

Challenges to geo-scientists in risk assessment for submarine slides

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The state-of-the-art in understanding submarine slides has advanced significantly in the past decade. The advances have been mostly driven by the need of the offshore petroleum industry to understand and quantify the risk associated with various seafloor geohazards. The paper reviews the major recent contributions in risk assessment of submarine slides, discusses the challenges to geo-scientists involved in the risk assessment and recommends a stage-wise approach for performing the risk assessment.

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Introduction

Exploitation of offshore resources, development of communication and transport corridors, fishing habitat protection, and the protection of coastal communities, have contributed to a growing interest in improved understanding of offshore geohazards, in particular seafloor mass movements and their consequences. Figure 1 shows the potential detrimental consequences of submarine mass movements to offshore installations

and people and infrastructure along the coastlines. The figure demonstrates the complexity of the phenomena and issues involved in a risk assessment study for submarine slides.

The first challenge that most geo-scientists face is to clarify or understand what is meant by "risk" and "risk assessment". The International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Risk Assessment and Management

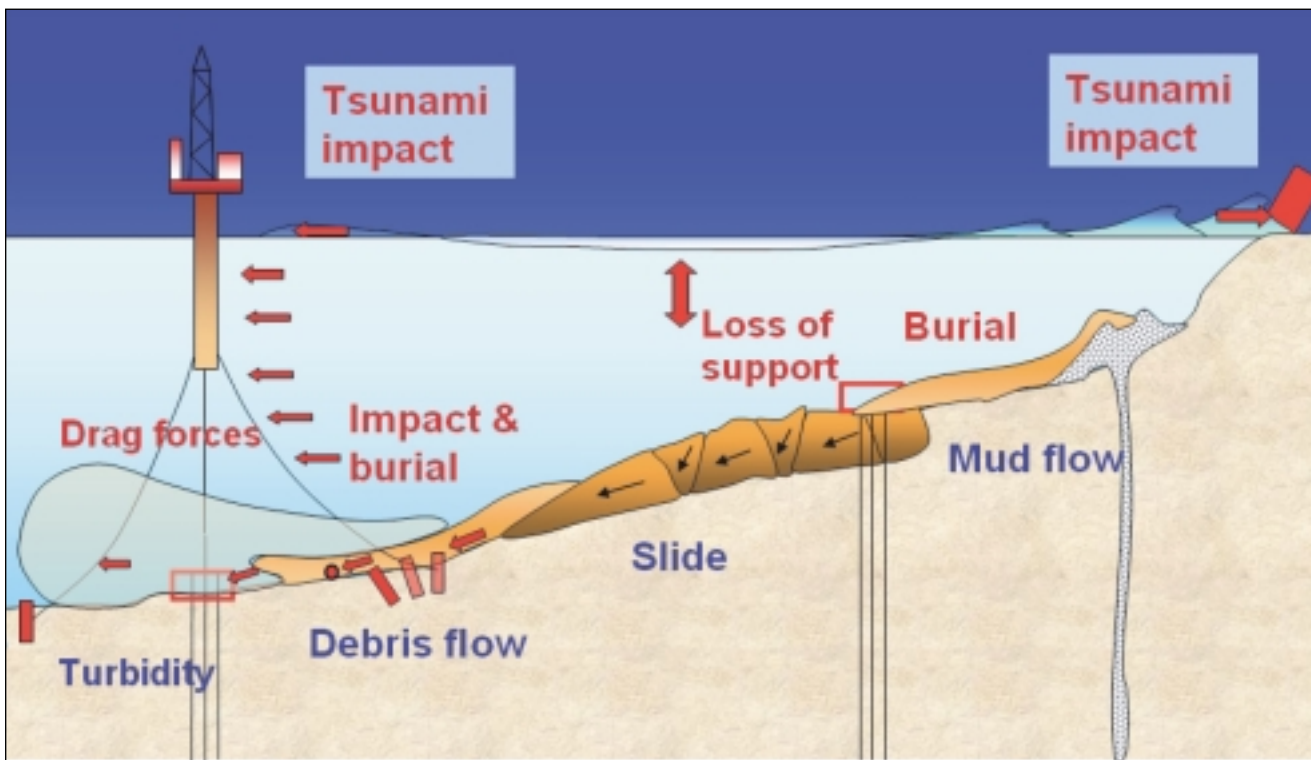


Fig 1: Consequences of submarine landslides that might pose a risk to people and offshore installations.

(TC32) developed a Glossary of Terms for Risk Assessment, based on earlier glossaries recommended by the International Union of Geological Sciences (IUGS), the International Commission On Large Dams (ICOLD); and National Standards such as British Standard BS 8444, Australia-New Zealand Standard AS/NZS 4360, and Canadian Standard CAN/CSA – Q 634-91. Readers are encouraged to use these terms to promote consistency across the Inter-national Community. The complete glossary of terms is provided at www.engmath.dal.ca/tc32. Definitions of the most important terms are provided in Appendix A.

Evaluation of the stability of natural or man-made slopes has traditionally been based on a deterministic approach where the level of safety is quantified by the safety factor. The factor of safety is defined as the ratio of the characteristic resisting force to the characteristic load (driving force). Many of the parameters that are used in a stability analysis, in particular the soil shear strength and the earthquake load effects (for seismic stability evaluation), are inherently uncertain. The uncertainties involved in assessment of site and soil conditions are in many cases amplified by the spatial extent and depth of the sediments and geological units involved, the presence of gas in sediments, and the practical and economical limitation of the site investigations. The conventional approach does not address the uncertainty in load and resistance in a consistent manner and is not well-suited for risk assessment. The

ambiguous definition of "characteristic" values allows the engineer to implicitly account for uncertainties by choosing conservative values of load (high) and resistance parameters (low). The choice, however, is somewhat arbitrary. Slopes with nominally the same factor of safety could have significantly different probabilities at failure because of the uncertainties and how they are dealt with. This is illustrated schematically on Fig. 2.

Reliability theory and probabilistic analyses provide a rational framework for estimating the probability of slope failure and are powerful tools for quantitative risk assessment. However, reliability methods require more data and estimates of the variances in significant parameters. This can be expensive and it will also require expert judgment. The cost and judgment are part of the price paid for a better answer. This tends to make the reliability methods more useful for major projects than for routine work. For this reason, application of reliability methods for evaluation of stability of soil slopes is more common in offshore geohazard studies than in traditional land-based geotechnical engineering. Depending on the level of sophistication, the probabilistic analyses provide one or more of the following outputs:

- Probability of failure (or probability of unsatisfactory performance), P_f = Probability that $FS < 1$ in Fig. 2.
- Reliability index, β
- The most probable combination of parameters leading to failure

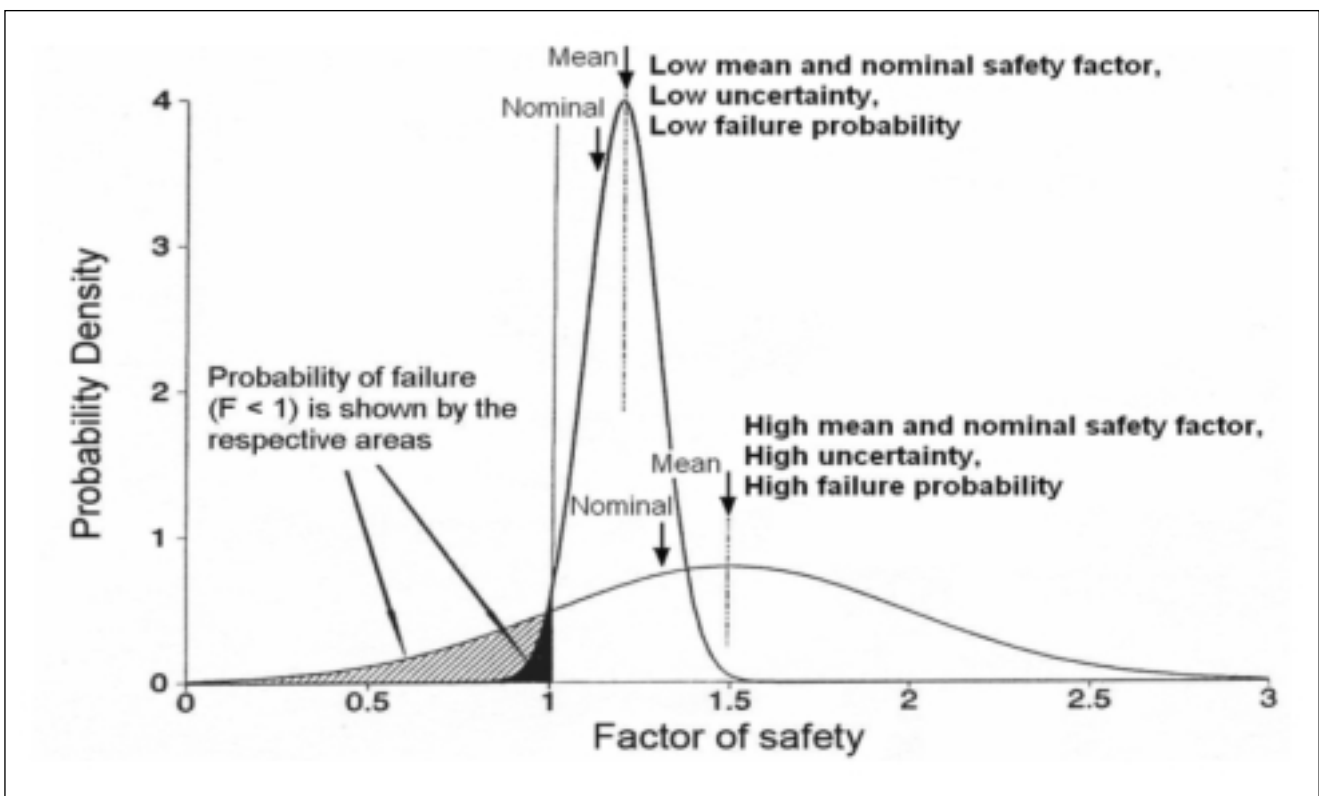


Fig 2: Comparison of two situations with different factors of safety and uncertainty.

- Sensitivity of result to any change in parameters

There are several definitions of reliability index (Nadim et al. 2005a). A simple and convenient definition is to relate β and P_f through the following equations:

$$P_f = \Phi(-\beta), \beta = -\Phi^{-1}(P_f)$$

where Φ is the standard normal distribution function.

The relationship between probability of failure and reliability index is illustrated on Fig. 3. The reliability index provides more information about the stability of the slope than is obtained from a factor of safety alone. It is directly related to the probability of failure and the computational procedures used to evaluate the reliability index reveal which parameters contribute most to the uncertainty in the factor of safety.

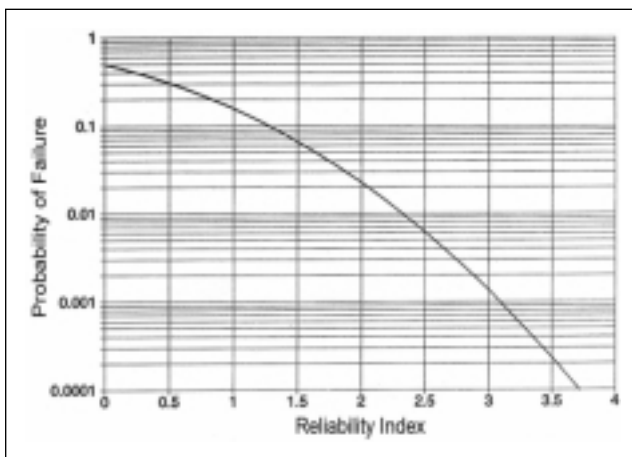


Fig 3: Relationship between reliability index β , and probability of failure P_f (assuming a Gaussian distribution).

Characteristics of submarine slides

Submarine slides are common and very effective mechanisms of sediment transfer from the shelf and upper slope to deep-sea basins (Hampton et al. 1996; Locat & Lee 2002; Syvitsky et al. 1987). During one single event enormous sediment volumes can be transported on very gentle slopes with inclinations in the range 0.5 to 3°, over distances exceeding hundreds of kilometers. Typically such events last from less than an hour to several days and can severely damage fixed platforms, pipelines, submarine cables and other seafloor installations. Research on understanding the mechanisms behind and the risks posed by submarine slides has intensified in the past decade, mainly because of the increasing number of deep-water petroleum fields that have been discovered and in some cases developed (Locat & Mienert 2003). Production from offshore fields in areas with earlier sliding activity is ongoing in

the Norwegian margin, Gulf of Mexico, offshore Brazil, the Caspian Sea and West Africa.

Submarine landslides occur frequently on both passive and active continental margins, especially on the continental slopes. Despite the generally low slope angles, these are areas of sloping stratigraphy, often with more active and vigorous geological processes, including seismicity, than those found in the shallow, sub-horizontal continental shelf areas. The shelf edge and slope area contain the most recently deposited materials, and in areas with high deposition rate, underconsolidation / excess pore pressure may exist. The excess pore pressure often plays a major role in destabilization of submarine slopes. The expenses of finding and developing new fields in deep water are very high, and this greatly increases the economic consequence part of the risk aspect connected to submarine slides in continental margin settings.

The assessment of the risk associated with submarine mass movements is thus not just a matter related to commercial interests of oil companies. The societal and environmental consequences of such events could also be enormous for coastal communities. For instance, large submarine slides may generate tsunamis with potential for severe damage along the coastline. The tsunami generated by the earthquake-triggered Grand Banks slide in 1929 killed 27 people in Newfoundland. The 15-m tsunami that killed more than 2000 people in Papua New Guinea in 1998 was also a result of an earthquake-triggered submarine slide.

Issues that should be considered in risk assessment

Assessment of the risk posed by a potential submarine slide requires identification and analysis of the relevant failure scenarios, *i.e.* failure modes, triggering sources and related failure consequences, which have a significant contribution to the total risk. The triggering mechanisms could be natural, such as earthquake, tectonic faulting, temperature increase caused by climate change, excess pore pressure due to rapid sedimentation and gas hydrate melting due to climate change with increased sea water temperature after glacial periods; or man-made, such as anchor forces from ships or floating platforms, rockfilling for pipeline supports, temperature change around oil and gas wells in the offshore field development area, underground blow-out, and reservoir depletion and subsidence (including induced seismicity). The key issue in the slide risk assessment is the identification of potential triggers and their probability of occurrence, the associated failure modes and their consequences.

Risk quantification has to be based on site investigati-

ons with mapping of topography and local gradients, identification of different geological/geotechnical units, assessment of soil and/or rock properties and *in situ* stresses, pore pressure and temperature conditions. An understanding of the regional and local geology, ongoing geological processes, and type, locations and extent of anomalies is required to quantify the potential impact and rate or frequency of ongoing natural processes (see also Leroueil et al. 2003; Locat 2001). This element is significant since one must be able to answer the question about whether or not a given process is active and in which direction it is going (Locat 2001).

If we look at a given natural slope, an important question to ask ourselves is whether or not the processes responsible for the formation of the slope are still active (Fig. 4), i.e. is the hazard evolving? If the answer is yes, then we can assume that the long term factor of safety, defined as the ratio between the resisting forces to the gravitational forces, is about one, i.e. the slope, on the long term, is responding (or adjusting) to the ongoing slope process(es). If the answer is no, then there are two other options related to the evolution of the geological processes which can either improve the stability situation or deteriorate it. For example, if we look at a submarine canyon slope and have indications that it had been created at the time of lower-than-today sea levels, then the actual condition may be that the stability is improving, since erosion has more-or-less ceased and partial filling may have started to take place. As another example, consider slopes which have been destabilized

by gas hydrates at times of low sea levels. The slopes may be more stable now, but local reservoir exploitation could change the confining stress conditions or fluid movements. These could in turn influence the gas hydrate stability and decrease the factor of safety, so as to re-activate or generate some slides (Kayen & Lee 1991). In the case of the Eel River Margin (Fig. 4), the actual slope processes are still very active: high sedimentation rate (potential for overloading the slope) and seismic activity (Lee et al. 1999) so that the estimated long term factor of safety must be close to unity.

Going from hazard to risk requires other considerations as shown by the general framework for risk assessment for submarine slides provided in Fig. 5.

Recent advances in the state-of-the-art

Detailed mapping and extensive studies of submarine slides in recent years have increased our knowledge immensely regarding slide morphology, extent and volume. However, there are still many unknowns concerning the triggering, development and dynamics of submarine slides and how various mechanisms relate to the geological setting.

The state-of-the-art in quantitative risk assessment for submarine slides is represented by the recent site-speci-

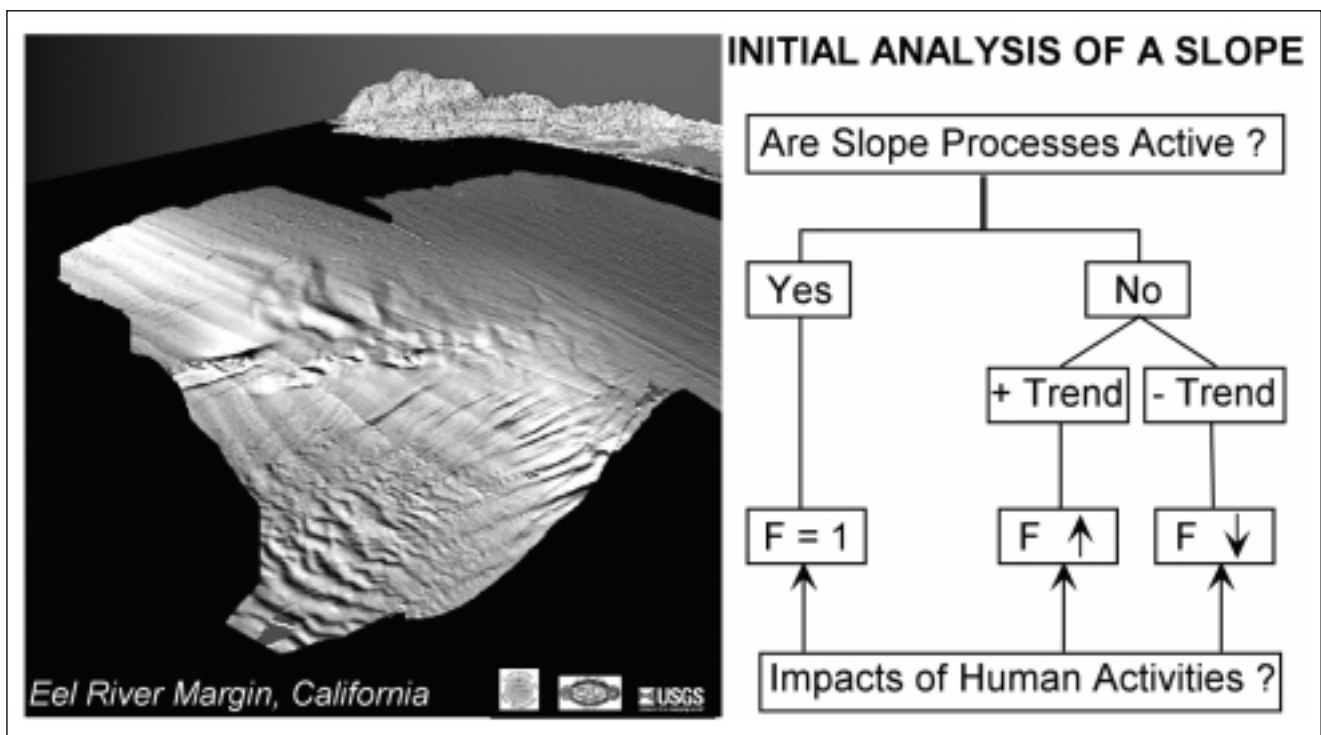


Fig 4: The initial analysis of the safety factor of a slope ($F = \text{Resisting Forces}/\text{Gravitational Forces}$) illustrated with a multibeam 3D view of the Eel River Margin off Eureka, California (multibeam image is from USGS, Locat 2001).

fic geohazard studies performed for the Storegga slide in the Norwegian Sea in connection with the Ormen Lange gas field development, the Mad Dog and Atlantis licenses in the Sigsbee Escarpment in the Gulf of Mexico, the ACG and Shah Deniz licenses in the Caspian Sea, and several studies off the west coast of Africa. Furthermore, the large research programs initiated by the European Commission; such as ENAM-I and -II (Mienert 2002), COSTA (Mienert 2004), and EuroSTRATAFORM (<http://www.noc.soton.ac.uk/CHD/EUROSTRATAFORM/>); European Science Foundation (Euromargins Project, http://www.esf.org/esf_article.php?activity=7&article=127&domain=3), and in North America; such as COSTA-Canada (<http://www.costa-canada.ggl.ulaval.ca/english.html>) and STRATAFORM (<http://geopubs.wr.usgs.gov/open-file/of01-190/of01-190/>); have contributed greatly to enhancing our understanding of the processes involved in submarine mass movements. The methodologies adopted in some of these studies are reviewed below.

Examples of recent submarine slide risk assessment studies

Major research efforts

One of the first steps in developing an approach to submarine slide risk assessment is to develop an understanding of the hazard itself, *i.e.* where, why and how

submarine slides occur and what are their geomorphological and sedimentological signatures. This can only be achieved through major projects aiming at understanding submarine mass movements and their consequences. Since the early eighties, significant steps were taken as part of major national and international projects which have been directly related to the study of submarine mass movements. Nadim & Locat (2005) provide a summary of the major international research efforts in the past 20 years.

Unfortunately, only a few of the international research efforts address the topic of risk assessment directly. As part of the COSTA Project, Leynaud & Mienert (2003) included reliability methods and Monte Carlo simulation to back-calculate the slide hazard for the Trænadjupet slide. Leroueil et al. (2003) have also developed the use of the geotechnical characterization of mass movement method as part of a risk assessment protocol.

Probabilistic slope stability analyses for the Sigsbee Escarpment

The development of the Mad Dog and Atlantis prospects in Gulf of Mexico included an integrated geohazard study which covered a variety of geological, geophysical and geotechnical subjects. Both prospect areas are located at the main geological feature in the area, the Sigsbee Escarpment. The challenges faced by the decision-makers in siting facilities along the Sigsbee Escarpment are described by Jeanjean et al. (2003). To

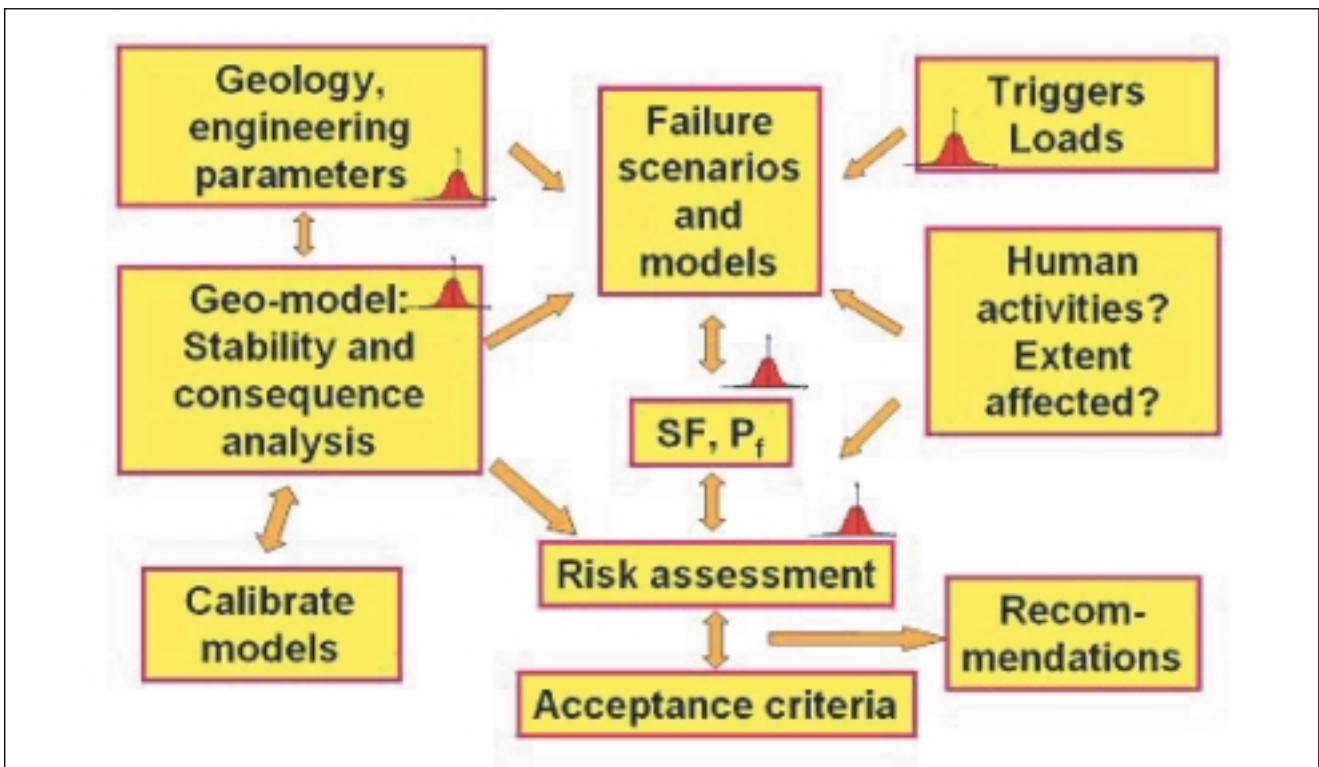


Fig 5: General framework for risk assessment for submarine slides.

assist the decision-making process probabilistic slope stability evaluations were performed for the Atlantis and Mad Dog prospects (Nadim et al. 2003).

The probabilistic slope stability analyses were performed for the most critical slopes in each area, for example Slump E in the Atlantis prospect. The starting point of the analyses was the critical failure mechanism identified in the deterministic slope stability calculations. For Slump E, this mechanism had a static safety factor of 1.52 (see Fig. 6). In the probabilistic analyses, the limit equilibrium model used in the deterministic analyses was coupled with the first-order reliability method (FORM) (Gollwitzer et al. 1988).

The following parameters were represented as random variables in the analyses: submerged unit weight in each layer (total of 6 distinct soil layers with total thickness of 105 m were involved in the critical failure mechanism shown on Fig. 6), undrained shear strength parameters in each layer, removed overburden in each layer, removed overburden at toe of the slope, shear strength anisotropy and modeling uncertainty. The probabilistic stability analyses gave a reliability index of $\beta = 3.34$ and a corresponding failure probability of $P_f = 4.2 \cdot 10^{-4}$ for the critical failure mechanism in Slump E. The variables contributing most to the total uncertainty were (in the order of importance):

- 1 Shear strength parameter in the deepest layer
- 2 Modeling uncertainty parameter
- 3 Strength anisotropy factor
- 4 Shear strength parameters in other layers (deep layers

- more important than shallow layers)
- 5 Removed overburden in deeper layers and at toe of slope
- 6 Submerged unit weights
- 7 Parameters describing the geometry of critical failure surface

Acceptable risk level

For offshore sites, defining the acceptable level of failure probability is usually done by the "problem owners", i.e. the operating oil companies, certifying agencies and government authorities. Typically, an annual probability of failure of 10⁻⁴ or lower is considered acceptable as long as the consequences of failure are local. When there is potential for significant damage to 3rd parties as a result of slope failure, stricter acceptance criteria may be established by the authorities (see following example for slides in the Storegga area).

New slides in Storegga area

The Ormen Lange field is the largest undeveloped gas field on the Norwegian Continental Shelf. The field is located in the Norwegian Sea in water depths of about 800 to 1,100 m. The field is situated approximately 120 km from the coastline, within the scar of the prehistoric Storegga slide (Fig. 7). The Storegga slide, which took place 8,200 years ago, is one of the world's largest known submarine slides with an estimated slide

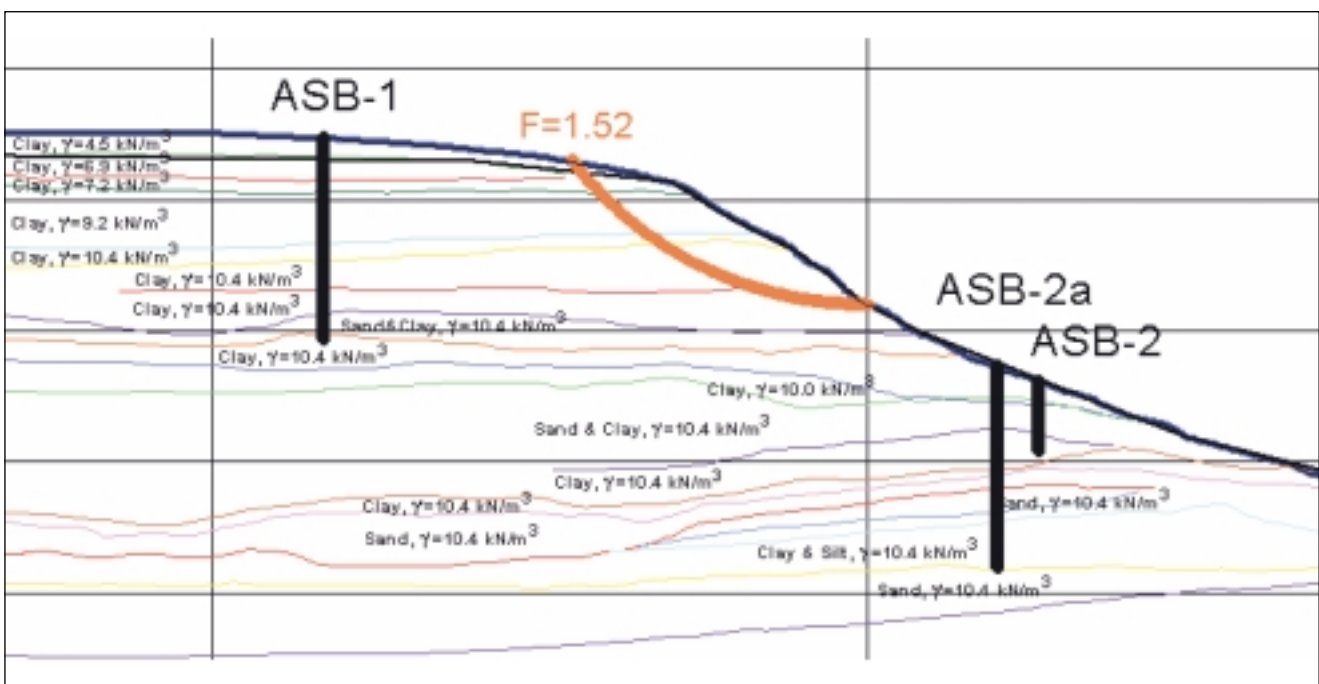


Fig 6: Soil layering, geotechnical boreholes and critical failure mechanism for Slump E in Atlantis prospect (Nadim et al. 2003).

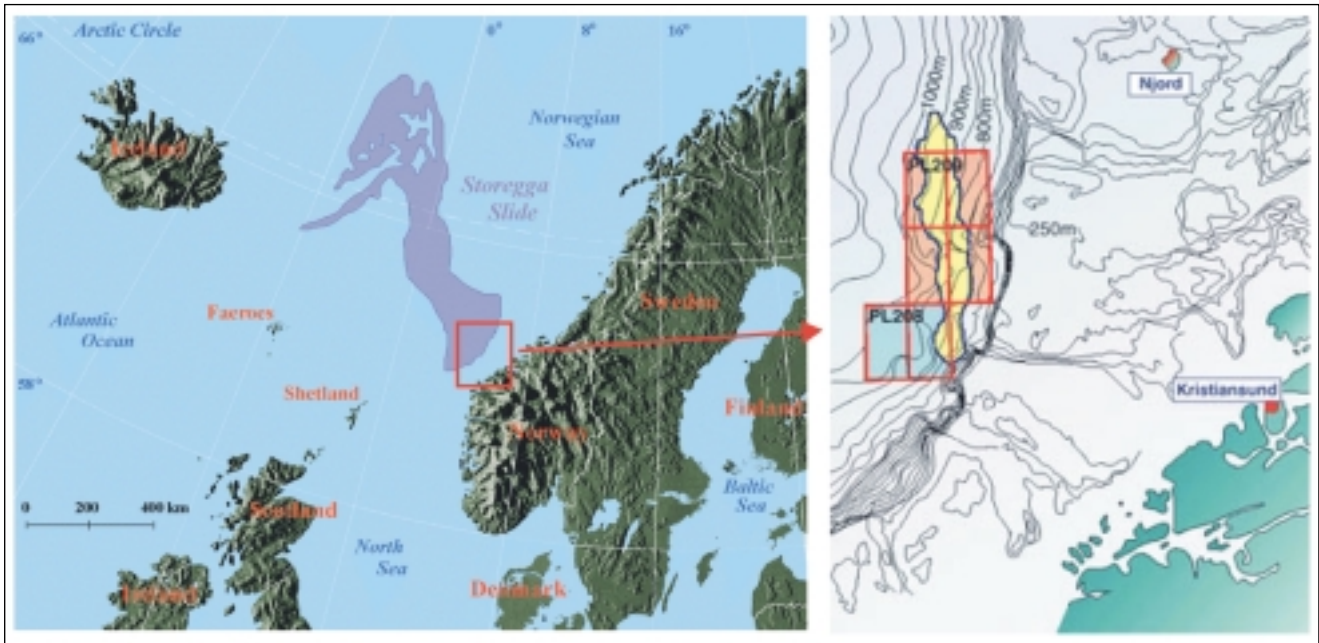


Fig 7: Location maps of the Storegga Slide (left) and the Ormen Lange field (right).

volume in excess of 3,000 km³. Evidence of a major tsunami generated by the Storegga slide has been found along the coasts of Norway, Scotland and the Faeroe Islands.

Considering the enormity of the Storegga slide and the potentially catastrophic consequences of a similar event today, it was essential to clarify and quantify the risks associated with submarine slides in the area to obtain approval for field development from the authorities. A major effort was therefore undertaken to evaluate the stability situation of the slopes in the Ormen Lange area today, identify the areas/volumes that might be negatively affected by slope instability, and quantify the 1st party and 3rd party risks. The risk assessment study was a multi-disciplinary project and the following key activities were performed in connection with the slide risk evaluation (Bryn et al. 2004):

- Establishing a regional and local geological model
- Establishing an explanation model for the Storegga Slide
- Evaluation of static stability of the escarpments in the vicinity of the development area
- Evaluation of natural slide triggering mechanisms and their relevance for slide risk, based on:
 - Earthquake analyses
 - Gas hydrate studies and gas hydrate dissociation modeling
 - Pore pressure measurements and modeling
 - Evaluation of reservoir subsidence and its possible influence on the slope stability
 - Evaluation of the possible effect of an underground blow-out on the present day stability

- Evaluation of the possible effect of the development activity on the local slope stability
- Dating the Storegga Slide and possible younger slide events in the area
- Evaluation of possible consequences of a new slide on the Ormen Lange field installations and for 3rd party (including run-out distances and tsunami analyses)
- Mapping of tsunami sediments onshore and in the fjords in Western Norway
- Establishing risk acceptance criteria and performing quantitative risk assessment
- External verification of work program and results.

Acceptance criteria for first party risk and environmental risk are mandatory for all offshore installations on the Norwegian Continental Shelf (NORSOK Standard Z-013: Risk and Emergency Preparedness Analysis, www.olf.no/norsok). The Ormen Lange field development is no exception in this context and conventional risk acceptance criteria were applied (Lund et al. 2004), i.e.

- The Group Individual Risk (GIR) shall not exceed 10⁻³ per year when at work. GIR shall be calculated for all defined personnel groups.
- The environmental risk acceptance criteria are based on the principle that the duration of environmental damage shall be insignificant compared to the expected time between such damages.

The main challenge for the Ormen Lange operator and partners was to formulate acceptance criteria related to risk to third party (i.e. the general public). Third party risk is normally not an issue for offshore activities.

However, for the Ormen Lange field development the slide risk called for acceptance criteria limiting the risk exposure of the people living along the coastline from the potential Ormen Lange generated slide events.

Third party risk acceptance criteria are normally expressed as limitations on the risk to most exposed person and societal risk. This concept, however, is not well suited for evaluation of consequences of a tsunami generated by a submarine slide. The local variations in wave run-up along the coast and the general model uncertainties made it impossible to identify the most exposed person and predict (with any confidence) the consequences expressed as fatalities. The chosen criterion defined the risk as intolerable if the frequency of a slide with "significant damage potential" generated by Ormen Lange activities exceeds 10^{-7} per year. Significant damage potential was defined as a tsunami with vertical run-up exceeding 1.5 m in representative coastal areas. Risk-reducing measures must be considered if the frequency is greater than 10^{-7} per year.

The potential triggering mechanisms for inducing a submarine slide in the Ormen Lange area were extensively evaluated. Both natural and man-made triggers were considered, and only a strong earthquake was shown to be capable of triggering a new slide. The assessment of risks associated with slope instability consisted of the following steps (Nadim et al. 2005b):

- 1 Evaluate the potential triggering mechanisms for initiating a new slide.
- 2 Identify the critical slopes along the steep escarpments of the Storegga slide where new slides could be initiated
- 3 Quantify the uncertainty in the soil shear strength in different soil units, and the uncertainty in earthquake motion (e.g. peak acceleration, frequency content, duration) and earthquake load effects (e.g. cyclic and

- permanent shear strains induced in weak soil layers).
- 4 Compute the probability of static slope failure and probability of slope failure after a major earthquake (i.e. an earthquake with annual exceedance probability of 10^{-4} or lower).
- 5 Based on the evidence that the slopes have adequate static stability, update the computed failure probabilities. This may be done using a Bayesian updating framework.
- 6 Evaluate the annual probability of an earthquake-induced slide for all the critical sections of the Storegga escarpments, which might affect the Ormen Lange facilities.
- 7 Evaluate the total probability of an earthquake-induced slide happening anywhere along the escarpment by modeling the potential slides as components of a series system.
- 8 Evaluate the conditions required for a slide to generate a significant tsunami and estimate the probability for such conditions to be present.
- 9 Evaluate the annual probability of occurrence of a slide with 1st and/or 3rd party consequence based on the results obtained in Steps 6 and 7.

Steps 1 through 3 are described in Kvalstad et al. (2005), Steps 4 through 7 and Step 9 are described in Nadim et al. (2005b), and Step 8 is described in Løvholt et al. (2005).

The potential slides were categorized into three consequence classes:

- a) **Major consequence slide:** A slide that could cause 3rd party damage. The sliding scenario of concern in this context is a tsunami generated by slide that causes wave impact in inhabited areas along the coast.
- b) **Medium consequence slide:** A slide with potential damaging effect in the development area. Either a

Table 1. Results of the risk assessment for new slides in Storegga area (Guttormsen et al. 2003).

| Consequence class | Volume | Description | 1 st party consequence | 3 rd party consequence | Results of risk analyses ($P_{f,annual}$) |
|-------------------|--------------------------|---|---|--|--|
| Major | 100–3000 km ³ | Regional mega-slides that related to glaciation – de-glaciation periods | Damage to structures, wells, pipelines and control cables | Tsunami wave that causes damage along the coast | Natural causes: None No project-generated risk |
| | 5–100 km ³ | Slide initiating from upper headwall of Storegga slide | Damage to structures, wells, pipelines and control cables | Tsunami wave that could cause damage along the coast | Natural causes: $< 4 \cdot 10^{-8}$ No project-generated risk |
| Medium | < 5 km ³ | Slide initiating from upper headwall of Storegga slide | Severe damage to pipe lines and control cables | None | Natural causes: $< 2 \cdot 10^{-8}$ No project-generated risk |
| Small | < 0.3 km ³ | Shallow slide at upper headwall of Storegga slide | Local damage to pipelines and control cables | None | Natural causes: $\sim 10^{-5}$ No project-generated risk |

deep cut outside the development area or run-out from a slide in the upper head wall may typically give medium consequences.

- c) **Small consequence slide:** The effect of a slide is local and only equipment and structures in the vicinity of the slide, for example a pipeline in the steep headwall would be affected.

The results of the risk assessment studies for the Ormen Lange field are provided in Lund et al. (2004), Bryn et al. (2004) and Nadim et al. (2005b), and are summarized in Table 1 (after Guttormsen et al. 2003).

Main challenges and best practice in risk assessment for submarine slides

Risk assessment is basically a tool for making decisions in the presence of uncertainty and most important offshore projects today require some sort of risk quantification. The approach adopted for risk assessment for submarine slides and other offshore geohazards depends on the elements at risk and consequences of sliding. A general approach that could be applied in all situations is neither logical nor desirable. Geo-scientists play a major role in the risk assessment. They are expected to define the relevant and critical failure modes, assess the probability of their occurrence (hazard evaluation) and calculate and/or predict the consequences of failure. Fulfilling this role requires a good understanding of natural and human-induced effects in order to identify the relevant failure scenarios, as well as a close multi-disciplinary cooperation among geologists, geophysicists, seismologists and geotechnical engineers.

Typically, risk evaluation for offshore geohazards requires a staged approach. In the first phase the geo-scientists are required to:

- Establish the geological model of the region (age and source of sediments)
- Evaluate in-line and cross-line shallow and deep seismics in the region
- Identify main stratigraphy and buried features
- Identify signs of slide activity. Are the slides recent, or older buried features?
- Identify active faults in the area of interest
- Evaluate bathymetric information and seabed inclination and morphology
- Identify recent slide scars, fluid escape features, pock marks, mud volcanoes
- Look for signs of seabed instability, special features etc. upslope and downslope of the area of interest
- Establish whether there is earthquake activity in the area

The first assessment of a geohazard situation is done on the basis of the above evaluations and should address

the following questions:

- Are there elements at risk, locally or regionally, from submarine mass movements?
- What are the potential triggering mechanisms for seabed instability?
- What is the slope stability situation in high gradient areas?
- Is there a need for better information? i.e.
 - Should one obtain more information outside the main region of interest, for example detailed bathymetric maps upslope and downslope?
 - Are additional/extended seismic profiles required?
 - Is there a need for high quality geotechnical data and pore pressure measurements?

The second phase of evaluations typically includes:

- Evaluation of 3D seismics, well logs, detailed shallow seismics, detailed bathymetry and side scan sonar
- Re-interpretation of seabed morphology and potential signs of instability and slide mechanisms
- Evaluation of pore pressure conditions, signs of overpressure
- Planning and drilling geo-borings to acquire site-specific soil data. Focus should be on shear strength and brittleness (sensitivity) of soils.
- Assessment of deposition rate and potential for excess pore pressure
- Establish occurrence frequency vs. magnitude of earthquakes, mud volcano eruptions etc.
- Establish whether other ongoing natural processes, such as erosion and diapir displacements, are present.

The second assessment of geohazards situations for petroleum exploitation projects typically involves the following steps:

- Study the field development plans and associated geohazard failure scenarios
- Evaluate heat flow through wells and its potential for gas hydrate melting
- Evaluate the potential for underground blow-outs
- Evaluate reservoir subsidence and potential for induced earthquakes
- Is there human influence on the geohazards situation, e.g. installation of structures, anchors, pipeline supports etc.
- Is there need for quantification of failure probability and risk? If yes, is sufficient information available?
- Identify final site investigation program if sufficient information is not available, e.g. locations of geo-borings, field and laboratory testing and interpretation, need for pore pressure measurements, local bathymetric surveys/pipeline corridors

Depending on the outcome of the second geohazards assessment, a final geohazard evaluation may be required. This involves the following steps:

- Select relevant failure scenarios and associated trigger

mechanisms

- Identify, describe and quantify relevant trigger sources; magnitude and frequency
- Develop a geo-model of the area: stratigraphy, bathymetry, relevant soil data and their uncertainty
- Apply geomechanical models for analysis of failure scenarios (stability analyses, finite element analysis, fluid flow, heat flow, slide run-out, etc.) and assess model uncertainty
- Evaluate annual probability of failure
- Evaluate physical consequences of failure (loss of support, slide run-out and impact, tsunami generation and impact, etc.) and associated damage
- Calculate risk contribution of all geohazard failure scenarios
- Are the calculated probabilities and risk within clients' and authorities' acceptance criteria? If not, what actions could be taken to mitigate the risk?

The main challenges that face the geo-scientists today are related to risk assessment for deep and ultra-deep sites. Our knowledge, technology and tools required for deep and ultra-deep water site investigations have improved significantly in the past decade. However, further improvements in the following areas are needed to reduce the uncertainties:

- Geophysical/geological and geotechnical site investigation techniques
- Describing the geological models and geomorphology in terms of numbers that could be used by other disciplines for quantitative risk assessment
- Control on possible deepwater effects on soil behavior in situ and the effect of sample disturbance
- Identification of shallow, weak layers that may affect the seabed stability
- Location and quantification of gas hydrates
- Tools and methodology for prediction and measurement of pore pressures
- Interpretation of sediment rate, stress conditions, pore pressure conditions
- Field measurements, monitoring, and early warning
- Analysis tools for assessment of seabed instability and failure probability
- Material models, mechanical models and analysis tools for stability assessment
- Slope stability and dynamic slide mechanisms (progressive and retrogressive failure)
- Effect of earthquake loading on soil strength and post-earthquake stability
- Effects of gas hydrates on soil behavior
- Probabilistic methods and quantification of uncertainty
- Analysis tools and methods for evaluation of consequences, e.g.
 - slide dynamics and run-out
 - slide velocity and impact
 - tsunami generation, impact and run-up

In summary, the objective of this paper was to present an overview of present experience, methodology and tools applied in risk assessment for submarine slides and to point out the challenges to geo-scientists and areas where further improvement is required. The field is undergoing continuous development and "best practice" will inevitably change and improve in the process.

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Appendix A

Glossary of selected terms in risk assessment

(recommended terminology by TC32 of ISSMGE, www.engmath.dal.ca/tc32)

Annual exceedance probability (AEP): The estimated probability that an event of specified magnitude will be exceeded in any year.

Consequence: In relation to risk analysis, the outcome or result of a hazard being realized.

Danger (Threat): The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as potentially unstable sediments). The characterization of a danger or threat does not include any forecasting.

Elements at risk: Population, buildings and engineering works, infrastructure, environmental features and economic activities in the area affected by a hazard.

Frequency: A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials (see also likelihood and probability).

Hazard: Probability that a particular danger (threat) occurs within a given period of time.

Individual risk to life: The increment of risk imposed

on a particular individual by the existence of a hazard. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the hazard did not exist.

Likelihood: Conditional probability of an outcome given a set of data, assumptions and information. Also used as a qualitative description of probability and frequency.

Probability: A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity, or the likelihood of the occurrence of the uncertain future event.

There are two main interpretations:

- i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It includes also the idea of population variability. Such a number is called an "objective" or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
- ii) Subjective probability (degree of belief) – Quantified measure of belief, judgment, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgment regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment. Quantitatively, Risk = Hazard x Potential Worth of Loss. This can be also expressed as "Probability of an adverse event times the consequences of that event".

Risk analysis: the use of available information to estimate the risk to individuals or populations, property or the environment, from hazards. Risk analyses generally contain the following steps: definition of scope, danger (threat) identification, estimation of probability of occurrence to estimate hazard, evaluation of the vulnerability of the element(s) at risk, consequence identification, and risk estimation. Consistent with the common dictionary definition of analysis, viz. "A detailed examination of anything complex made in order to understand its nature or to determine its essential features", risk analysis involves the disaggregation or decomposition of the system and sources of risk into their fundamental parts.

Qualitative risk analysis: An analysis which uses word form, descriptive or numeric rating scales to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

Quantitative risk analysis: An analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Risk assessment: The process of making a decision recommendation on whether existing risks are tolerable and present risk control measures are adequate, and if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk analysis and risk evaluation phases.

Risk control: The implementation and enforcement of actions to control risk, and the periodic re-evaluation of the effectiveness of these actions.

Risk evaluation: The stage at which values and judgment enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk management: The systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, mitigating and monitoring risk.

Risk mitigation: A selective application of appropriate techniques and management principles to reduce either likelihood of an occurrence or its adverse consequences, or both.

Societal risk: The risk of widespread or large scale detriment from the realization of a defined risk, the implication being that the consequence would be on such a scale as to provoke a socio/political response.

Temporal spatial probability: The probability that the element at risk is in the area affected by the danger (threat) at the time of its occurrence.

Tolerable risk: A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Vulnerability: The degree of loss to a given element or set of elements within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). Also, a set of conditions and processes resulting from physical, social, economic, and environmental factors, which increase the susceptibility of a community to the impact of hazards.