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Risk assessment of natural hazards with applications to landslides and abnormal waves

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ABSTRACT: This paper presents a review of the state-of-the-art to identify emerging ideas and solutions which hold promise for practical implementation in risk management strategies of natural hazards with focus on landslides and extreme waves.

1 INTRODUCTION

It is always a difficult dilemma with research projects on natural hazards if it should focus on certain aspects of the hazard (its probability of occurrence, its damage potential, the effectiveness of mitigation measures and building codes, its human behavior and injury causation during the catastrophe, etc), or if the project should be addressed as a complete entity which involves physical, technological, economic and social realities. In this paper the first option is chosen, although now and then parts of the second option are presented.

Many books on natural hazards lack a serious academic treatment of the subject. This is in contrast with one of the first complete treatises on natural hazards by White et al. (1975). Since the book is over 30 years old, many of the issues in this book are outdated unfortunately. It describes the status of natural hazards research in the USA in the 70s, and it gives recommendation for future research. The main message in their book is that research in the 1970s concentrated largely on technologically oriented solutions to problems of natural hazards, instead of focusing equally on the social, economic and political factors which lead to non adoption of technological findings, or which indicate that proposed technological steps would not work or only tend to perpetuate the problem (according to the authors).

For floods the authors propose five major lines of new research: Improving control and prediction, Warnings and flood proofing, Land Management, Insurance, Relief and Rehabilitation basic data and methods. For other natural hazards, 15 in total, similar lines are outlined. Interesting is that the authors already present methods of estimating research results within an evaluation framework, including economic efficiency, trade-offs and values.

Bryant (1991) gives a complete overview on natural hazards, as well as its social impacts. Apart from how natural hazards occur, the author also presents (controversial) methods how to predict hazards from occurring again (on short and long term). The author claims that there is sound scientific evidence that cosmic/planetary links exist with the occurrence of earthquakes and floods. The 11-year sunspot cycle and the 18.6-year lunar cycle (caused by the moon's orbit fluctuation) are used to show a correlation with the ENSO index, occurrences of floods and droughts in North America, Northern China, Australia, Patagonia, amongst others.

Very surprising Bryant (1991) shows that in some parts of the world (such as the Mediterranean) the sunspot frequency and the seismic activity are correlated, via fluctuations in the Earth's rotation (in the order of milliseconds). However, if earthquake occurrence is dominated by some force external to the Earth (as mentioned by the author), then one would expect clustering to be taking place at the same time worldwide, which is not supported by the data.

Cannon et al. (1994) claim that natural disasters are not only caused by the natural environment, but also (or maybe even more) by the social, political and economic environment. This is shown throughout their work when they concentrate on the various hazard types: floods, coastal storms, earthquakes, landslides, volcanoes, biological hazards and famine. The authors consistently use a flow diagram describing the framework of the root causes, dynamic pressures, unsafe conditions (on the one side), the hazard (on the other side), and the disaster (in the middle).

Cannon et al. (1994) describe 12 principles towards a safer environment. It cannot be made by technical measures alone. It should address the root causes by challenging any ideology, political or economic system which causes or increases vulnerability. It should reduce pressures by developing by macro forces such as urbanization, reforestation, a.o. It should achieve safe conditions by protected environment, resilient local economy and public actions, such as disaster preparedness. Together with technical measures to reduce certain hazards (such as flood defenses, shelter breaks, etc), it should all lead to a substantial reduction in disaster risk.

The authors illustrate natural hazards from a social studies point of view, with striking observations, such as the bureaucratic blindness and biased relief assistance in South Carolina following hurricane Hugo in 1989 to the needs of many African Americans who lacked insurance and other support systems. The huge North Vietnam floods in 1971 only resulted in a few hundred deaths, largely because of a highly efficient wartime village-level organization that allowed rapid evacuation and provision of first aid, whereas the similar 1970 Bangladesh floods killed a record 300,000 people.

Natural hazards considered under climate change have been studied by McGuire et al. (2002) and heavily based on the results of the 3rd assessment report of 2001 by the IPCC (Intergovernmental Panel on Climate Change), who upgraded their temperature rise forecasts to 8 degrees Celsius by the end of the century. The natural hazards in McGuire (2002) are described in the light of IPCC's forecasts.

Windstorms are described to anthropogenic climate change and are shown to have the potential for large changes for relatively small changes in the general climate. Its natural patterns of climate variability are discussed by McGuire, amongst which ENSO, NAO, and PNA (Pacific North American teleconnection). Studies are presented which try to observe and predict the frequency and severity of extreme windstorms on a spatial and temporal scale.

Also, river and coastal floods under global warming are examined. Most research on river floods has concentrated on changes in observed precipitation and prediction methods, but the authors also present non-climatic factors involving human influences on the river basin. Coastal flooding from tropical and extra tropical storms under sea level change is investigated, as well as sea temperature changes (heat—and cold waves).

The 1999 Venezuela landslides, causing 50.000 fatalities, have put this undervalued natural hazard on the agenda again. The authors concentrate on the water accumulation below the surface of unstable slopes. The landslide's theological properties (which resist the movement) are studied under environmental change.

McGuire et al. (2002) ends with some results from a recent paper in Science (v 289, p 2068–74, DR Easter ling et al.) on different forecasts of climate extremes. The authors plead for political will from industrialized countries such as USA, Japan and Australia to invert their increase in gas emissions before the hazardous aspects of climatic shift make themselves felt.

Many references are available on this subject but it was chosen to address only some books as examples of the state of affairs. These books provide an overview of the status of understanding in the field and make clear that there can be considered some 15 natural hazards, too many to be dealt with in this paper.

Based on the current understanding of the field, this paper starts by providing an overall approach on how to assess and deal with natural hazards from a risk analysis point of view. Then one application to the case of landslides is presented, as an example of how the methodology can be applied. Then a very recent problem area is presented, which has not yet been established as a natural hazard in the specialized literature, but which has been topic of recent in the recent past: the occurrence of abnormal or freak waves at sea.

2 A RISK MANAGEMENT APPROACH OF NATURAL HAZARDS

In recent years probabilistic and statistical approaches and procedures are finding wider applications in all fields of engineering science, starting from nuclear power aeronautic applications to structural mechanics and engineering, offshore and coastal engineering, and in more or less sophisticated forms are the base of many of the most recent versions of Structural Codes of Practice throughout the world. Detailed commentaries of these codes have been written as CIRIA (1977) or ISO (1973) reports. Applications to civil engineering are described by the comprehensive text of Benjamin and Cornell (1970). More recent similar comprehensive texts are Augusti et al. (1984) and Thoft-Christensen and Baker (1982). A general application to structures in a coastal environment is provided by Burcharth (1997).

Risk analysis is usually structured in:

1. analysis of hazard (risk source, natural processes causing damages),
2. analysis of failure (risk pathway, mechanisms through which hazard causes damages).
3. analysis of vulnerability (behavior of the risk receptors).

For the first analysis, extreme events and joint probabilities of natural processes making up the hazards should be statistically described. In the second analysis, components of the defense systems should be identified, characterized and processes leading to failure are deterministically described. In the third analysis, understanding and assessment of direct and indirect damages and intangible losses including risk perception and acceptance from population, social and ecological reaction (resilience). The second step is process specific and will be described below, separately for each considered hazard. This step is structured, however, in identification and prediction of failure modes, reliability analysis of defense structure or systems (combination of hazard statistics and structure behavior) and modeling of post failure scenarios aiming to identify damages.

Damages caused by natural disasters can be distinguished as economical and non-economical, depending on whether or not a monetary value can be assigned to a specific damage. In addition, these damages are distinguished as direct and indirect, depending on whether the damage is the results of direct contact with the natural hazard or whether it results from disruption of economic activity consequent upon the hazard (Penning-Rowsell, 1992). The economic approaches on the valuation of disaster generally pursue an objective of public policy: Given a set of courses of action to take to alleviate damages from hazardous events, what is the one with highest economic value? To answer that question, the literature has followed two approaches.

The first approach is that in which the value of a given public policy comes from the avoided damage. There is a series of damages associated with hazardous events, some of those that come to mind are loss of property, injury and loss of human life, or natural habitat disruption. Farber (2001) and Yohe et al. (1999) illustrate complex cases of valuation of property loss and disruption of economic activity caused by potential storm and flooding events. A qualitative list of potential losses can be found in Penning-Rowsell and Fordham (1994). A benefit transfer exercise consists in a statistical estimation of a function based on existing evidence in order to transfer value ("benefit") from the various study sites to the policy site, (Brouwer, 2000) and Bateman et al. (2000). On the basis of the evidence gathered to estimate the transfer function, it is possible to assess the risk of error in transferring values. End-users may then decide what risk they are willing to run for a particular application. The trade-off is between administering an expensive valuation survey (with low risk of error) and an inexpensive transfer of values with a potentially high risk of error depending on the particular site analyzed.

The second approach is more direct in the sense that the researcher directly asks the relevant public to value the public policy itself, including its effects on flooding risk and potential physical damage. This approach has been illustrated in Penning-Rowsell and Fordham (1994) and relies on "stated preferences" methods such as the contingent valuation or choice experiments; see Carson (2000) and Haab and McConnell (2002) for recent reviews on the former and Louviere et al. (2000) on the latter. Contingent Valuation surveys consisted of the following steps: survey design, whose aim is to draw up a questionnaire suitable for the specific situation considered; sample design, to provide guidelines to obtain a random sample; pre-test of 30/50 interviews to check the wording of the questionnaire; main survey on the field of at least 600 interviews. As regards sites under risk of flooding, in general it is possible to carry out: site specific surveys to obtain data about property damages and to estimate damages from flooding, and post-flood household surveys to identify the immediate needs of the flood victims and to assess the intangible or non-economical flood effects (Penning-Rowsell et al., 1992).

Historically human civilizations have striven to protect themselves against natural and man-made hazards. The degree of protection is a matter of political choice. Today this choice should be expressed in terms of risk and acceptable probability of failure to form the basis of the probabilistic design of the protection. It is additionally argued that the choice for a certain technology and the connected risk is made in a cost-benefit framework. The benefits and the costs including risk are weighed in the decision process. Engineering is a multi-disciplinary subject, which also involves interaction with many stakeholders (individuals or organizations who have an interest in a project). This paper addresses the specific issue of how numerical occurrence probability levels of natural hazards are both formulated and achieved within the context of engineering design and how these relate to risk consequence.

A proposal for a common framework for risk assessment of any type of natural hazard is given by adapting the general theoretical approaches to the specific aspects of natural hazards, such as mass movements, and extreme waves. The specific features of each case will be presented in this paper and it will be shown that the common procedure proposed is able to deal appropriately with the specifics of each of the natural hazards considered.

Statistical methods are abundantly available to quantify the probability distributions of the occurrences of different hazards with special topics such as treating very seldom events, dealing with spatial and temporal variability of data, as well as with joint occurrences of different types of data. The two cases will demonstrate the applicability of the general methods to the specific aspects of the data from mass movements, and extreme waves. The 1st step in a structured risk analysis of natural hazards is:

Step 1. Statistical analysis of observations
Data is collected from mass movements, flooding, extreme waves and earthquakes and analyzed with statistical methods. Proper tools are used in order to harmonies data which comes from different sources (for instance instrumental or historical observations of natural hazards).

Step 2. Integration of mathematical-physical models in probabilistic models
The possible progress of a natural hazard from phase I to phase I + 1 is described with transition probabilities in Markov models. Mathematical-physical models are used to generate data to be combined with observations and measurements for statistical analysis.

Step 3. Estimation of dependencies between natural hazards
Collected data from mass movements, flooding, extreme waves and earthquakes in some instances are analyzed with respect to linear correlations and non-linear dependencies. Mathematical-physical-based reasons can be investigated to explain the existence of correlations and dependencies between the occurrence of hazards at the same time.

Step 4. Use of multivariate statistical models
Joint Probability Distribution Functions (JPDFs) describe the probability that a number of extreme events happen simultaneously. Dependencies between events cause difficulties in deriving these JPDFs.

Elements characterizing the degree of the past and future hazards can be combined with indicators for the vulnerability of the inhabited areas or of infrastructure installations. In databases, the damage is expressed in terms of fatalities and damage costs for private buildings, infrastructure installations and agricultural land. In the next steps it is necessary to relate the expected physical damage to the expected economic losses and expected losses of life.

Step 5. Economic models to derive (in)direct consequences of hazards: FD-curves
Risk is considered as the product of probability and consequences. All natural hazards are analyzed with respect to their economic impacts on society. This leads to so-called FD-curves (the cumulative distribution function of the amount of damage D). Economic expertise is an important part in this step.

Step 6. Models to estimate loss of human lives: FN-curves.
Apart from economic damage, natural hazards can also lead to human casualties. Estimates are derived and covariates are found of the possible number of casualties caused by natural hazards.

Step 7. Cost-benefit transfer
The aim of step 7 is to examine whether or not it possible to transfer values from natural disasters mitigation, and in case it is, to extract a transfer function. First the different methodologies used to value hazardous events are compared and whether and how they can be aggregated. Then, the construction of the actual value database can be carried out. Finally, if sufficient data quality criteria are met, a statistical analysis is performed in order to extract a benefit transfer function for one or several categories of values of hazardous events.

The methods presently accepted to set the acceptable risk levels related to industrial risks can be considered and their applicability to set acceptable risk levels of natural hazards can be studied. An approach is proposed to determine risk acceptance levels for different types of natural hazards, discussing in particular the specific aspects of mass movements, flooding, extreme waves and earthquakes.

Step 8. Acceptable risk framework development
Decisions to provide protection against natural hazards are the outcome of risk analyses and probabilistic computations as an objective basis. Development of concepts and methods to achieve this are available from literature. It covers both multiattribute design and setting of acceptable risk levels. The research reinforces the concept that efficient design not only requires good technical analysis, but also needs to consider the social aspects of design as well and incorporate the concerns and aspirations of stakeholders. Each stakeholder has a different perspective on the objectives of a particular project and it is the designer's challenge to manage these multiple concerns and aspirations efficiently. If the efficiency of decision making can be improved then it is quite possible that a 5% saving or larger can be achieved.

The main approaches to assess costs and benefits of different risk reduction measures can be analyzed dealing in particular with the approaches to deal with multiple risk and to take in consideration their interaction. An approach is proposed to determine actions leading to As Low As Reasonably Possible (ALARP) levels of risk for different types of natural hazards, discussing in particular the specific aspects of mass movements, flooding, extreme waves and earthquakes. For cost benefit analysis it is necessary to have models of the costs and of the benefits. Rough estimates on these numbers for the two cases will be shown in Sec. 3 and 4.

Step 9. Cost analysis of mitigation measures
In order to reduce the risks of natural hazards, mitigation strategies are applied. To answer the question if more mitigation is necessary (or in general the question "how safe is safe enough"), insight is developed in the costs of mitigation measures of natural hazards.

Step 10. Effectively analysis of mitigation measures
Apart from insight in the costs of mitigation measures, it is also necessary to quantify the effectively of these measures, in other words, how much can they reduce the consequences of natural hazards or reduce the probability of occurrence of these negative impacts.

The above 10 steps are proposed as an overall integrated and structured way to analyze risks from natural hazards and are identified as 'best practice'. In Sec. 3 and 4, two types of natural hazards will be discussed in detail, namely landslides in Sec. 3 and freak waves in Sec. 4.

3 CASE STUDY ON RISK ANALYSIS OF LANDSLIDES: GLOBAL HOTSPOTS

Landslides cause major disasters on a global scale every year, and the frequency of their occurrence seems to be on the rise. The main reasons for the observed increase in landslide disasters are a greater susceptibility of surface soil to instability as a result of overexploitation of natural resources and deforestation, and greater vulnerability of the exposed population as a result of growing urbanization and uncontrolled land-use. Furthermore, traditionally uninhabited areas such as mountains are increasingly used for recreational and transportation purposes, pushing the borders further into hazardous terrain.

Climate change and the potential for more extreme weather conditions may also be a contributing factor. Recent examples of major slide disasters are the debris floods and mudflows in Venezuela in December 1999, which caused over 20,000 fatalities; the El Salvador earthquake of January 2001, which caused 600 fatalities in just one landslide; and the debris flows and landslides on Hispaniola Island in May 2004, which caused over 2,500 fatalities in Haiti and the Dominican Republic.

Although slides and avalanches occur more frequently than other major natural hazards, in terms of the number of fatalities from different hazards, they rank rather low as seen from Table 1. There is however, reason to believe that the number of causalities due to landslides shown in the table is grossly underestimated. This is because the loss figures in the international data bases are normally recorded by the primary triggering factor, and not by the hazard that causes the fatalities. For instance the 1999 Venezuela Disaster with more that 20,000 deaths is recorded as a flood, while most fatalities were caused by landslides in form of debris flows and mud flows.

Information on natural hazards, vulnerabilities and risks at an appropriate scale is of fundamental importance for the design and implementation of policies and programs for risk mitigation. Contingency planning, disaster preparedness and early warning systems require the knowledge of what kind of losses could be expected from what type of hazard. Lack of such data on a global scale led to an initiative from the ProVention Consortium of the World Bank to launch a collaborative project on "Identification of Global Natural Disaster Hotspots" in 2001—the "Hotspots Project", for short. The aim of the Hotspots Project was to perform a global assessment of the risk of mortality and economic losses for six major natural hazards: droughts, floods, windstorms, earthquakes, landslides and volcanoes. The results of the project are available in a World Bank publication (Dilley et al., 2005).

This section describes the assessment of the global distribution of landslide hazard and risk, which was performed by the Norwegian Geotechnical Institute (NGI), (Nadim et al., 2006) in collaboration

Table 1. Ranking of major natural hazards by number of deaths reported in EM-DAT (2003).

Rank	Disaster type	All deaths	Deaths 1992–2001*
1	Drought	563,701	277,574
2	Storms	251,384	60,447
3	Floods	170,010	96,507
4	Earthquakes	158,551	77,756
5	Volcanoes	25,050	259
6	Extreme temperature	19,249	10,130
7	Landslides	18,200	9,461
8	Wave/surge	3,068	2,708
9	Wild fires	1,046	574
Total		1,211,159	535,416

*2002 IFRC World Disaster Report (http://www.cred.be/emdat/intro.htm) with the United Nations Environment Programme (UNEP) and Global Resource Information Database (GRID-Europe) for the Hotspots Project.

3.1 *Landslide hazard assessment*

The general approach adopted in the study for the identification of global landslide hazard and risk hotspots is depicted in Figure 1. The study focused on slides with rapid mass movement, like rockslides, debris flows, snow avalanches, and rainfall- and earthquake-induced slides; which pose a threat to human life. Slow moving slides have significant economic consequences for constructions and infrastructure, but rarely cause any fatalities. The risk computation was calibrated against the past human losses recorded in various natural disaster impact databases. The estimation of expected losses was achieved by first combining frequency and population exposed, in order to provide the physical exposure, and then performing a regression analysis using different sets of uncorrelated socio-economical parameters in order to identify the best indicators that were the best proxy for approaching human vulnerability to landslides in a given country.

Details of the landslide hazard and risk estimation models are provided in the paper by Nadim et al. (2006). A brief summary is provided in this section.

Landslide hazard level depends on the combination of trigger and susceptibility (Figure 1). In the first-pass estimate of landslide hazard, five parameters are used:

i. slope factor within a selected grid (S_r), range of index: 0–4;
ii. litho logical (or geological) conditions (S_l), range of index: 1–5;

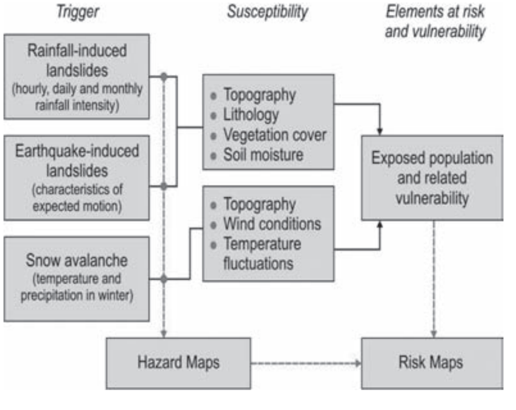

Figure 1. General approach for landslide hazard and risk evaluation.

iii. soil moisture condition (S_h), range of index: 1–5;
iv. precipitation factor (T_p), range of index: 1–5; and,
v. seismic conditions (T_s), range of index: 1–10.

The relative landslide hazard level was estimated using a model similar to that suggested by Mora and Vahrson (1994) for regional analyses. For each factor, an index of influence was determined and the relative landslide hazard level $H_{landslide}$ was obtained by multiplying and summing the indices using the following equation:

$$H_{landslide} = (S_r \cdot S_l \cdot S_h) \cdot (T_s + T_p) \qquad (1)$$

The following sources were used to obtain the input data in Equation 3.1.

Slope factor, S_r: NASA's global elevation dataset SRTM30 was used as the starting point. After correcting the anomalies by using other datasets, Isciences (www.isciences.com) derived the grid of slope angles for the study.

Litho logy factor, S_l: The dataset used in this study was the Geological map of the World at 1/25,000,000 scale published by the Commission for the Geological Map of the World and UNESCO (CGMW, 2000).

Soil moisture factor, S_h: The data for th2 study were extracted from Willmott and Feddema's Moisture Index Archive (Willmott and Feddema, 1992).

Seismicity factor, T_s: The data set used for the classification of the seismic trigger factor was the expected Peak Ground Acceleration (PGA) with 475-year return period (10% probability of exceedance in 50 years) from the Global Seismic Hazard Program, GSHAP (Giardini et al., 2003).

Precipitation factor, T_p: The categorization T_p was based on the estimate of the 100-year extreme monthly rainfall (i.e., extreme monthly rainfall with 100 years return period). The source of data was the monthly precipitation time series (1986–2003) from Global Precipitation Climatology Centre (GPCC) run by Germany's National Meteorological Service, DWD (Rudolf et al., 2005).

The ranges of the parameters used in Equation 1 are given in Tables 2 through 6. The resulting land-

Table 2. Categorization of slope data.

Range of slopes angle (unit: degrees)	Classification	S_r
0–1	Very low	0
1–8	Low	1
8–16	Moderate	2
16–32	Medium	3
>32	High—Very high	4

Table 3. Categorization of susceptibility classes for litho logy.

Litho logy and stratigraphy	Susceptibility	S_l
• Extrusive volcanic rocks—Precambrian, Proterozoic, Paleozoic and Archean. • Endogenous rocks (plutonic and/or metamorphic)—Precambrian, Proterozoic, Paleozoic and Archean.	Low	1
• Old sedimentary rocks—Precambrian, Archean, Proterozoic, Paleozoic. • Extrusive volcanic rocks—Paleozoic, Mesozoic. • Endogenous rocks—Paleozoic, Mesozoic, Triassic, Jurassic, Cretaceous.	Moderate	2
• Sedimentary rocks—Paleozoic, Mesozoic, Triassic, Jurassic, Cretaceous. • Extrusive volcanic rocks—Mesozoic, Triassic, Jurassic, Cretaceous. • Endogenous rocks—Meso-Cenozoic, Cenozoic.	Medium	3
• Sedimentary rocks—Cenozoic, Quaternary. • Extrusive volcanic rocks—Meso-Cenozoic.	High	4
• Extrusive volcanic rocks—Cenozoic.	Very high	5

Table 4. Classification for soil moisture index.

Soil moisture index (Willmott and Feddema, 2002)	Susceptibility	S_h
–1.0––0.6	Low	1
–0.6––0.2	Moderate	2
–0.2–+0.2	Medium	3
+0.2–+0.6	High	4
+0.6–+1.0	Very high	5

Table 5. Classification of the 100-year extreme monthly.

100-year extreme monthly rainfall (mm)	Susceptibility	T_p
0000–0330	Low	1
0331–0625	Moderate	2
0626–1000	Medium	3
1001–1500	High	4
>1500	Very high	5

Table 6. The GSHAP PGA_{475} categorized into 10 classes.

PGA_{475} (m/s^2)	T_s
0.00–0.50	1
0.51–1.00	2
1.01–1.50	3
1.51–2.00	4
2.01–2.50	5
2.51–3.00	6
3.01–3.50	7
3.51–4.00	8
4.01–4.50	9
>4.50	10

slide hazard parameter, $H_{landslide}$, was used to identify 9 hazard classes as listed in Table 7.

3.2 *Landslide risk assessment*

A major part of the global hotspots project involved the prediction of the geographical distribution of landslide risk expressed as the number of people predicted killed per year per km^2. In these predictions the distribution of hazard, frequency of occurrence, and population density as well as loss figures from historical events were the major input parameters.

The regression analyses showed strong correlations between high risk and physical exposure, and high risk and low Human Development Index (HDI) as determined by United Nation Development Program (UNDP). The analysis also showed high correlation between high risk and high percentage of forest cover, which is somewhat surprising. This might reflect the fact that the countries with highest forest coverage might also be the ones with the highest degree of deforestation. Deforestation is an important factor that needs to be addressed in more detail (World Disaster Report 2004), but the parameter is difficult to determine on the global basis with the existing data sets. The percentage "arable land" also showed a strong correlation with landslide risk, which indicates that rural population are more vulnerable to landslides than urban population.

The result of the regression analysis for landslide risk is shown on Figure 2. It should be mentioned that out of the 249 countries that were included in the analysis, the model failed to explain landslide risk in nine countries. This demonstrates the need for better data sets, especially on deforestation.

Figures 3 and 4 respectively show the results of the landslide hazard evaluation for Central Asia

Table 7. Classification of the landslide hazard potential $H_{landslide}$.

Values for $H_{landslide}$	Class	Classification of landslide hazard potential	Approximate annual frequency in 1 km^2 grid
<14	1	Negligible	Virtually zero
15–50	2	Very low	Negligible
51–100	3	Low	Very small
101–168	4	Low to moderate	Small
169–256	5	Moderate	0.0025–0.01%
257–360	6	Medium	0.0063–0.025%
360–512	7	Medium to high	0.0125–0.05%
513–720	8	High	0.025–0.1%
>720	9	Very high	0.05–0.2%

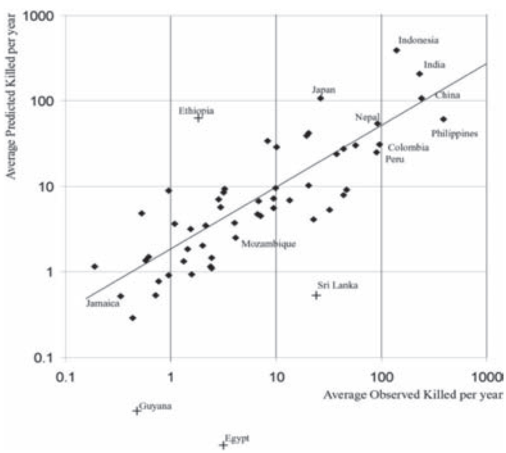

Figure 2. Predicted killed versus observed landslide fatalities.

Figure 4. Landslide hazard zonation for Central America.

Figure 3. Landslide hazard zonation for Central Asia and the Middle East (Nadim et al., 2006).

and the Middle East, and for Central America. Figures 5 and 6 show the predicted landslide risk in terms of expected human fatalities per year per km^2 for the same regions.

3.3 *Landslides Hot Spots*

The probability of landslide occurrence was estimated by modelling the physical processes and combining the results with statistics from past experience. The main input data used in the hazard assessment were topography and slope angles, extreme monthly precipitation, seismic activity, lithology, mean temperature in winter months (for snow avalanches) and hydrological conditions.

Although the first-pass analyses were done with relatively simple models, a fairly good estimate of landslide hazard was made by using the global data sets on slope, lithology, soil moisture, precipitation and seismicity. Validation of the global

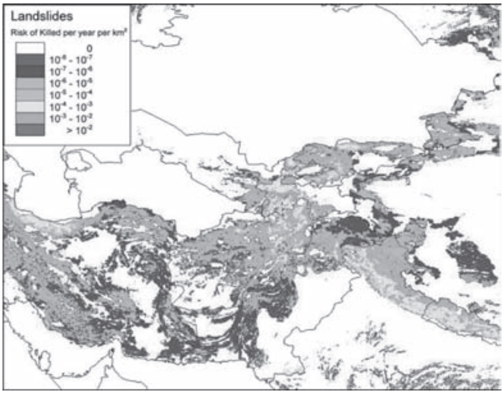

Figure 5. Landslide risk zonation for Central Asia (Nadim et al., 2006).

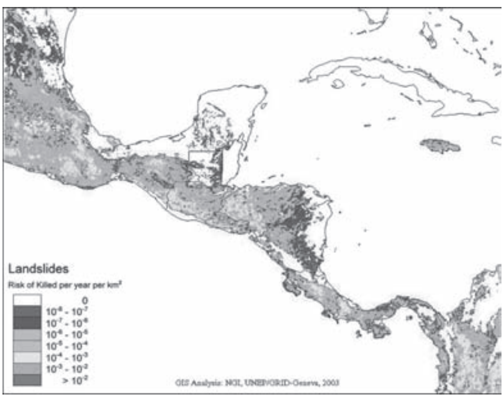

Figure 6. Landslide risk zonation for Central America (Nadim et al., 2006).

hazard prediction, which was carried out for 6 countries, namely Georgia, Armenia, Sri Lanka, Nepal, Jamaica and Norway, showed fair agreement between the boundaries of the known slide-prone areas and the hazard zones predicted by the global model. However, the analyses suffered from significant shortcomings in the quality and resolution of the available global data sets.

For the estimation of risk, the computations were based on human losses as recorded in various natural disaster impact databases. The estimation of expected losses was achieved by first combining the landslide frequency and the population exposed, in order to estimate the physical exposure, and then doing a regression analysis using different sets of uncorrelated socio-economical parameters.

The study identified the socio-economic parameters that seem to have the strongest correlation with expected fatality due to landslides. Improved data quality, adding new type of data sets to the model, and having loss data from the landslide-prone countries that are presently missing, are important for better understanding and identification of the most relevant socio-economic parameters that affect landslide risk.

Working in a smaller area, it should be possible to refine the analyses using better resolution in the input data, as well as adding supplementary parameters such as land cover, deforestation and effects of long-term climatic change. With use of more comprehensive sets of site-specific data, it should also be possible to make a prediction of economic losses with the model, and not only fatalities, as was done in this study. The study clearly showed that the following countries and geographical areas are among the landslide hazard hotspots:

- Central America
- North-western South America
- The Caucasus region
- The Himalayan belt
- Taiwan
- Philippines
- Indonesia
- Italy
- Japan

The conclusions of the study were all based on a global model, which does have shortcomings when applied at a local level. Use or interpretation of the results for specific national conditions is not recommended without further investigations. Several factors contribute to uncertainties in the predictions, the major one being the scarcity of high-quality, high-resolution data at a global scale.

4 NATURE AND PREDICTION OF FREAK, ROGUE OR ABNORMAL WAVES

Several full-scale measurements of extremely large waves have been reported by Kjeldsen, (1982), Sand et al. (1990), Skourup et al. (1996), Yasuda et al. (1997), and Haver (2004), among others. Several records of ships sunk or damaged by very large waves that were "appearing from nowhere" very suddenly (Kjeldsen, 1996; Faulkner and Buckley, 1997), have appealed for concerted efforts to understand these occurrences.

As the general believe is that these waves do not fall within the population of the random waves described by the various existent theories, they have been denoted as abnormal (Dean, 1990; Guedes Soares et al., 2003) and in some sense considered as rare occurrences as other natural disasters that one is used to deal with.

There has been much interest during last decade about abnormal or freak waves and various possible mechanisms for their generation have been identified, as reviewed by Kharif, and Pelinovsky (2003) and Guedes Soares et al. (2003), for example. However, the nature of abnormal or freak waves is not known yet, the wave generation mechanisms are not fully understood, and there is no generalized agreement about the criteria to classify one extreme wave as an abnormal one.

White and Fronberg, (1998), and Lavrenov, (1998) explained the appearance of the abnormal waves by a wave amplification due to current. Pelinovsky and Kharif (2000) modelled the temporal and spatial focusing as a result of the wind wave dispersion and of special distribution of its frequency. Trulsen and Dryste, (1997) and Osborne (2000) suggested that the Benjamin-Feir instability can cause breaking of a wave train into periodic groups, and further within each group a focussing takes place producing very large and steep wave. Henderson, et al. (1999) also suggested nonlinear instability as a cause of the big waves. Other approaches to focusing waves in model basin are due to Clauss (2002) and Bateman et al. (1999).

Whatever the nature of the generation process, the designers and operators of marine structures require information about the representative shapes of these large waves so that they can be appropriately considered in design. This is supported by the examples of heavy weather damages caused by giant waves that have been presented in the literature during the last twenty years, as for example by Kjeldsen (1996), and Faulkner and Buckley (1997), which contributed to a more widespread belief that the damage to engineering facilities operated at sea for extended periods is often determined by the few extreme sea states than by the frequent and moderate ones. Also in these sea states the damage will generally be induced by few extreme waves than by the large majority of other waves. Therefore in the engineering communities there has been a major interest in properly understanding and describing the conditions associated with extreme waves so that they can be used in the design process of ships (Fonseca et al., 2006, Guedes Soares et al., 2008) and offshore structures (Clauss et al., 2002, 2004b, Fonseca et al., 2008).

While in the earlier publications these waves were designated as *freak*, some later considered that term to be inaccurate and began to call them *rogue* waves. However, as these waves are being defined as the ones that are outside of the normal population of expected waves, they also became known as *abnormal* waves. When they appear in the literature these terms should be understood as equivalent.

The designations and definitions used for freak, rogue or abnormal waves seem to vary widely. The quantitative criteria to identify one such wave from a wave trace that is most used presently can possibly be traced back to Dean (1990), who defined it as a wave that would be outside the normally expected ones within the accepted linear wave theory. Based on 20 minutes duration and the Rayleigh model for wave height he concluded that in those cases waves with a height larger than twice the significant wave height would be already a freak wave.

Tomita and Kawamura (2000) suggested that in addition to the abnormality or amplification index $AI = H_{max}/H_S$ a crest index $CI = C_{max}/H_S$ should also be considered in the definition of an abnormal or freak wave. They called genuine freak waves the ones that satisfied both criteria $AI > 2$ and $CI > 1.3$ while the ones that only satisfied one of the criteria were designated simply as freak waves. Clauss (2002), on the other hand applies a combination between the abnormality index and some global wave parameters. For him an abnormal wave should have $H_{max} \geq 2.15H_S$ and $cr_{max} \geq 0.6H_{max}$. These ratios have had a tendency to become the standard ones for identification of this type of waves despite being associated with a linear theory assumption and with a given wave record duration.

While for ships and other floating structures wave height is governing for its dynamic behaviour and associated loads, in the case of fixed offshore platforms wave crests are more important as they can impinge decks. The differences between wave heights predicted by linear and second order theory are not very large but the differences in crest height are significant. This explains why in the offshore industry the use of second order theory is much more widespread than within the ship industry.

Accordingly Haver (2004) provided an updated definition for rogue waves as being the ones that have a height, crest or steepness that would represent an outlier as compared with the values predicted by second order theory. However there is still no consensus on how that formulation translates in thresholds of H_{max}/H_S or C_{max}/H_S which are the ones adopted by most researchers.

Guedes Soares et al. (2003) have analysed records of wave measurements in the North Sea and concluded that indeed in several cases the sea states in which abnormal waves occurred would not conform to second order theory, as in this case the excess of kurtosis of the sea state should be zero, which was not observed in the data.

Various recent papers have presented the analysis of extreme and abnormal waves recorded in the North Sea (Guedes Soares et al., 2003; Stansell, 2004), Japan Sea (Mori et al., 2002), Black Sea (Divinski et al., 2004), the Gulf of Mexico (Guedes Soares et al., 2004a) and off the coast of Taiwan (Chien et al., 2002). Measurements of many individual waves should receive more attention, since many are necessary to identify true rogue waves.

Indeed, although there are yet not many sets of data to support probabilistic assessments, Guedes Soares et al. (2003) have suggested that the probability of occurrence of such waves in the North Sea could be of the order of 10^{-7}.

There is at present an unfortunate compromise to be made between quality and quantity of measurements, and little progress should be expected until numerous measurements such as satellite ones with SAR instruments (Lehner, 2005) become more reliable, or measurements with reliable sensors such as those from offshore platforms become more numerous.

Numerical models are in progress, focusing mainly on the analysis of non-linear interactions, mixing long and short-term interactions, so as to explain how these waves can be formed and disappear. The studied wave characteristics generally do not actually correspond to situations representative of the sea-state design conditions (pure wave packet, no energy exchanges with wind or wave breaking), i.e., situations closer to swell/wave pure propagation.

As for the theoretical basis, long time evolution of the Benjamin-Feir instability, is now generalized to the appearance of an envelope solution and breather type solutions, which are regarded as seeds of freak waves in the coherent sea. Kharif and Pelinovsky, (2003) have presented an interesting review paper of the various theories and approaches adopted.

Janssen (2003) presented a paper on the occurrence of freak waves including theoretical models of four-wave interaction, numerical simulations using the Monte Carlo technique and stochastic properties in a real seaway. Using the Nonlinear Schroedinger equation as well as the Zakharov equation he accommodated coherent resonant and non-resonant interaction of sea waves with both homogeneous and inhomogeneous random processes having a high value of kurtosis in relation to the Benjamin-Feir Instability index (BFI) (Mori and Janssen, 2004).

Slunyaev et al. (2005) have conducted numerical studies to explain the propagation of various abnormal waves measured in the North Sea. They considered the Dysthe equation, the Nonlinear Schroedinger equation and also the focusing effect with linear theory. They concluded that the Benjamin-Feir instability is important for the description of freak wave evolution, while the significant wave enhancement by itself may be achieved even in the linear approximation.

Onorato et al. (2004) conducted extensive wave tank measurements in a large offshore tank with emphasis on the role of BFI parameter (0.2, 0.9, 1.2) using the JONSWAP spectra. The probability of high waves was found to increase with BFI parameter (it represents the ratio of wave steepness to spectral bandwidth). Clauss et al. (2004a), Ten and Tomita (2005) and Waseda et al. (2005) examined both physically and numerically, the generation of freak waves in a wave tank.

Numerical and tank simulations do not correctly account for the random variations of the sea state details, and the insights that they do provide on the mechanisms of extremes are limited to a small neighbourhood in space and time around the wave that is considered. Actual waves at a few wavelengths or periods away from the extreme no longer fit with the model ones because of the influence on the system of energy sources (directional focusing, wind shear) and sinks (breaking, etc.). However the models can be very important for assessing the effect of such waves on ships and offshore platforms.

Clauss et al. (2004b) and Guedes Soares (2006) have conducted tank tests to assess the motions and bending moments induced by an abnormal wave on a FPSO.

Concerning the probabilistic description of the abnormal waves, reference is made to the work of Mori and Janssen (2004), who included the effect of kurtosis in his earlier formulation and concluded that the occurrence probability of a freak wave would depend linearly on kurtosis for a small number of waves. Stansell (2004) has adopted distributions of extremes to fit freak waves measured in the North Sea and concluded that the Rayleigh distribution under-predicts the occurrence of these freak waves. Stansell (2005) also studied the distributions of wave crests and troughs and concluded that the statistics of wave crests and troughs depend strongly on significant wave height.

Efforts have been made to use forecast data to infer what might be the probability of occurrence of abnormal waves, or at least to include this information in marine forecast warnings. Holt et al. (2004) aimed at forecasts from which a Benjamin-Feir index would be calculated and used to determine when to issue warnings. However, parameters inferred from theoretical results, such as the Benjamin-Feir Instability index exhibit a high variability and the shape of the hindcast spectra is not very accurate making the quantification of the indices from such spectra very uncertain and thus of little real use.

Hindcast data can be used to provide a more global analysis of the sea state situation in space or in time (Boukhanovsky et al., 2004). In fact the analysis of several cases of occurrence of abnormal waves has shown that in general they were associated with very quick transitions of spectral shape at the location so that Lopatoukhin et al. (2005) suggested that the probability of this kind of transition could be used as an indication of the probability of occurrence of abnormal waves.

Another interesting issue related with the freak waves is the ability to describe their shape.

Theoretically the normalized autocorrelation function of a Gaussian distributed processes presents the most likely profile in some neighborhood of a normalized extreme, be it a crest or a trough. For ocean waves, even for the largest ones, Gaussianity is established to some level of confidence. Therefore Tromans et al. (1991) proposed the New Wave method, which uses the autocorrelation function to estimate design wave profiles.

The New Wave model proves to be very flexible, to predict mean profiles, with a domain of application that includes severe states. However, care should be exercised when describing individual crests especially in sea states that have large skewness and large kurtosis. Indeed it has been shown by Guedes Soares et al. (2004b) that the individual large waves in storms are asymmetric and thus the New Wave theory, which predict symmetric profiles could not be applicable in all cases.

5 CONCLUSIONS

This paper has introduced the area of natural risks and has presented a framework to deal with them within a risk based approach. The variety of natural risks is large and thus only one (landslides) was chosen to discuss in more detail its characterization on a risk setting. Finally the emerging area of abnormal or freak waves was addressed and a review was presented of the main recent achievements.

While not aiming to be comprehensive, the risk based approach has been formulated and applied to the established area of landslides, suggesting directions that can be adopted for other natural hazards.

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