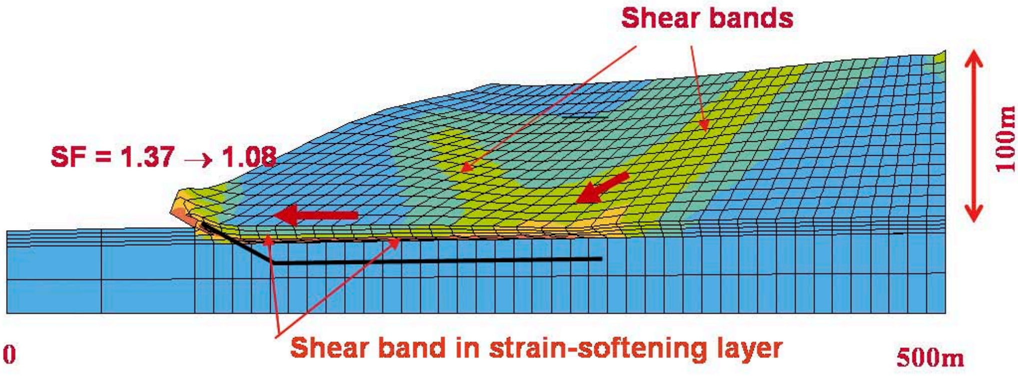


Figure 18 – Progressive upslope spreading of shear bands in a strain softening base layer and in the slope material due to unloading in the toe area. Deformed mesh plot showing degree of strength mobilisation in colours (FE analysis, Andresen, 2001).

Analysis of retrogressive slide processes

With increasing development of the progressive failure process, the material displacements will increase rapidly. The slope failure may change from a slow quasi-static process to a dynamic slide process. If the mobility of the mass is sufficiently high, the slide may develop into a retrogressive slide event.

A simplified wedge model for evaluation of the dynamic mobility of a failure model developing in Figure 18 was developed for the Ormen Lange/Storegga slide study (Kvalstad et al., 2005). A prerequisite is that progressive failure develops along the base slip plane by elastic unloading of the escarpment front as demonstrated in the FE analysis in Figure 18. The model is a kinematically admissible energy model, where the released potential energy is in equilibrium with the consumed energy along the slip plane and in the distortion zone and the kinetic energy of the accelerated mass. This model was further developed to a multi-wedge model, based on the same energy principle (Figure 19). A predefined deformation pattern is required, and should be based on the failure pattern that can be deducted from seismic profiling and surface bathymetry of slide events.

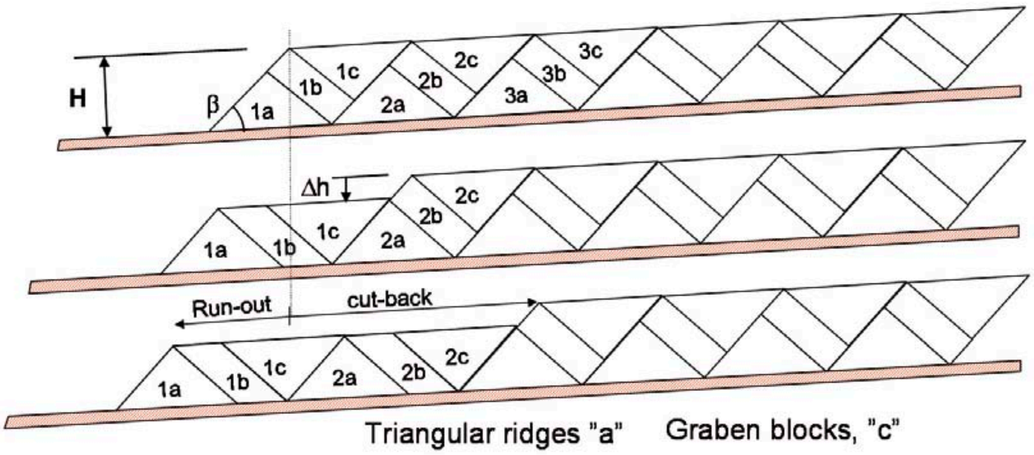


Figure 19 – Multi-wedge model for dynamic simulation of retrogressive slides allows estimation of run-out and cut back distances.

Computational fluid dynamics

Computational fluid dynamics (CFD) codes can simulate flow of Bingham fluids, i.e. fluids with yield strength and a viscosity. Back-calculation of the upper part of the Storegga slide where the failure pattern is well preserved, was carried out with the CFD code CFX (AEA Technology, 1995) . A user defined material model was developed with strain-softening of the Bingham yield strength in the slide mass. Full strain softening in the base slip plane was assumed. The CFD simulations (Figure 20) produced failure patterns with intact triangular blocks and graben formations separated by shear band and distortion zones in the slide mass. These failure patterns were remarkably similar to observed failure patterns, confirming that the simplified tri-block model is a simplified but feasible approach.

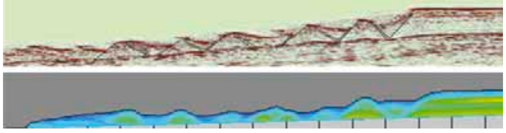


Figure 20 – Computational fluid dynamics simulation of retrogressive slide process, towards upper headwall of the Storegga slide compared with seismic profile.

5.1.3 Probabilistic analyses

Probabilistic analyses of failure scenarios are required to establish estimates of the frequency of occurrence (Figure 21). As a part of the geohazard studies for the Atlantis/Mad Dog projects at the Sigsbee Escarpment (Jeanjean et al., 2003) and the Ormen Lange project located in the Storegga slide scar (Bryn et al., 2005), probabilistic slope stability analyses were performed (Nadim et al., 2003 and Nadim et al, 2005).

Failure probability, reliability and frequency

Probabilistic slope stability analyses	FORMS/SORM
Return period of triggers (EQ return period vs. PGA)	Deformation-development rates of ongoing processes (slope steepening)

Figure 21 – Assessment of frequency

A simplified approach with a 2-wedge model was developed and evaluated with the first order reliability method (FORM) (Hasofer and Lind, (1974). The 2 wedge model allows a closed form solution of the static factor of safety to be obtained for a 5 layer model of the slopes. The SHANSEP approach was applied to establish undrained strength profiles, and anisotropy was included in the model. All relevant parameters included in the closed form solution were modelled as random parameters with a mean value, a variance and an assumed distribution function.

Applying FORM with the probabilistic 2-wedge analyses allows calculation of the reliability index, which is the number of unit standard deviations between the most likely failure point (the design point) and the failure surface in a multidimensional space of independent Gaussian variables. The reliability index is directly related to the probability of failure. This method allows the sensitivity factors of the individual random variables to be quantified, which in a relative manner describe the contribution of each parameter to the total uncertainty.

5.1.4 Annual probability of failure.

The FORM analysis takes into account uncertainties within the system to provide an estimate of the probability that a system , if "built" today, would fail immediately. This is a straightforward interpretation for man-made slopes like earth dams and embankments. For natural slopes this interpretation is not straight forward. As the slope has not failed today, its probability of "static" failure is zero. If there are no triggers causing changes to the system, a slope that stands today would never fail. The probability of failure provided by the FORM analysis is not the annual probability of failure.

Two types of trigger mechanisms may have to be considered; random trigger mechanisms like earthquakes and wave loading or slowly varying trigger mechanisms like sediment deposition and fault or diapir displacements. The random type trigger mechanism is discussed and evaluated by Nadim et al., 2005 and the slowly varying type, by Nadim et al., 2003.

Probabilistic earthquake hazard assessment will provide site specific PGA at bedrock vs. recurrence period. This allows a connection to be established between earthquake intensity and earthquake recurrence period, which again can be transformed to a relationship between recurrence period and post earthquake strength reduction, and finally to an annual probability of earthquake induced failure.

When the occurrence frequency or the development rate of triggering sources are estimated, tectonic and climate changes must be taken into consideration. Glacial cycles with eustatic sea level variations have had a strong impact on sediment deposition rates on the continental slopes and formation of major river delta and glacial fan structures. Many of the major submarine slide events seem to be connected to these variations, and the present interglacial climate with sea level high-stand is generally associated with strongly reduced sedimentation rates along the deepwater margins. A reduction in sedimentation rate below a certain value will lead to a gradual reduction in excess pore pressure and thus a gradual improvement of slope stability. A comparison of slump rate vs. sedimentation rate was described for the drape sediments at Sigsbee Escarpment (Nadim, 2003) and showed a clear reduction in slump rate with decreasing deposition rate.

5.2 Consequence estimation

5.2.1 Systematic approach

The potential consequences of the failure scenarios need to be estimated from an engineering point of view as well as from HSE and economical points of view. A systematic compilation of estimated damage vs. estimated probability of occurrence is required for all identified failure scenarios to assess the cumulative geohazard risk. Different techniques exist that can be applied to all kinds of risk assessment.

Consequence analyses

Impact analyses, slide-structure interaction	**Tsunami analyses**
Debris flow against/around pipes/piles (CFX)	Water level change, wave and water particle velocities
Structural resistance and damage potential vs. debris thickness and velocity	Relationships slide size-slide dynamics – tsunami effects

Figure 22 – Consequence analysis

Typical consequences are related to:

- Loss of foundation support or capacity causing tilting, sinking, pull-out of piles, anchor and mat foundations
- Structural damage to foundation elements, subsea structures and pipelines like shearing, buckling and bending, caused by impact from debris flow
- Damage to wells during drilling and production
- Burial of installation in slide debris
- Total collapse and large displacements of field installations located in major slide events

5.2.2 Areal extent of seabed instability

The run-out distance of debris flows and the cut back distance of retrogressive slides are important factors in the consequence evaluation. Analysis methods described above can be applied. However, there is considerable uncertainty related to the disintegration process of the slide debris from slide initiation to completed run-out. Intrusion of water in the slide mass or into the slip surface will increase the disintegration of the debris and the sliding resistance along the slip surface causing higher velocities and longer run-out distances. Debris disintegration is an area of ongoing research, but clear conclusions and recommendations are not yet available.

Run-out and cut-back distance estimates need to be complemented with estimates of the lateral extension of the slide event. Numerical or analytical methods are generally 2- dimensional, and the width estimates will generally have to be based on observed slide geometries and the bathymetry in the area.

5.2.3 Debris flow forces on structures

Installations located within the potential run-out or cut back zone of slides and debris flows should be designed to resist the impact and drag forces. Debris flow forces against cylindrical elements have been studied (Pazwash and Robertson, 1975, Georgiadis (1991), Shapery and Dunlap, 1978). Most tests have been performed with low velocities and strain rates. Use of CFD codes allows numerical evaluation and has been checked against static and dynamic test data NGI (2003). The drag force increases rapidly with increasing velocity and debris thickness, and debris resistant design of piles, wells and structural members of subsea installations is probably limited to relatively shallow failure events in soft clay drapes.

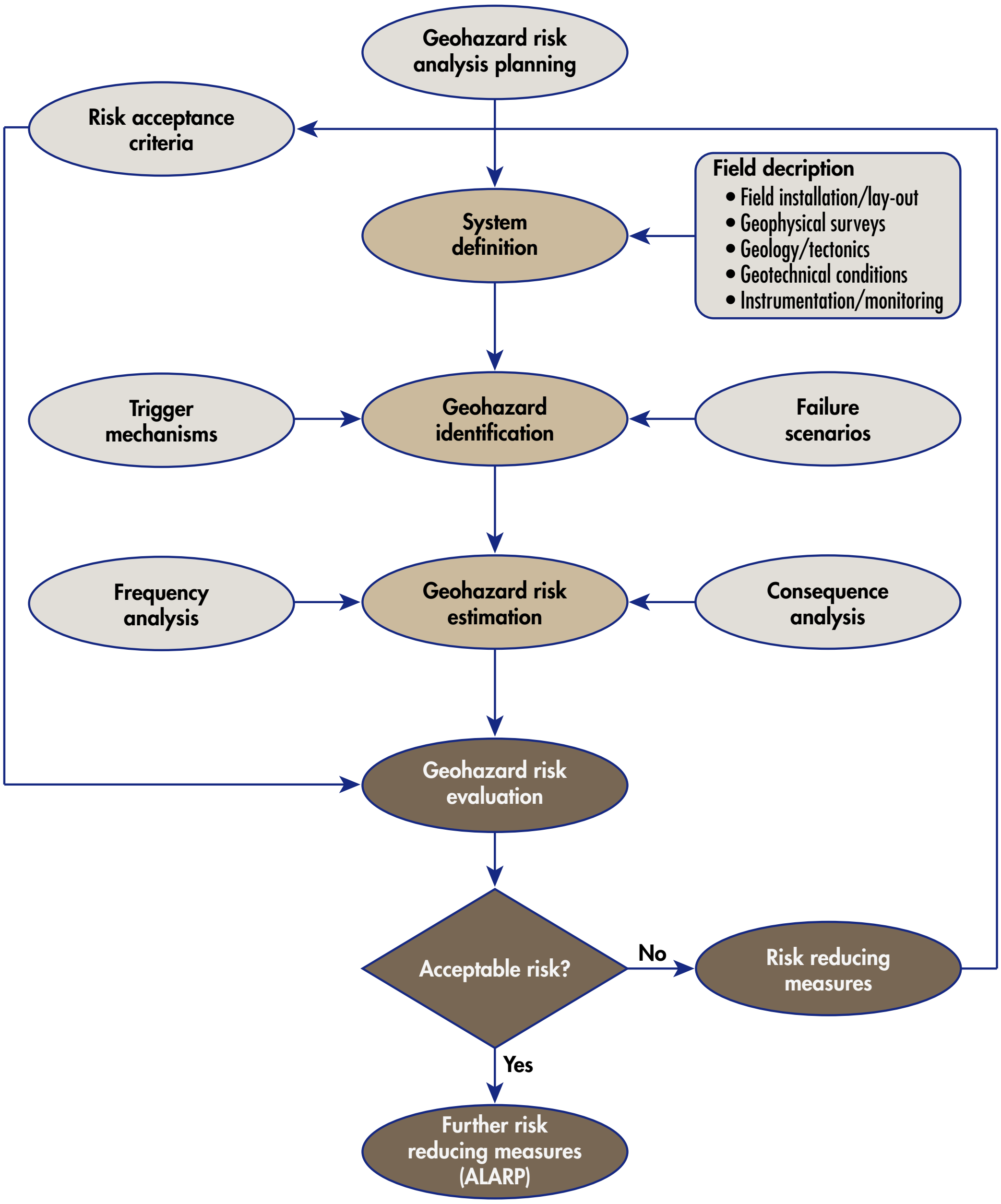
5.2.4 Vulnerability of structures and systems

The evaluation of structural capacity and vulnerability of structures and systems under the various geohazard loads is a necessary link to establishing failure criteria, damage severity and risk estimation.

5.2.5 Tsunami generation

Large scale slide events may generate tsunami waves. The wave height is dependent on the water depth and the volume and shape of the slide mass, and acceleration/velocity development. In deeper water the surface effects are limited and will generally not be critical for offshore platforms and vessels. With decreasing water depth towards shore, the wave height increases and can have devastating effects. The Storegga slide (8200 years BP) created a tsunami that left deposits more than 10 m above sea level in western Norway and up to 20 m above sea level in the Shetland Islands (Bondevik et al., 2005). The consequence of this event was probably catastrophic for the coastal areas. Tsunami analyses can give an estimate of the sea level variations along the coastline and in the field area vs. slide characteristics (See Løvholt et al, 2005).

6 Risk evaluation



The geohazard risk needs to be included in the overall project risk evaluation. If the risk contribution is significant and not acceptable, risk reducing measures should be sought. In areas with significant natural slide risk potential, this is primarily relocation of wells, structures and pipelines to less hazardous areas, alternatively to protect structures against slide impact.

High risk levels can also be a result of large uncertainty connected to strength and pore pressure data, and may indicate that more extensive investigations should be carried out.

Human induced risks can be reduced through careful planning and engineering aimed at minimizing effects of human influence, or by increasing the redundancy of the field development system.

7 Staged approach

The assessment of geohazard risk is usually based on available information about regional and local geology and site specific conditions regarding bathymetry, stratigraphy, soil conditions and field exploration and lay-out plans. In areas with potential geohazards there should be a high degree of interaction between field development planning and geohazard evaluations. During the project development the amount of information will increase, plans will typically be modified and thus a staged approach is required. The number of stages required will depend on the findings from the previous stage and the complexity of the project. An example of such an approach is given below.

7.1 First stage

First stage system definition and HAZID:

- Geological model of region (age and source of sediments)
- Evaluate in-line and cross-line shallow and deep seismics in region
  - Main stratigraphy and buried features
  - Signs of slide activity? Recent, older buried?
  - Active faults, anticlines, diapirism?
  - Seeps, fluid escape features, gas blanking
  - Signs of gas hydrates (bottom simulating reflectors present?)
- Evaluate bathymetric information and seabed inclination and morphology
  - Major slide scars
  - Signs of local seabed instability, slumps, grabens, compression ridges, other special features in licence area/upslope/downslope/general in region?
  - Fluid escape structures, pock marks, mud volcanoes, salt diapirs
- Drilling experience in area?
- Earthquake activity in area?
- Establish a preliminary ground model
- First stage field development plans – first stage identification of failure scenarios

First stage assessment of geohazard situation:

- Clear signs of potential geohazard risk? Locally, regionally?
- Potential trigger mechanism for seabed instability?
- Other hazards: shallow gas, potential for shallow water flow
- Slope stability: rough evaluation of high gradient areas
- Compare with field development plans: wells and field installations, export pipeline corridor
- First stage geohazard screening and guidance for the avoidance of geohazards
- Need for better information? Cooperation with other licences in region? Planning and optimisation of data acquisition for next stage
  - More detailed bathymetry required
  - Extended bathymetric maps upslope/downslope
  - Additional/extended seismic profiles required?
  - Additional geophysical investigations, shear waves, electromagnetic waves?
  - Need for geotechnical data? Pore pressure measurements?

7.2 Intermediate stage(s):

Intermediate stage HAZID and system definition:

- Evaluation of 3D seismics, reprocessing of 3D seismics, UHR 2D seismics, well logs, detailed shallow seismics, detailed bathymetry (multibeam bathymetry, side scan sonar
- Reinterpret morphology and potential signs of instability and slide mechanisms
- Evaluate pore pressure conditions, signs of overpressure
- Plan and possibly carry out geoborings, acquire site specific soil data. Focus on compressibility, permeability, strength and brittleness (sensitivity) of soils
- Calibrate first stage geomodel and soil parameters for design
- Assess deposition rate/sedimentation history, potential for excess pore pressure, dating requirements
- Occurrence frequency vs. magnitude of earthquakes, mud volcano eruptions, *etc*.
- Other ongoing natural processes? Erosion? Diapir displacements?
- Updated field development plans and associated geohazard failure scenarios

Intermediate stage assessment of geohazard situation:

- Natural processes:
  - Ongoing changes in seabed gradient due to erosion, deposition, compaction, active faulting
  - Updated earthquake hazard assessment
  - Slope stability assessment, regional/large scale, local
  - Excess pore pressure conditions/fluid flow
- Human influence on situation?
  - Wells – heat flow – gas hydrate melting
  - Underground blow-outs
  - Subsidence – induced earthquakes
  - Installation of structures, anchors, pipeline supports etc.
- Screening of geohazards
- Need for quantification of failure probability and risk?
- Possibilities for avoidance through lay-out modifications and/or mitigation through design
- Sufficient information available?
- If not, identify final site investigation program
  - Geoborings, field and laboratory testing and interpretation
  - Pore pressure measurements
  - Local bathymetric surveys/pipeline corridors

7.3 Final stage

Final stage HAZID and system definition:

- Refine/recalibrate geomodel of the area; stratigraphy, bathymetry, relevant soil data and uncertainty.
- Select failure scenarios and associated trigger mechanisms to be included in risk assessment analysis
- Identify, describe and quantify relevant trigger sources; magnitude and frequency
- Final stage geohazard risk analysis:
- Apply geomechanical models in analysis of failure scenarios (stability analyses, FE analysis, fluid flow, heat flow, *etc*) and assess model uncertainty
- Assess probability of failure
- Evaluate physical consequences of failure (loss of support, slide run-out and impact, tsunami generation and impact, *etc*) and estimate associated damage
- Quantify risk contribution of relevant geohazard failure scenarios
- Evaluate possibilities for mitigation through design
- Check compatibility with clients and authorities' acceptance criteria?
- Develop hazard zonation maps for detailed layout and engineering.

8 References

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International Association of Oil & Gas Producers

209-215 Blackfriars Road
London SE1 8NL
United Kingdom
Telephone: +44 (0)20 7633 0272
Fax: +44 (0)20 7633 2350

165 Bd du Souverain
4th Floor
B-1160 Brussels, Belgium
Telephone: +32 (0)2 566 9150
Fax: +32 (0)2 566 9159

Internet site: www.ogp.org.uk
e-mail: reception@ogp.org.uk