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On probability in risk analysis of natural disasters

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Abstract

Purpose – The purpose of this paper is to show how the common practice of applying the frequency interpretation of probability in risk analysis of so-called low-probability and high-consequence disasters can prove to be flawed, and to present a possible remedy.

Design/methodology/approach – The common practice is reviewed by using the Åknes case from Norway where an up to 100 million m^3 rock slide is threatening one of Norway's most visited tourist sites, Geiranger. The same case is also reworked using the alternative approach and then a comparison is made. The study is therefore a comparative study.

Findings – The paper clearly shows the fallacy of using the frequency interpretation of probability in cases where the data are limited because the natural disasters under study appear very rarely. By exploiting the fact that responsible decision-makers in public offices cannot claim that human losses today are worse than human losses tomorrow (human lives cannot be discounted, as it were), the alternative approach provides much more realistic decision-support.

Practical implications – The paper presents a new approach to analyzing the risk of low probability, high impact natural disasters that can be readily applied in other low probability, high consequence cases.

Originality/value – As far as is known, the paper presents an original contribution to the analysis of risk of low probability, high consequence natural disasters in that it is shown that the commonly used frequency interpretation of probability can prove to be flawed in such cases. An alternative approach is provided.

Keywords Probability calculations, Frequencies, Risk analysis, Natural disasters

Paper type Research paper

1. Frame of reference

Natural disasters have always been a part of human existence, but for the majority of our history we have seen natural disasters as acts of the gods. To avoid disasters we had to appease the gods in various ways.

Luckily, as risk analyses have come to age, these techniques have lifted disaster management away from the superstitious to the more scientific, but even today natural disasters claim many lives – in fact, the last two decades have claimed more than 1.5 million people due to natural disasters (United Nations Development Programme, 2004). Unfortunately, risk analyses are not without problems because the choice of risk analysis approaches may impact the identification of risk sources in terms of magnitude and location, see (Emblemsvåg and Kjølstad, 2006). In fact, three independent consulting companies performed a risk analysis of the same hydro-electric power plant and reached widely different conclusions as reported by Backlund and Hannu (2002). Risk analyses have also lead to decision-makers taking risks they otherwise would not have taken, see (Bernstein, 1996). For example, the Vajont disaster in Italy in 1963, where at least 2,000 lives were lost, was due to over-reliance on the models of engineers and geologists that failed to read the signs of the mountain. This

Disaster Prevention and Management
Vol. 17 No. 4, 2008
pp. 508-518

0965-3562
DOI 10.1108/09653560810901755

disaster has become a classic example of the consequences of the failure of engineers and geologists to understand the nature of the problem that they were trying to deal with.

In the next sections, a critical problem of the traditional risk analysis in Disaster Prevention and Management (DPM) is discussed in detail and how it can be remedied. The problem starts by the very definition of probability and hence the estimation of probability. It should be noted that there are other shortcomings as well, but that they are not addressed in this paper. The interested reader are referred to (Emblemsvåg and Kjølstad, 2002, 2006) for thorough discussions on various problems with the traditional risk analyses. In Section 3, the Åknes case is presented to illustrate the problem and a possible remedy. A closure is provided in Section 4.

2. The dangers of frequency interpretation

Since I do not intend reviewing the entire risk analysis process, interested readers on the process of risk analyses are referred to (ICAEW, 2000; Government Asset Management Committee, 2001; Kohler *et al.*, 2004; Kunreuther *et al.*, 2004; United Nations Development Programme, 2004). Note that terminology differs from one source to the other, but they all define risk as the combination of probability and consequence in some way or the other. Some also prefer to distinguish between the probability and the measure of probability as well as consequence and its measure while others do not make such distinctions at all.

First, I would like to stress that probability can be defined in many ways using other terms like subjective probability and possibility that incorporate many similar ideas but not exactly the same ideas, see the discussion in (Emblemsvåg and Kjølstad, 2002). Consequently, probability can be assigned in countless ways. The most common approach regardless of domain – according to Honderich (1995) – is based on the so-called frequency interpretation of probability. This holds that for n repetitions of an experiment (Cramér, 1966):

> The probability that the frequency ν/n differs from its mean value p by a quantity of modulus at least equal to ε tends to zero as $n \rightarrow \infty$ however small $e > 0$.

For example, if something has occurred ten times over a 200 year period the probability estimate would be one occurrence pr 20 years or 5 per cent probability of occurrence pr year. Using data like this are very common in DPM to estimate probability, but this definition can be highly deceptive and lead to erroneous conclusions as is illustrated in Section 3. The reason is that there are certain assumptions that are difficult to fulfill in natural settings. The most important one for this paper is (see Hodges and Lehmann, 1964) that the conditions of the repetitions must remain constant. If that is not the case, the probability estimates are not reliable. With this in mind, the problems are clearly visible for low probability disasters such as large rockslides, see Section 3.1. First, derived from the very definition; the frequency of occurrence is low (n is small). In other words; in a geological perspective we have virtually no data available for estimating the frequency. Second, a violation of the aforementioned assumption; areas of instable rock slopes erode and change constantly so that the conditions change. In other words, none of the important assumptions associated with the frequency interpretation of probability are fulfilled. The theoretical basis for using frequency for estimating the probability is therefore risky – particularly when the data are very limited.

If we are to use the frequency interpretation of probability we must be able to model the fact that deteriorating conditions leads to an accelerating frequency, i.e. the probability of failure increase exponentially from year to year as we approach the time of failure, and we need a long geological record as a basis for data sampling. While the latter is possible to solve realistically, the former is very difficult if not impossible. It would be impossible for two reasons:

1. we do not know when the fractures in the rock formations started; and
2. we do not know what the critical fracture size right before failure is.

Moreover, these two parameters would ideally have to be known for a large variety of rockslides in order to take into account the problem of random variations. To date, none of these problems have been solved to my knowledge.

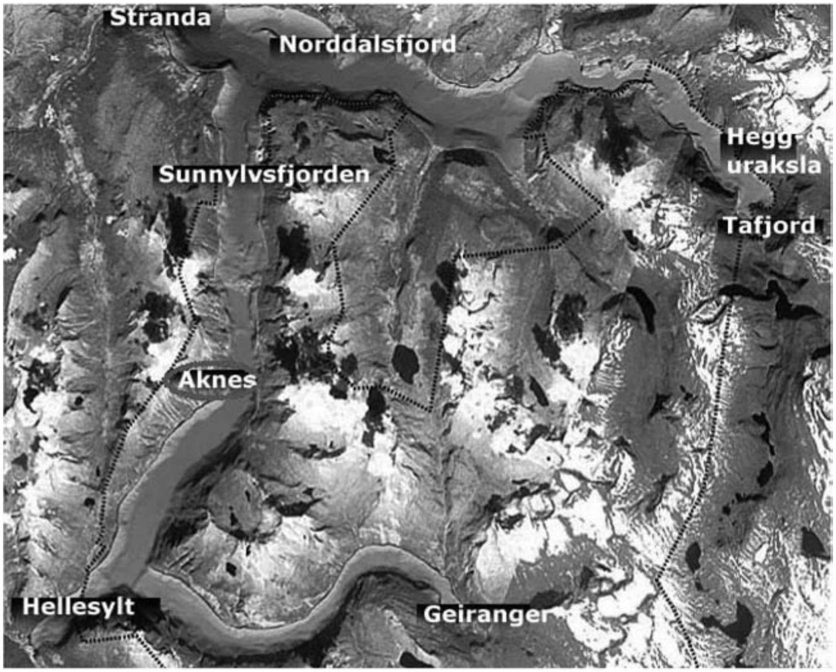
To omit this problem, probability is defined as "degree of belief" in this paper in which probability is a relative term – in other words, probability can be only defined relatively to something else. This can be accomplished relatively easily as explained in Section 3.2. The absolute sense of probability which requires probability to be mutually exclusive and all exhaustive (classic probability theory) is thus rejected on the grounds that it is impossible to operationalize due to the limited set of data available. Furthermore, nobody can identify all risk exhaustively and many are interrelated or interdependent and hence not mutually exclusive regardless of the access to data. For a thorough discussion on this, see (Emblemsvåg and Kjølstad, 2002).

Before continuing the definition of risk and uncertainty applied in this paper should be presented. According to *Webster's Encyclopedic Unabridged Dictionary of the English Language* (1989), risk is the "exposure to the chance of injury or loss; a hazard or dangerous chance", and risk can be measured as "the degree of impact combined with the degree of belief", see (Emblemsvåg and Kjølstad, 2002). That is, risk arises due to choices made or choices not made – we choose to expose ourselves to a natural hazard. Uncertainty, on the other hand, exists in two distinct forms: fuzziness and ambiguity. Fuzziness occurs whenever definite, sharp, clear or crisp distinctions are not made whereas ambiguity is the result of unclear definitions of various alternatives (outcomes). Uncertainty is therefore the result of lack of information or clarity, and has nothing to do with choice. For a more extensive discussion on the nature of risk and uncertainty see (Emblemsvåg and Kjølstad, 2002).

In the next section, the danger of using the frequency interpretation of probability is illustrated in a specific case.

3. The Åknes case

Åknes (or Åkernes) is a bend in an about 500 meter deep fjord in the northwestern part of Norway called Synnylvsfjorden. The surrounding mountains are roughly 1,500 m high (see Figure 1). With such steep mountains, this beautiful area is treacherous. So far, the geologists have identified about 70 rockslides larger than 0.5 million m^3 in this area since the last ice age (Blikra *et al.*, 2006a). The largest rockslide in this area – it is in fact visible in Figure 1 right below the text "Synnylvsfjorden" – is estimated to be around 400 million m^3. In the last century three major rockslides in this region claimed 175 lives alone.



Source: NGU (The Geological Survey of Norway)

Figure 1.
The location of the Åknes

The problem with Åknes today is that it is a site of a steep unstable rock slope that will almost with complete certainty turn into a rock slide – it is only a matter of time. Since 1985 measurements of the cracks visible at the top indicates that the crack is widening. In fact, "... continuous extensometer measurements showed an opening of fractures at a mean rate of about 4 cm/year in the upper part of the slope, with values up to 15 cm/year in the most active part" (Roth *et al.*, 2006). The instable rock slope can be divided into two broad sections, see (Blikra *et al.*, 2006a). The smallest moves the fastest and constitute of roughly 8-16 million m^3 of rock. The largest section (including the smallest) moves more slowly, but has an estimated volume of between 30-40 million m^3 or there is an alternative interpretation of 80-100 million m^3 rock. The scenarios NGU (The Geological Survey of Norway) has been working on are 10 million m^3 and 35 million m^3 rock. For simplicity, I use the same definition of scenarios in this paper, denoting the largest (35 million m^3 rock) Scenario 1 and denoting the smallest (10 million m^3 rock) Scenario 2.

The interesting with respect to this paper, however, is not the measurements and estimations NGU has provided so far in this case, but rather how they use this information to estimate risk and provide recommendations. NGU has chosen a conventional approach – prescribed by most. This is discussed in the next section. Then, in Section 3.2, an alternative approach is presented to show how to analyze and improve decision-support further for this specific case.

3.1 The NGU approach to Åknes

This section is a brief presentation of (Blikra *et al.*, 2006a), including my remarks and comments.

In the aforementioned report they base their estimates of probability using the frequency interpretation of probability. They note that the last time there was a rock slide larger than 15 million m^3, was in 1756. Geologically, however, they find that such large rock slides tend to appear once every 2,500 years in this area. This estimate is based on the fact that they have identified four rockslides in this region since the last ice age (about 10,000 years ago), but by using additional information they use the probability estimates shown in Table I. That is, they estimate that the probability of a Scenario 1 type rockslide is between 1/3,000 and 1/1,000, while the probability estimate of a Scenario 2 type rockslide is set in the range of between 1/100 and 1/300.

When it comes to the calculation of the potential for loss of lives, they have studied the demographical and geographical data for the counties involved, which are Stranda, Norddal, Stordal and Ørskog. The number of people at risk is presented in Table I. The "number of tourists" is the maximum number of tourists in the peak season, however, these numbers are expected to increase as Geiranger has recently obtained status as World Heritage site by Unesco. To calculate the possible loss of lives they furthermore assume that inhabitants and tourists are 50 per cent and 25 per cent respectively of the time within the danger zone. They also assume that there is a 30 per cent probability of surviving a tidal wave and that the tourist season is three months long. This gives that for Scenario 1 there is a potential loss of lives in the range of 630 to 1,470 and between 280 and 490 for Scenario 2.

After choosing what they conceive as the most likely numbers, they calculate the risk as shown in Table II. It should be noted that other reports, see for example (Blikra *et al.*, 2006b), from the same project with much the same people offer slightly different numbers. Why these discrepancies occur is unclear when the publication date only differs by a month.

Table I.
Persons at risk

County	Community	Number of tourists	Number of inhabitants	Sum
Stranda	Geiranger	15,000	100	15,100
	Hellesylt	5,000	300	5,300
	Stranda	400	500	900
	Gravaneset	200	0	200
	Rubbervika	0	20	20
Norddal	Eidsdal	1,500	160	1,660
	Norddal	60	60	120
	Fjørå	20	25	45
	Valldal	600	350	950
	Tafjord	600	50	650
	Linge	1,200	10	1,210
	Vika	0	10	10
Stordal	Stordal	100	250	350
Ørskog	Sjøholt	100	1,200	1,300
Sum		24,780	3,035	27,815

Source: Based on data from Jarle Hole from the county of Stranda

By comparing the risk of Åknes to snow avalanches and similar they conclude that the risk associated with a rock slide at Åknes is 200-1,000 times lager. According to the Norwegian law the general accept criteria for loss of lives is 0.1 per cent or 1‰ (Aven *et al.*, 2004), which means that the Åknes risk is too high. For this reason they are now installing surveillance – and an evacuation system, which they claim will reduce risk by at least 90 per cent – hence, reducing the risks to below acceptable levels.

While all this sounds good, there are some fundamental flaws in the analysis they have conducted. First (using numbers from Scenario 1 for the sake of argumentation), calculating the annual loss over a 2,000-year period of lives is nonsensical in a situation where we know with almost 100 per cent certainty that a rock slide will come – and probably sooner than later, see (Røsjø, 2005). Not only are the probability estimates highly uncertain, but they are also fundamentally flawed as explained in Section 2 because the rock slope is "instable" (see (Roth *et al.*, 2006)) and the geological record is very limited.

Second, they offer no credible plans for reducing the risk by 90 per cent (or more) via effective surveillance and evacuation system beyond describing the purely technical gadgets. The most difficult question in this case is not the technology nor the geological issues but when to decide to evacuate and when not to evacuate. The reason is that the tidal wave will strike in less than ten minutes after the rockslide hits the fjord – hence, evacuation must take place before the slide takes place. Yet, if they attempt a pre-emptive evacuation they run the risk of sounding the alarm when there in reality is no imminent danger, which may cause people to stay away from their homes for weeks – then what? Furthermore, with the majority of the people at risk being tourists, how are we supposed to alarm them? Not to mention during night when people sleep, which after all constitute about one-third of the day. Finally, the large cruise ships cannot be moved quickly enough to be out of harms way if the tidal wave strikes at the most vulnerable moment, and closing the fjord for weeks or months on end is not a viable option. In short, there is very little thinking done around the decision aspect of the case, which is in my opinion by far the most difficult aspect.

Clearly, the work done so far in this case has its shortcomings, but much good geological groundwork has been done and the reports so far are only preliminary status reports. In the next section, I will rework the same case using their data to show how a different approach can give much better decision-support in this case at this stage.

3.2 The alternative approach to Åknes

First of all, note that in the alternative approach there is no base scenario – this is because according to Professor Bjørn Nilsen of The Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, there is only a theoretical possibility

Scenario	Probability (Per year)	Consequence (Lives per year)	Risk (Loss of lives per year)
10 million m^3 (Scenario 2)	1/200	400	2.000
>35 million m^3 (Scenario 1)	1/2,000	1,050	0.525

Source: Blikra *et al.* (2006b)

Table II.
Annual probabilities, consequences and risks

that the movement of the rock slope will stop, see (Røsjø, 2005). Thus, based on the literature on the Åknes case, it is considered too improbable to consider "no rock slide" as a (base) scenario. Therefore, there are only two interesting questions from a geological perspective:

1. When will the rock slide(s) take place?
2. How large will the tidal waves be, which will be created at the various settlements and towns?

However, from a decision-makers perspective, which is the most important since unless we decide what to do we are definitively at risk, only the second question matters. The reasons is that as long as we know there is at best only a theoretical chance for the base scenario, the question of when is not very relevant for a decision-maker because the decision-maker cannot discount the future. Put differently; a decision-maker – particularly an elected representative of the people – cannot think that saving 1,000 lives now is more important than saving 1,000 lives 100 years from now. This is an additional reason (in addition to those in Section 2) why using the frequency interpretation of probability as done by Blikra *et al.* (2006a) is fundamentally misleading. A frequency interpretation lends itself to time-series thinking, which is devoid from reality.

What is much more interesting is when, for any given year. This is because a rock slide in the peak of the tourist season – with maybe three to five cruise ships anchored up in Geiranger in addition to the thousands of tourists that come by car and other means of transportation – will have far greater consequences than in the middle of the winter on a weekday (see Table I). Another improvement made in this approach is to avoid excessive usage of averages in the modelling as prescribed by Emblemsvåg (2005). The third major improvement is that uncertainty is explicitly modelled as uncertainty distributions and then calculated numerically using Monte Carlo methods (see Emblemsvåg, 2003).

This model gives the results for the deterministic case as presented in Table III. For most decision-makers it will be far more compelling to know that you may face an average loss of lives in the range of about 1,500 to 3,000 depending on the size of the rock slide, the time of year and when it strikes in the time of the day, than knowing that about two lives will be lost on average per year over a 2,000-year period. Note that what time it is during the day is incredibly important, but so far the model does not encompass such considerations. This may be included at a later stage.

Table III.
Summary of the deterministic model

Scenario 1	Probability (%)	Consequence	Risk
Tourists	25	8,345	2,086
Inhabitants	75	1,402	1,051
Sum			3,138
Individual risk (%)		10.6	
Scenario 2			
Tourists	25	3,679	920
Inhabitants	75	701	526
Sum			1,445
Individual risk (%)			4.9

However, to get a better idea of the potential loss of lives uncertainty must be included in the analysis. In Figure 2 the probability distributions for the risk of both scenarios are shown. Clearly, there is a small probability for losses up to 4,500 lives and they will always exceed about 1,000 lives.

There are three chief reasons for these numbers being so much higher than those presented in Section 3.1. First, the numbers are not multiplied by the frequency of large rockslides. Second, this model avoids excessive usage of average numbers. Third, uncertainty is included – average numbers can be very deceiving.

Using the Monte Carlo methods also allows applying sensitivity analyses to the risk analysis. Then, we can identify the most important factors in the case, see Figure 3. Many of the factors are hard to deal with such as the length of the tourist seasons and the exposure of the tourists since the fjord itself is one of the main attractions. However, what might be of interest is to increase the probability of survival when the tidal wave comes. Maybe building concrete emergency shelters that people can run into once the alarm is set off where the doors closes after five to ten minutes before the tidal wave arrives? In any case, this analysis clearly offers much more insight and a far more compelling message to the decision-makers.

When it comes to the other shortcoming of (Blikra *et al.*, 2006a) discussed at the end of Section 3.1, the recommendations are quite different. Because no decision criteria exist on when to evacuate or not evacuation as a strategy seems improbable unless

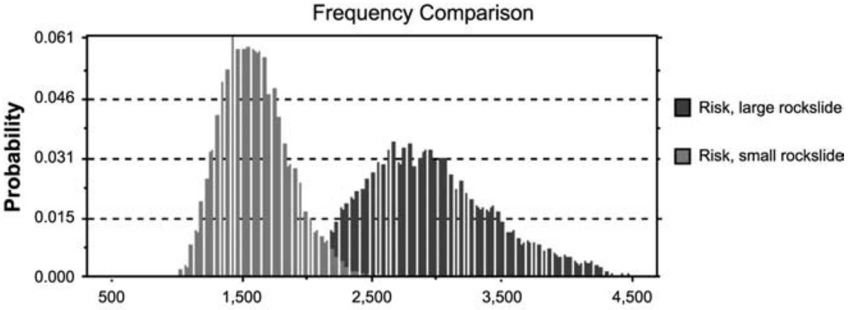
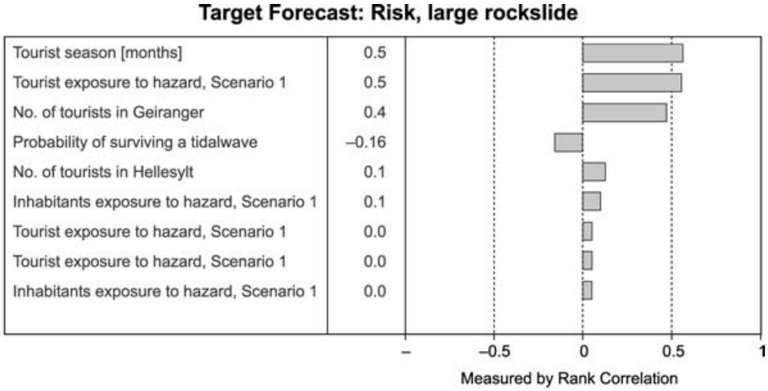


Figure 2.
Overlay chart showing the risk of the two scenarios



Tourist season [months]	0.5
Tourist exposure to hazard, Scenario 1	0.5
No. of tourists in Geiranger	0.4
Probability of surviving a tidalwave	–0.16
No. of tourists in Hellesylt	0.1
Inhabitants exposure to hazard, Scenario 1	0.1
Tourist exposure to hazard, Scenario 1	0.0
Tourist exposure to hazard, Scenario 1	0.0
Inhabitants exposure to hazard, Scenario 1	0.0

Figure 3.
Sensitivity analysis of scenario 1

there is some sort of emergency sheltering available. Therefore, to start reallocating infrastructure would probably make most sense in any case – possibly in combination with the emergency shelter idea. This idea carries much merit as we realize that the infrastructure will be lost anyway, and to further strengthen the argument; a tidal wave will cause great economic disruption unless we act proactively.

However, this does not solve the problem with the cruise ships that may sink. The only way to solve this problem completely is to actually take down the rockslide. This is a daunting proposition, but maybe not impossible. After all, when Kennedy proclaimed in 1961 that the USA should be the first to put a man on the moon – they also did not know how . . . There are probably other ways as well – the point is that at this stage we should not limit the solution space.

Resolving these issues, however, is a part of the future work. But before that can be done, some more time must be spent on qualifying the numbers and their uncertainties in the model. However, it seems obvious that the Åknes situation requires action now on a far greater scale than merely relying on surveillance and evacuation – particularly when this plan lack critical issues like unambiguous evacuation criteria. Next, a few generic lessons are presented.

3.3. Preliminary lessons of the Åknes case

The Åknes case illustrates the importance of treating cases where the outcome is partly given (i.e. there will be a rock slide) differently than those in which there is a realistic outcome of no loss. Using frequency estimates as a proxy for probability in such cases is more or less the same as making a time series of the disaster, which obviously gives the wrong picture of the situation. Furthermore, the usage of frequencies as an estimate for probability can also be highly deceptive and should be used much more carefully or possibly abolished completely in cases of very rare events because the assumptions for the frequency interpretation of probability are not fulfilled or possibly even outright wrong.

The second lesson to be highlighted here is that in a case like this where there are very small chances of realistic predictive modelling available, one should be much more careful about what strategies are chosen than what is the case. The project team has not made any thoughts on the decisional aspects of evacuation nor have they done any publishable economic analysis. The number of critical questions therefore remains unanswered, such as:

1. What is the critical fracture size before the rockslide will come? Here, they will probably find no answer, which will enhance the relevance of the questions below further.
2. For how long will they keep up an evacuation while waiting for the rockslide?
3. What will be the criteria for calling off an evacuation?

In many ways, the Åknes case is much more about making decisions in lieu of reliable information than about geological issues. While geology is important, nothing is more important than to tailor the information gathering and analyses towards the questions that really matter – and here the reliance on the frequency interpretation of probability has lead the project team astray and led them into a chain of arguments that are irrelevant.

4. Closure

The purpose of analysis is to gain insight – not obscure – and hence misapplication of methods must be avoided because otherwise decisions can be made on erroneous basis. Unfortunately, studies show that "Two of the principal reasons individuals do not invest in cost-effective loss-reduction measures include underestimation of probability of a disaster and high discount rates coupled with short-term horizons" (Kunreuther *et al.* 2004). Unfortunately, this is also the quintessential problem of the Åknes case due to misapplication of methods and techniques. While Kunreuther *et al.* (2004) argue that such problems are principally confined to private persons, I believe it is a far greater problem possibly due to the blind application of methods outside the methods inherent domain. We must after all remember that the probability theory came out of the studies of games and throwing dice, not natural disasters – after all; "God does not play dice". Hence, it might be that disasters with low frequency should be treated entirely differently than the more frequent ones – certainly when it comes to estimating probability. The case reported in this paper clearly supports that notion.

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