

Freak Events, Black Swans, and Unknowable Unknowns: Impact on Risk-Based Design

M.A. Maes and M.R. Dann

Abstract To design means making informed decisions about suitable alternatives in the face of uncertainties. As a result, structural design criteria and inspection plans reflect the objective of satisfactory performance under well selected extreme conditions. The extent to which the extreme boundary is “pushed” depends on the design approach (ex: component vs system design), the nature and the consequences of the hazards, and risk acceptance, all of which fit neatly into the traditional framework of decision theory. This basic framework is also broad enough to include wider socio-economic and environmental objects, so that provisions with respect to robustness, resilience, sustainability, and risk mitigative measures in general, can be effectively accounted for. Various civil engineering fields suffer from a perception that we don’t dig deep enough, that we fail to consider “beyond extreme” scenarios. Every major accident, or any exceptional natural disaster, or any surprising combination of circumstances, triggers a new call for re-examination of the design rationale: if a freak event can be explained, then surely it should be (have been) accounted for. This paper looks at what really lies beyond our “design frontier”. We distinguish between three broad classes of events: far-out extremes for heavy-tailed hazards, scenarios marked by very unlikely combinations of events (perfect storms), and so-called unknowable unknowns. We identify, from a decision making point of view, which objectives, which tools, and which risk measures can be used, and which lessons can be learned.

Keywords Extreme design scenarios • Black swans • Perfect storms • Unknowable unknowns • Risk-based design

M.A. Maes (✉) · M.R. Dann (✉)

Department of Civil Engineering, University of Calgary, Calgary T2N 1N4, Canada
e-mail: mamaes@ucalgary.ca

M.R. Dann
e-mail: mrdann@ucalgary.ca

M.A. Maes
Department of Structural Engineering, Ghent University, 9052 Ghent, Belgium

1 Introduction

We live in a world of interconnected networks of almost everything. The interconnected world evidently offers a myriad of benefits to its “members”. This can easily be tracked in terms of ever increasing metrics ranging from efficiency, productivity, technological performances, to quality of life. However, any kind of disturbance—external or internal—has the potential of upsetting the system, paralysing the network, and causing damage far beyond its perceived boundaries (Jowitt 2010). In other words, interdependency has led to increased and more widespread vulnerability.

Very rare incidents having extraordinary consequences form the main subject of this paper. They are not new; they are in fact the same as all of the “mysterious” events ascribed by the ancient Greeks to the god Poseidon. A recent trend is to refer to them as beyond-extreme events or very exceptional disasters that carry metaphorical names such as black swans, freak events, perfect storms, nightmare scenarios, and, also, events perceived to have risen from the unknowable unknown.

2 Infrastructure: Evolving Expectations

It is important to reconsider the proper context of design decision making in order to evaluate the role and the impact of extraordinary events. Skilled builders, designers, architects and engineers serve as the custodians of past, current, and future infrastructure. Over the past 30 centuries, the needs of infrastructure have changed and expanded. This evolution occurred more or less at the same pace as the hierarchical expansion of human needs (Maes and Stewart 2004).

Historically, infrastructure has always been the sole and common stable platform upon which civilization rests. Its main role was to bring people and views together, to provide shelter and basic comfort, and to provide a true forum for interaction—in the literal sense of the meaning. Much later arose the need for infrastructure to be efficient, cost effective, and functional, as the human need for an acceptable quality of life became tied to basic infrastructure functions. The specific character of modern societies is largely defined by culture, heritage, and vision, all of which are heavily influenced by its infrastructure. In a sense, infrastructure came to “shape” our world (Jowitt 2010). It is only very recently in this historical sequence that the ultimate step in this hierarchy of needs appears: it focuses on a society’s vulnerability in times of unexpected distress and/or abnormal conditions. Hence the requirements for infrastructure to be resilient against disasters and sustainable in the long-term (Rodrigues-Nikl 2015). In summary, and in the order of historical evolution, we expect infrastructure to be:

- reliable and safe, since it is the critical stable platform upon which civilization depends
- efficient and functional, since our quality of life is linked to it

- equitable, since it “shapes” our world
- resilient and sustainable, since society has become painfully vulnerable when infrastructure systems fail.

3 What We Know, What We Should Know, What We Don't Know

In recent years the notion of the “unknowable unknown” (UU) has taken a life on its own. Because of its relation to extraordinary low-probability, high-consequence events, it is worthwhile examining its genesis, its use—and its misuse—from the point of view of decision making (DM). The notion and the use of UUs in offshore structures design and operations was popularized by Bea (1997). In an industry that is heavily self-centred and famous for its unwillingness to share experiences and its failure to learn and adapt in the wake of serious incidents, the UU transformed itself into the ultimate excuse: we did not know, we could not know, and we could never have known, no matter what.

In 1979 a British Columbia royal commission of inquiry into the benefits and the dangers of uranium mining first used the term UU in its final report (British Columbia Royal Commission of Inquiry 1979). The commission referred to UUs as “unforeseeable conditions which pose a potentially greater risk [than known unknowns] because they cannot be anticipated based on experience or investigations”. In other words, should indicators of a threat to people be present or be suspected then these “known unknowns” (KU) can/should be the subject of scientific risk assessment. If neither indicators, nor an experience base, nor a knowledge base exist, then we deal with UUs. The question of whether or not a UU should “pose a potentially greater risk” is debatable, for if we know nothing about the UU, not even its existence, then there is *a priori* no compelling reason to fear “it”, let alone associate it with potential greater risk.

A 1982 investigation of the metal fatigue failures of the 1950s Havilland aircrafts also cited the role of UUs. At the time of the incidents, fatigue was not an established concept of its own right. It was “unknown” as a cause of failure, but as failures accumulated, one can hardly continue to blame evidence of malfunction to an unknowable unknown: the effect was known but not the cause. This points to epistemic limitations rather than UUs: as the experience-base broadened and research intensified, a proper “name” was eventually given to the phenomenon. As in the case of a new virus or infectious disease, its sudden observation or realization (“discovery”) is rather like a black swan: an epistemic breakthrough of something that was certainly not meant to remain “un-knowable”.

It would be tempting to divide the knowledge base using the breakdown shown in Fig. 1a. Apart from the trivial class of knowns (K), the largest set of uncertainties consists of KUs, i.e. those of which decision makers are well aware and upon which their uncertainty modelling focuses (Maes and Milke 2015). Then there would be

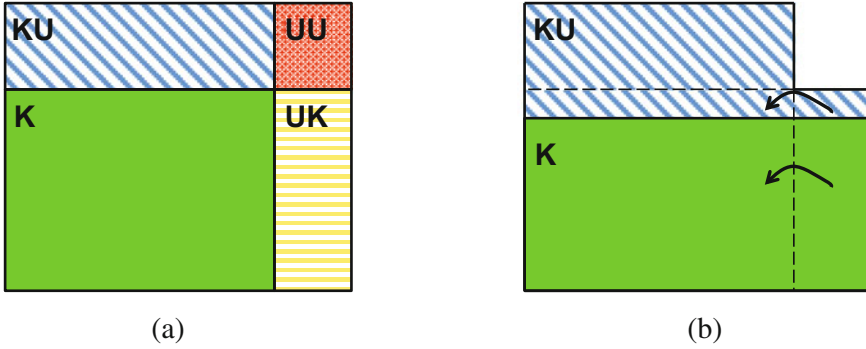


Fig. 1 Knowledge base breakdown (K = known, KU = known unknown, UK = unknown known, UU = unknowable unknown)

the class of UK which would include information or data that is either not (easily) recalled or (intentionally) suppressed. Finally there would be a separate group of UUs (Haugen and Vinnem 2015).

However, this picture is definitely flawed by our obsession to break down (un)certainty along abstract lines. Informed decision making (DM) is intrinsically concerned with the framework for developing optimal decisions based on:

- what we know
- what we should know, or what we need to know

This basis for traditional DM therefore includes K and KU. We possess techniques to resolve, learn about, update, monitor, and model any of the uncertainties involved in this process. Now, to add a third component to the “knowledge basis” in the form of:

- what we do not know (and can never know)

would suggest that there are uncertainties we should be able to know but cannot know. But this leads to a paradox, as either such uncertainties are already part of system of beliefs/knowledge (but we may be unaware of them or give them different names), or else they lie truly outside our domain of knowledge. In the first case the supposed UU is in fact a KU; in the second case, Platonic logic tells us that we can never learn what we do not know since if we would “find” it, we would not be able to recognize it.

Either way the supposed UU can never be an issue in the context of rational and informed decision making. Therefore, a “true UU” can as well not exist since it can, by definition, never penetrate the state of knowledge and, accordingly it does not influence DM in any formal or informal way. If a specific uncertainty is marked as a UU, perhaps, but not necessarily, in an a posteriori sense, then it ceases to be a UU and becomes a KU since it is then part of the decision maker’s basis of beliefs.

For informed DM, it is, on balance, better to replace Fig. 1a by Fig. 1b which does not show UUs and dilates UK into K (through investigation and research) or into KU (using uncertainty modelling).

4 Black Swans and Perfect Storms

Before 1697, expressions in the English language that used the term “black swans” (BS) were in fact very common. They pointed to something that was non-existent or physically or conceptually impossible. In that year the first reports of actual BS sightings in Western Australia reached Europe. Subsequently, the BS terminology became synonym of any perceived impossibility that is, or may, later be disproven.

In 2000 unexpected financial market fluctuations were baptized BSs and since that time BSs came to denote almost any unexpected high-impact event. In that same year the use of the term “perfect storm” (PS) was popularized by the movie based on Junger’s (1997) novel. Both BS and PS concepts have many aspects in common:

- they are both “freakish” in nature, causing surprise and generating sudden newsworthiness
- they both may result in significant damage and widespread impact
- they can both be rationalized by hindsight (Taleb 2007):
 - a BS may never have been observed before but may have precursors or (at least) vague indicators: they can be imagined a priori and explained a posteriori
 - for a PS, root-cause scenarios can be proposed and verified; usually, the (regular) individual underlying events/processes are well understood, but, a priori, their very rare conjunction or sequencing is subject to considerable uncertainty
- before their occurrence or observation, they are considered “truly unthinkable”; this is normally a correct and rational point of view with respect to the specific knowledge base and the state of belief at the point in time that such an evaluation is made.

One possible distinction that could set apart a BS from a PS, is suggested by Paté-Cornell (2012): a BS engenders the ultimate epistemic uncertainty due to a profound lack of fundamental knowledge, while a PS embodies the ultimate rare conspiracy of aleatory uncertainties, an extremely bad roll of dice so to speak. It is important, however, to realize that even this possible distinction between BS and PS depends entirely on one’s perspective and state of belief. It is hardly relevant before the fact, as well as after the fact.

In modern use, a BS or a PS refers to a very unexpected event (with respect to the *a priori* knowledge base), that is felt to be nightmarish in terms of the high profile consequences that it carries. This points to two explosive ingredients: *fear* and *surprise*.

Fear is known to possess considerable potential to interfere with informed DM and effective risk management (Maes and Milke 2015). As soon as fear looms over the decision making process, it has the potential to start weighing too heavily (Schneier 2013).

As pointed out in the case of UU, the knowledge base as well as the system of beliefs expand as a function of time. Any *surprise* event, i.e. yesterday's BS, is short lived once the event is experienced. The surprise punctures at least some bubble of (yesterday's) epistemic limitations.

There can of course be many epistemological reasons why the BS remained unexposed in the timeline before its first "sighting":

- inappropriate assumptions and models suggesting that such a BS cannot occur
- improper uncertainty models/analysis leading to incorrect likelihood evaluation
- overall chance of occurrence of a possible BS deemed too small to be considered; this assessment can either be valid, i.e. justified using risk-based acceptance, or may stem from incorrect analysis
- erroneous induction/deduction due to serious fallacies in logic
- incomplete information
- failure of the knowledge management systems (e.g. incompetence, illusory superiority)
- inappropriate belief structures, e.g. the use of priors that express faith in likelihoods (Haugen and Vinnem 2015)
- ignorance of lower-level signals/warnings/precursors
- local "thinking", i.e. focusing on one link in the chain rather than on the entire chain, and lack of creative thinking and network modelling

Following a similar line of thought, Aven (2015) identified three types of BSs:

- (A) (true) UUs
- (B) UUs only for the decision maker(s) prior to the occurrence of the BS, but not to (some) others
- (C) UKs (originally) estimated to have a negligible probability of occurrence

The notion (A) of true UUs was questioned in the previous section; the second type (B) goes back to the above list of epistemological shortcomings. Group (C) is discussed next.

5 The “Very” Extreme

The large majority of black swans, freak events, perfect storms refer in fact to the kind of very unlikely extreme events, Aven’s type (C) above. Analysis has been performed but the hazard is found to lie well below some occurrence rate threshold (typical for offshore design practice) or its aggregate risk is deemed to be negligible. Although its unexpected occurrence may well be surprising, the event itself is not. It is not per se a BS—although one could consider it to be so depending on one’s state of knowledge—rather, it is just an extraordinary extreme event.

The question of “past-extreme events” or “beyond-abnormal-events” is not uncommon in certain fields of engineering practice. For instance, in arctic offshore structures design, three categories of events are considered (Thomas 2015):

- extreme events and extreme scenarios which serve as the basis for ULS verification
- abnormal events which includes accidents and large environmental hazards which are used in ALS verification and includes system effects and robustness
- “selected” beyond-abnormal-events for which additional operational measures, shut-down contingencies, evacuation and other mitigative strategies are mobilized to check (conditional) life-safety targets and system performance objectives

While well-intentioned, the danger with the latter set of design hazards is that it opens the door to consideration of absolute worst-case design and assessment scenarios that are no longer tied to probability.

Fundamentally, in the face of uncertainty, the theory of design DM accounts for precisely how “deep” extremes need to be for design and planning. At the same time the designer accepts the possible occurrence of “worse” extremes; for such events robust planning and precautionary mitigation are called for. Clearly, in structural design, there is no operational need to separate different kinds/sources of uncertainty as it is the aggregate state of knowledge that governs structural safety. Counter-productive is the situation where a standard technical committee studies a required increase in partial load factors based on far-fetched design scenarios developed in the wake of a “perfect storm”; the idea would be to multiply the basic partial factor representing aleatory uncertainty with a variable “ignorance” factor to reflect epistemic uncertainty and further with a variable “fear” factor to represent whatever nightmarish is imagined to lie beyond that.

We do find ourselves in a useless war of words and pointless terminology when it comes to black swans, perfect storms, and beyond-extremes-events. For instance, certain extraordinary hazard scenarios may be “known” in advance, but a specific sequence/combination of such scenarios may be unknown. Or, if the sequence had been anticipated, it could have been judged too unlikely to be included in the decision making process anyways. Either way: it makes little difference for design and inspection.

Perfect storms and beyond-extremes involving KUs with very low probabilities should therefore not be termed as such, neither in an aleatory nor in an epistemic sense; they do not form a limitation of rational decision making. However, we need to accept that metaphors denoting apocalyptic events with a catchy name are always mesmerizing and invariably mobilize one's imagination (Evans 2012). They suggest an element of magic and of the supernatural (act of God).

The real danger, however, is that they trigger worst-case thinking (Mueller and Stewart 2011; Schneier 2013) where:

- thinking is replaced by imagining
- reason turns into fear
- decision analysis becomes overshadowed by speculation
- low-probability suddenly becomes certainty (i.e. a lack of probabilistic context)

Best is, therefore, to use black swans, perfect storms, nightmare scenarios and unknowable unknowns only in a very narrow metaphoric sense, or—better—not to use them in the context of design, assessment, and risk analysis whatsoever. Above all, one should avoid using BS, PS and UU as an excuse for failure to act effectively and proactively.

In the following two sections we focus on two case-studies of perceived black swans and/or perfect storms:

- the 2000 Carlsbad pipeline rupture incident (Sect. 6)
- the 2011 Fukushima Daiichi nuclear power plant disaster (Sect. 7)

6 The Carlsbad Black Swan: El Paso Natural Gas Pipeline Rupture, 19 August, 2000

Corrosion is a major cause of rupture for gas transmission pipelines. Figure 2 shows the number of rupture events per year due to corrosion for the US gas transmission pipeline network from 1986 to 2001. It represents pipelines located in Class 1, the lowest of 4 population classes. Class 1 represents about 375,000 km of pipelines (80 % of the total network) and it applies to sparsely populated areas defined as having an average population density not exceeding 0.04 people/hectare. Figure 2 also shows the associated number of fatalities caused by the rupture events. It can be observed that corrosion in Class 1 has not resulted in any fatalities, except for one event that took place on August 19, 2000, near Carlsbad, New Mexico which caused 12 fatalities (NTSB 2003). This black swan is examined below.

The incident occurred near the Pecos River, approximately 48 km south of Carlsbad, NM. Four natural gas pipelines, which are part of the transmission network delivering gas from Texas to California, cross the river at that location (Fig. 3). The pipelines had been built in the 1950s and signs “Caution—High

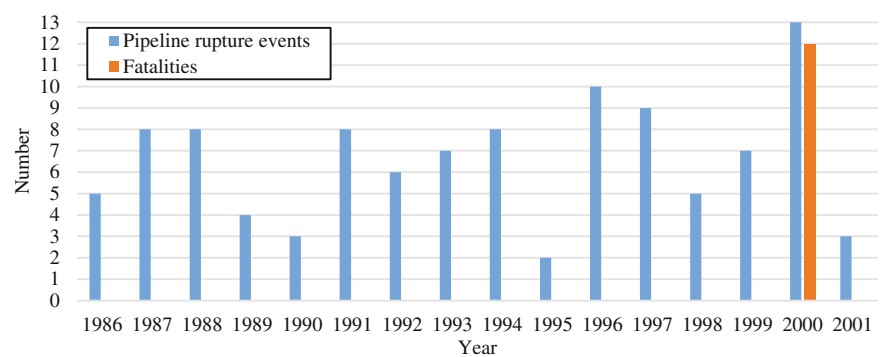


Fig. 2 Number of ruptures and fatalities due to corrosion for the US gas transmission pipelines located in sparsely populated areas (Class 1)

Pressure Gas Line” were posted. The initial pipeline design did not allow for inspections of the pipeline using in-line tools to detect and size corrosion in the lines. In 1975 some sections of the pipelines were equipped for in-line inspections, but the sections close to the Pecos River never had the facility for internal inspections and for the operation of internal cleaning tools. Note that all the pipelines were classified as Class 1 around the river due to the sparse population.

Over the years, an unofficial, but popular campsite established itself adjacent to the river and to the two 30-inch-diameter pipelines (Fig. 3).

On Saturday, August 19, 2000, at 5.26 am one of the two 30” pipelines ruptured due to corrosion approximately 205 m from the campsite (Fig. 3). The released gas

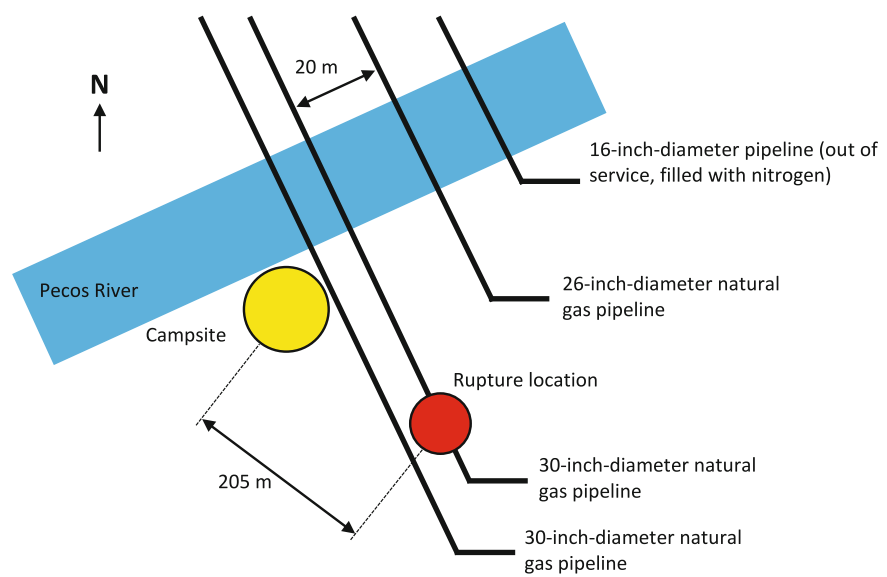


Fig. 3 Overview of the accident site

ignited at the rupture location and the corresponding jet fire burnt for almost 1 h. The campsite was occupied at the time of the accident and the fire fatally injured 12 campers. The rupture did not cause any damage to the other three pipelines.

A quick analysis of the high consequence area (HCA) is in order. The HCA around gas transmission pipelines is defined as the area where the “potential consequences of a gas pipeline accident may be significant or may do considerable harm to people and their property” (Federal Register 2002). The radius r of the HCA is determined as the distance around the (assumed) pipeline accident location where a person is exposed to fatal heat radiation from the ignited gas (Stephens et al. 2002):

$$r = \sqrt{\frac{cpD^2}{I}} \quad (1)$$

where $c = 0.1547 \text{ kW/m}^2\text{Pa}$ is a multiplier, p is the pipeline pressure, D is the pipeline diameter, and I is the heat intensity threshold that causes fatal injury. The lower and upper bounds for I are 12.6 kW/m^2 and 31.6 kW/m^2 , respectively, for outdoor heat exposure. The maximum allowable operating pressure for the failed pipeline was 5.77 MPa and the actual operating pressure at the time of failure was 4.65 MPa. Table 1 shows the estimated radii of the ruptured pipeline HCA.

The informal campsite, which was adjacent to the two 30-inch-diameter pipelines (Fig. 3) is clearly located within the HCA. It seems that no attempts were ever made to move the campsite outside the HCA before the incident, possibly due to the fact that the pipeline operator was never informed about the existence of the campsite by local authorities. There is a clear information gap and communication failure. Clearing the HCA from occasional and permanent use was in fact even more important in this case, because the lack of inspection capability; moreover, solid and liquid deposits in upstream (piggable) sections of the pipeline were evidence of an elevated likelihood of advanced internal corrosion.

The campsite was located 205 m from the location of the rupture, which slightly exceeds the estimated distance of 182 m in Table 1. The expected number of fatalities N for a corrosion related rupture of a gas pipeline in a given population class can be estimated as follows (Nessim et al. 2009):

$$N = 4.4 \times 10^{-8} \rho p D^3 \quad (2)$$

where ρ is the mean population density in number of people per hectare, p is the pipeline pressure in psi, and D is the pipeline diameter in inches. For Class 1, $\rho = 0.04$ people per hectare and based on the pressure at the time of rupture, the expected number of fatalities would have been 0.03 people versus the 12 people that actually got killed in this accident.

Table 1 Radius of the high consequence area for the failed 30 inch pipeline

	Maximum allowable operating pressure: 5.77 MPa	Pressure at time of rupture: 4.65 MPa
Certain fatality ($I = 31.6 \text{ kW/m}^2$)	128 m	115 m
Possible fatality ($I = 12.6 \text{ kW/m}^2$)	202 m	182 m

In hindsight, this extreme pipeline rupture event was caused by inadequate risk management:

- Operating the gas pipeline without sufficient efforts to prevent corrosion failure
- Not enabling in-line inspection facilities around the Pecos river crossing
- Ignoring evidence of internal corrosion in adjacent pipeline sections
- Allowing the creation of a campsite within the HCA of the pipeline
- Not communicating the creation of a campsite to the pipeline network management
- Not enforcing a no-entry zone around the river crossing

Note that a more conservative design of the pipeline, for example an increase of the design wall thickness, would have delayed the failure event, but it could still have caused the same number or even more fatalities.

7 The Fukushima Daiichi Perfect Storm, 11 March 2011

On March 11, 2011, an earthquake with a magnitude of 9.0 on the Richter scale hit the East coast of Japan International Atomic Energy Agency (IAEA) (2015). The Fukushima Daiichi nuclear power plant with its six nuclear reactor units was operating three units at full capacity with the other three units in shutdown mode for maintenance at the time of the event. The three in service reactors were automatically shut down as part of the regular procedure for earthquakes. The earthquake caused relatively minor damage at the plant, but fully disabled the off-site electrical power supply and, therefore, the emergency diesel generators were activated to provide electricity for the cooling system of all 6 units.

The subsequent tsunami arrived at the nuclear power plant about 40 min after the earthquake. The maximum run-up height of the tsunami waves at the plant location was 15 m, which exceeded the seawall that was to protect the plant for run-up heights up to 5.5 m. This run-up resulted from a maximum water height of the tsunami of 38.9 m. The flooding of the plant site caused failure of the diesel generators resulting in a so-called station blackout for reactor units 1–5. The power plant was designed to withstand such a blackout for 8 h by relying on a battery system to provide energy for running the basic reactor functions. However, the flooding also affected the battery system located in the basement and within 15 min of the flooding failed to provide power for units 1, 2, and 4.

The total power loss in three units was never considered as a possible scenario, and procedures to cope with this event were therefore not at hand. Consequently, reactor units 1–3 overheated, nuclear fuel melted, and subsequent hydrogen explosions lead to the release of radioactive material to the atmosphere and to the ocean. A general evacuation occurred around the nuclear power plant.

The Fukushima Daiichi nuclear power plant was designed for a design basis earthquake ground motion (DBGM) around 440–480 cm/s². Although the earthquake on March 11, 2011, exceeded this design limit by about 20 %, the plant did not suffer direct major damage due to the earthquake except for the loss of off-site power supply. The main safety features and the emergency cooling systems of the power plant remained intact before the arrival of the tsunami.

Subsequent flooding was the shared cause for failure of the emergency diesel generators and the battery system as the final backup system to provide power for the cooling system. The complete loss of power in several units of a nuclear power plant was never considered in the design of the plant and, therefore, no procedures were in place to respond to the problem. The tsunami also caused major damage in the area around the power plant, which made it difficult to get support and equipment to cope with the overheating reactors, particularly under the enormous time pressure to find a solution within hours and days. The release of radiologically contaminated air to the environment was the only solution to lower the pressure in the reactors.

With respect to flooding, the power plant was not designed for extreme floods based on the historic data. Figure 4 shows the source locations of tsunamis on the East coast around the plant from 1900 to the day of the accident. In total, 101 events are recorded at the National Centers for Environmental Information (NOAA 2016). The events are here classified according to their location with respect to a power plant in Location A (south of Fukushima), Location B (proximity of Fukushima), and Location C (north of Fukushima).

The exceedance probability plot for the maximum tsunami water height is given in Fig. 5 for the three sets of source locations. Assuming for simplicity that the run-up height is at most equal to the maximum water height, then it appears that the records for the 110 years prior to the accident do not show maximum water heights in excess of 2 m in the proximity of Fukushima (location B); accordingly the seawall height of 5.5 m at the nuclear plant seems to provide sufficient safety.

However, the recorded maximum water heights north and south of Fukushima (locations C and A) clearly exceeded the 5.5 m. Vulnerability reassessments for extreme natural events had not been required, the operator's analysis had already indicated before the accident that the run-up height could be of the order of the one experienced on March 11, 2011 and that therefore the design height of the seawall was not sufficient. The major reason why the no action was taken was based on the thinking that Japan's nuclear power plants are sufficiently safe and that perfect storms such as the one that subsequently hit Fukushima were simply unthinkable.

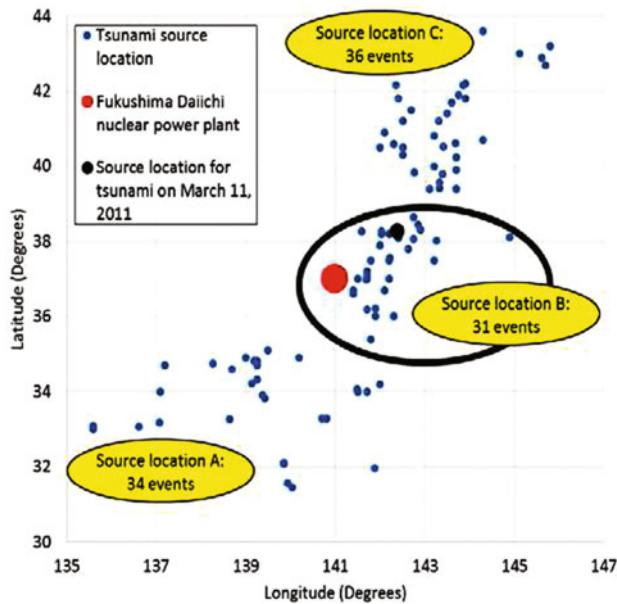


Fig. 4 Source locations of tsunamis around Fukushima Daiichi (1900 to 11 March, 2011)

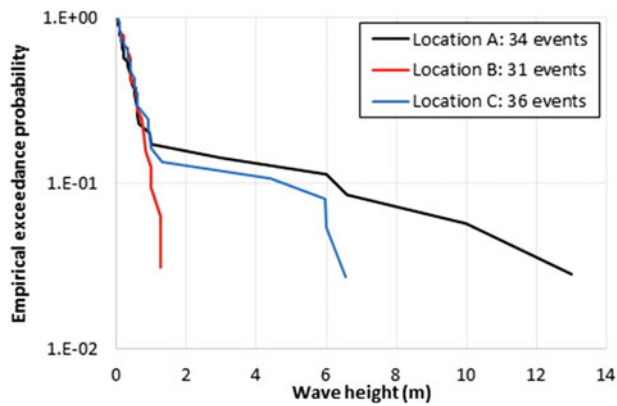


Fig. 5 Exceedance probability plot for tsunami maximum water heights around the Fukushima Daiichi nuclear power plant

8 Conclusions: Demystifying the Extraordinary

As shown in the previous sections, the peril of catchy metaphors such as perfect storms, black swans, beyond extremes, nightmare scenarios, freaks, and unknowable unknowns is that:

- (1) they gradually turn into a readily available apology for poorly informed decision making and sloppy risk management
- (2) they come to be viewed as actual obstacles or technical limitations in design decision making and probabilistic analysis
- (3) they promote worst-case thinking and thereby stoke fear

All of these can seriously undermine the practices of quantitative risk analysis, probabilistic design and assessment.

The reality, however, is that with or without BSs, PSs or UUs, the fundamental approach to decision making and risk management remains the same. It continues to be supported by:

- the extensive toolset of best practices in risk-informed decision making (Faber 2015)
- the proactive use of techniques to enhance robustness, resilience, preparedness
- effective and tempered risk communication

It is worthwhile to emphasize some specific strategies that assist in demystifying the role of the extraordinary. First, as a profession, we must continue to emphasize that epistemic limitations do not invalidate decision making and, especially, design DM; neither can they be used as an excuse for inaction. Design criteria and specific strategies to combat extraordinary events, including beyond-extreme scenarios, need to be assessed within the well-known design DM context of affordability and acceptability (Faber 2015).

Second, the decision analytical framework involving perceived BS, PS, and UU must explicitly show sufficient robustness to imprecision and to epistemic uncertainty. For the purpose of Bayesian methods of analysis, strong and appropriate priors must be carefully selected, efficient updating and small sample likelihood techniques must be favoured, and robust belief networks having a sturdy logical basis need to be developed to address network complexity and root-cause mitigation. Clearly, suitable extreme value modelling techniques need to be employed; prudence also prevails when using recent simulation techniques for small failure probabilities (see e.g. Au and Wang 2014). Focus must be on event precursors in pre-posterior analysis (see e.g. Khakzad et al. 2015). Also, human behaviour and operational error ought to be included in DM; this practice has become quite common and it is certainly not as out-of-touch as some people make it out to be.

Third, with the aim of planning and preparing for exceptional incidents, it is essential to monitor all precursors/indicators carefully so as to ensure early detection and reaction. This should happen in a proactive culture of alertness, anticipation, and early response, while promoting a balanced and risk-based attitude of caution and precaution.

Resilience continues to be the key concept for systems vulnerable to extraordinary events: it is essential to contain social and economic impact of BSs and PSs. An effective way to ensure this is to use assessment metrics similar to those used in the area of sustainability which similarly aims at reducing socio-economic impact

with respect to ordinary events rather than extraordinary ones as is the case for resilience (Rodrigues-Nikl 2015).

As in a complex interconnected world interdependency comes with vulnerability, it is essential that we rely again on our ability to fix things quickly, especially in the wake of major systemic disruptions with largely unpredictable consequences. The primitive skill of how to do “stuff” and do it quickly was in fact borne out of the human condition itself so it can easily be re-learned, strengthened, and championed. Plus it comes for free—we can as well make good use of it. Even artisanal skills with minimal tools can be important as in the example of Apollo 13’s mid-mission emergency fix.

Finally, careful and balanced risk communication is essential for risks that have a weaker knowledge base. Critically, a reasoned reaction to surprise must always be at hand. Uncertainty should never be talked about as being a synonym of fear. Among designers and decision makers for different systems, networks, and operations, the transfer and the sharing of all available knowledge needs to be enforced. Importantly, risk communication should be attentive to the many perils of disinformation, lack of information, and over-information. Each may stoke fear in a different manner; to quote Bruce Schneier (2013): “my nightmare scenario is that people keep talking about their nightmare scenarios”.

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