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CONSIDERATION AND QUANTIFICATION OF UNCERTANTIES IN NPP DESIGN AND OPERATION: A VIEW AFTER KASHIWASAKI AND FUKUSHIMA RECENT EVENTS

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Introduction

- Repeating the first paragraph of a recently submitted paper (*Uncertainties 2012)*, I will begin this presentation by quoting Aristotle, who observed that *most debates would instantly deflate if disputants would care to define their terms*. This applies as well to the debates sparked by Kashiwasaki-Kariwa and later Fukushima events, that will be discussed at the end of the lecture.

- In this context, few other notions in the history of science have been subjected to more *interpretations* than *probability*. In fact, since the XVIII Century, the meaning of probability remains at the center of heated debates on the matter.

Introduction

- The basic issue is the need to *quantify* the intensity of our beliefs about what *we perceive*, in the first place, and about *notions*, reached at after more complex mental processes, in second place. This intensity is denoted as *uncertainty*.

- It is obvious that probability, as well as other alternative mathematical theories proposed as *measures of uncertainty* (Bernardini, 2000) are simply mathematical models, that may prove useful to for that specific purpose.

Introduction

- One additional, rarely considered difficulty, is that *past events are qualitatively different from future events*. In flagrant contradiction with hundreds of fiction stories, *it is not possible to travel to the past*. The past is real, in the sense that it cannot be changed.

- If this view is correct, then uncertainty about any past event should be distinguished from uncertainty about a (still nonexistent) future event.

Introduction

- A proposal advanced by the author (Riera & Rocha, 1997) is to employ *likelihood*, denoted herein by *L* (*Wahrscheinlichkeit* in German, *verosimilitud* in Spanish, *vraisemblance* in French, *verosimilhança* in Portuguese) to designate uncertainty about a past event, and *proneness*, denoted by *P* (*Neigung* in German, *propensión* in Spanish, *propension* in French, *propensão* in Portuguese) to designate uncertainty about a *future* event.

Introduction

- The last term has already been used by Blockley (2000) and other authors, but with a slightly different meaning. Note that the essential issue is the need to differentiate our uncertainty about past events from our uncertainty about future events, not the words chosen for such purpose.

- How to measure *likelihood L* or *proneness P* is another matter, to be discussed next.

Measures of Likelihood and Proneness

- This is a problem that exceeds the realm of reliability theory. It demands a cooperative effort among branches of science, such as physics, psychology, neurology and mathematics.

- For engineering purposes, Bernardini (2000) presents a unified treatment of mathematical measures that may be used to quantify likelihood and proneness. These are (a) the axiomatic theory of probability, as formulated by Kolmogorov, (b) Zadeh's fuzzy sets or possibility theory, (c) convex modeling and (d) interval analysis, through the theory of random sets.

Measures of Likelihood and Proneness

- Note that likelihood and proneness are *necessarily* subjective, that is, both *depend on the observer*. Moreover, in our view, it makes no sense to speak of *subjective probability*.

- In connection with the widespread usage of the term, it is germane to quote Pinker (1997) who, after a discussion of the "gambler's fallacy"- expecting that a run of heads increases the chances of a tail - observes that “*probability has many meanings*: one is the relative frequency in the long run, another is the subjective confidence about the outcome of a single event”.

Measures of Likelihood and Proneness

- Thus both likelihood *L* and proneness *P* are assessed rationally as well as *subconsciously*. If a scale is used to measure *rationally* assessed likelihood or proneness, a scale to measure their subconscious components appears to be just as necessary. However, these issues are beyond the scope of the present discussion.
- The preceding argument implies that the *assessment of any individual observer*, being subjective, will be affected by an internal bias or error.
- The properties of this bias, *i.e.* of the *subjective* filter, are important in evaluating the possibility of reducing the degree of subjetivity of risk assessments.

Bayesian and Classical Staticians

Singpurwalla (1988) states that "probability is always *conditional*, conditioned on all the background information *H* that we have at the time we quantify our uncertainty - the now time. The background information *H* will include all previous data, if any. Given *H*, that is, conditioned on *H*, the probability of occurrence of an event *E*, denoted $Prob(E|H)$, is a number between 0 and 1".

- With the terminology proposed herein, it seems obvious that when Singpurwalla refers to *probability*, he means *proneness (assessed with a probability measure)*. Moreover, it is also clear that by *event*, Singpurwalla has an occurrence in mind, such as the *future* failure of a mechanical component.

Bayesian and Classical Staticians

- Classical staticians treat data with religious zeal. Consequently, misgivings in connection with the bayesian approach are rooted in the fact that in the latter the available evidence seems to be *unduly mixed up*.

- In assessing the Proneness $P(E)$ of the *future* outcome E of an experiment or observation, it is reasonable to resort to the relative frequency of occurrence of *similar* events in the past $N(E)$.

- This is the usual response in engineering when E occurs repeatedly in time. But even in such case, it might be wise to keep in mind, whenever a *probability measure* is proposed to quantify $P(E)$, that the latter does not necessarily satisfy the three axioms.

Bayesian and Classical Staticians

- If a future event *E is by definition unique*, then its Proneness *P*(*E*) cannot be assessed by resorting to a past relative frequency. The associated notion of probability becomes meaningless, although a probability measure (a dimensionless number varying from zero to one that satisfies the basic axioms of the theory) might still be used to quantify the proneness of the event *P*(*E*).

- Finally, no consideration is currently given in reliability assessments to the influence of *Phenomenological Uncertainty*, issue discussed by Riera and Rocha (1997) in connection with engineering systems. The issue received renewed attention, in a slightly different context, in *The Black Swan* (Taleb, 2007).

Description and Quantification of Uncertainties

- In Structural Engineering, uncertainties are usually classified in the following groups:

- *(1) Uncertainty derived from the random nature of loads and external actions (input).*
- *(2) Uncertainties concerning material properties and dimensions (system).*
- *(3) Model Uncertainty.*
- *(4) Phenomenological Uncertainty.*
- *(5) Human Error*

Description and Quantification of Uncertainties

- In the development of Structural Reliability, in particular, as well as in engineering applications in general, the first two groups have received most of the attention and may be considered fully developed fields.

- Model Uncertainty, Phenomenological Uncertainty and Human Error, on the other hand, have been rarely explicitly taken into account in Reliability or Risk studies or in NPP design. However, there is is an increasing awareness of their importance.

Model Uncertainty

- In spite of its importance, the subject received very little attention until the end of the XX Century. A project conducted by CIGRÉ (1990) to determine the variability in the response of steel transmission line towers due to the mechanical model adopted by the designer constitutes an excellent introduction to the subject.

- A group of twenty seven international designers analyzed two standard transmission line towers, with *given dimensions and material properties*, under an equally *completely defined wind loading*.

Model Uncertainty

- Each designer, employing his own methods and computer programs, determined the axial forces and the strengths of preselected bars and the load-carrying capacity of the tower for the *given wind load*. In spite of the simple structures of the towers, a *large variability in the computed response was verified*. The CV (*coefficient of variation)* of computed axial forces in tower elements was around 10% while the CV of computed tower loading capacities exceeded 30%.

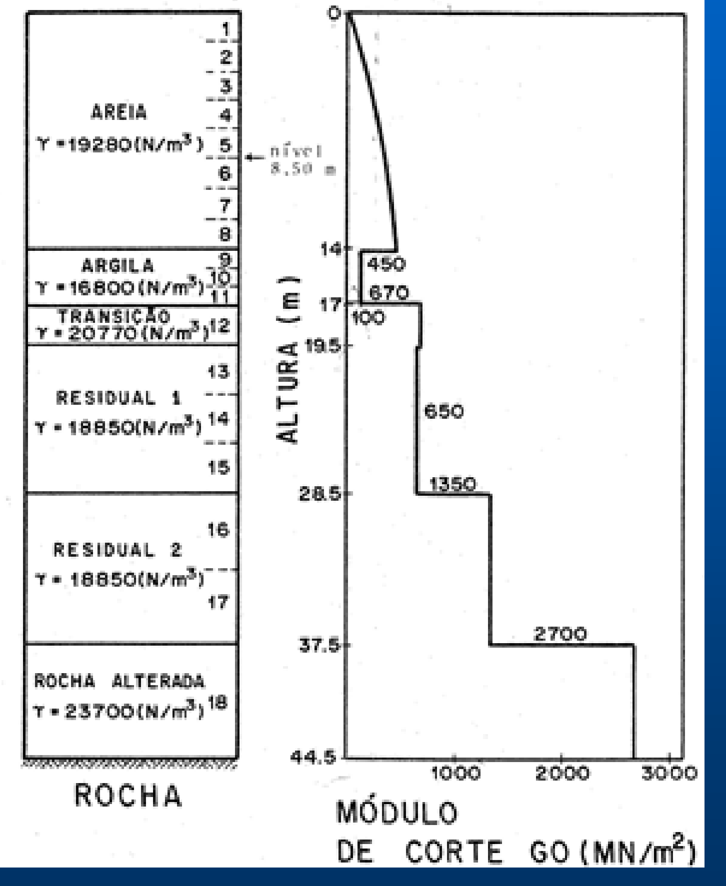
Model Uncertainty

- Also in relation to TL towers under static loading, Kaminski Jr. (2006) estimates in 3% the contribution of model uncertainty to the coefficient of variation of axial loads in tower members. In case of dynamic excitation, model uncertainty leads to coefficients of variation that are considerably larger.

- Carqueja and Riera (1997) report results of the dynamic analysis of a turbo-generator foundation employing three different FEM models of the structure. The frequencies of the first ten modes predicted by the models presented a mean CV close to 6%. The CV of the predictions of peak dynamic displacement was close to 30%.

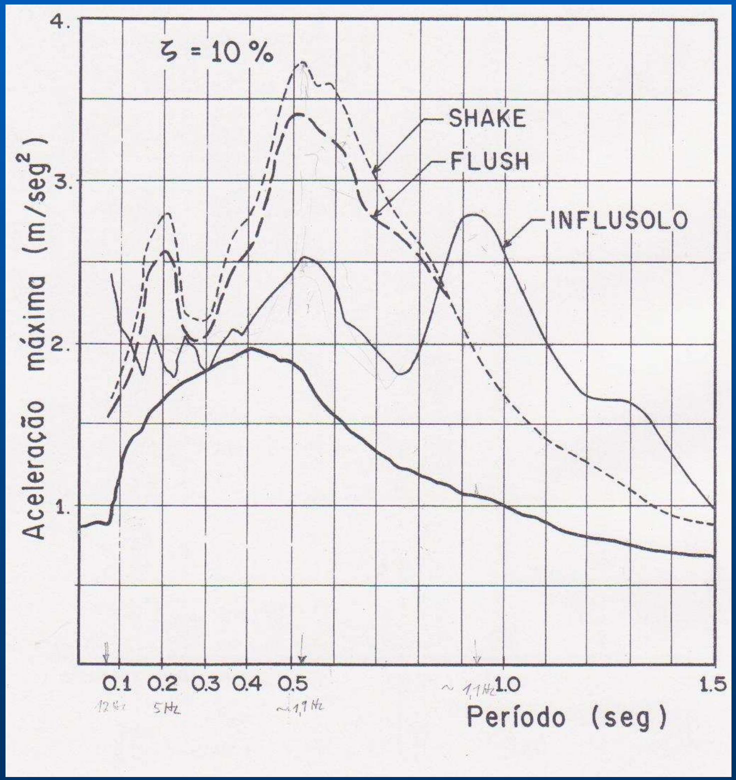
Model Uncertainty

Soil Profile at centre of reactor building (Angra 2 NPP)



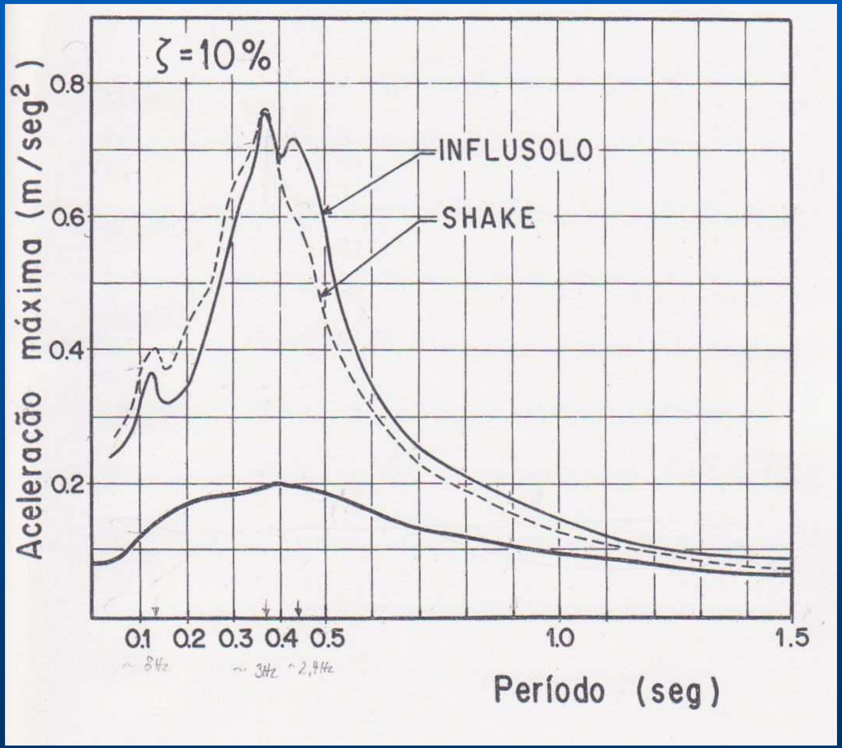
Model Uncertainty

Pseudo-Acceleration spectra at rock interface and soil surface (10% g)



Model Uncertainty

Pseudo-Acceleration spectra at rock interface and soil surface (1% g)



Model Uncertainty

- Additional assessments of model uncertainty in seismic soil amplification studies were conducted by Capelli and Riera (1993). The objective was to determine the error that results from uni-dimensional models (as in the previous example), which neglect the influence of the other two seismic acceleration components.

- On the basis of a limited number of simulations, Riera (2010) suggests an expression for the expected value of the coefficient of variation of the spectral amplitudes at the surface of *soft soil sites*, in terms of the PGA at the underlying rock interface, applicable to standard engineering solutions:

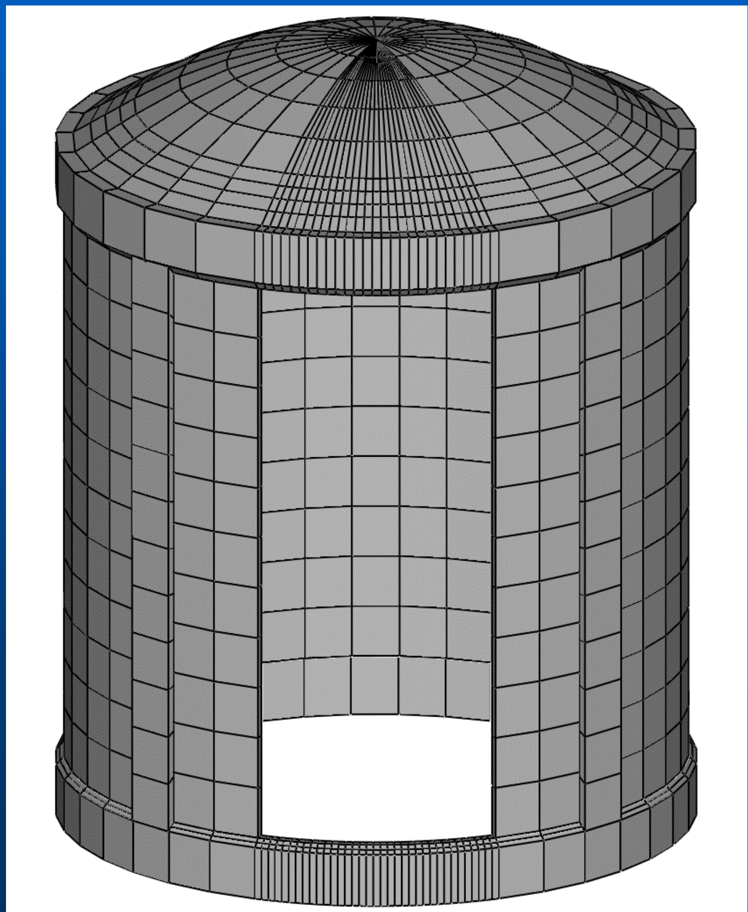
$$\mu_{CV} = 0.05 + \ (PGA/g) \qquad\qquad (PGA/g) < 0.5$$

Model Uncertainty

- Two important projects, which are expected to yield valuable data both on model uncertainty and analyst qualification, should be mentioned before closing this section: the BARCOM Project (Singh, 2009) that examines the problem in connection with a containment vessel subjected to internal pressure, and the IRIS Project, concerned with predictions of the dynamic response of reinforced concrete plates to impact.
- Some preliminary results of the BARCOM Project will be advanced next. Next Figure shows a view of the FEM model in which a DEM panel with 800000 DOF was inserted to determine the ultimate pressure of the Tarapur NPP containment structure, schematically shown in the Figure (Riera *et al*, 2010).

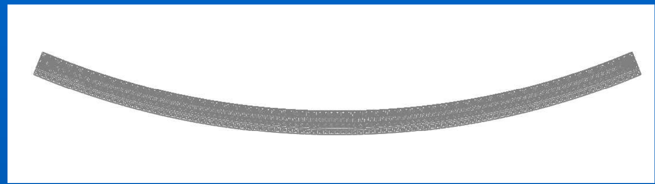
Model Uncertainty

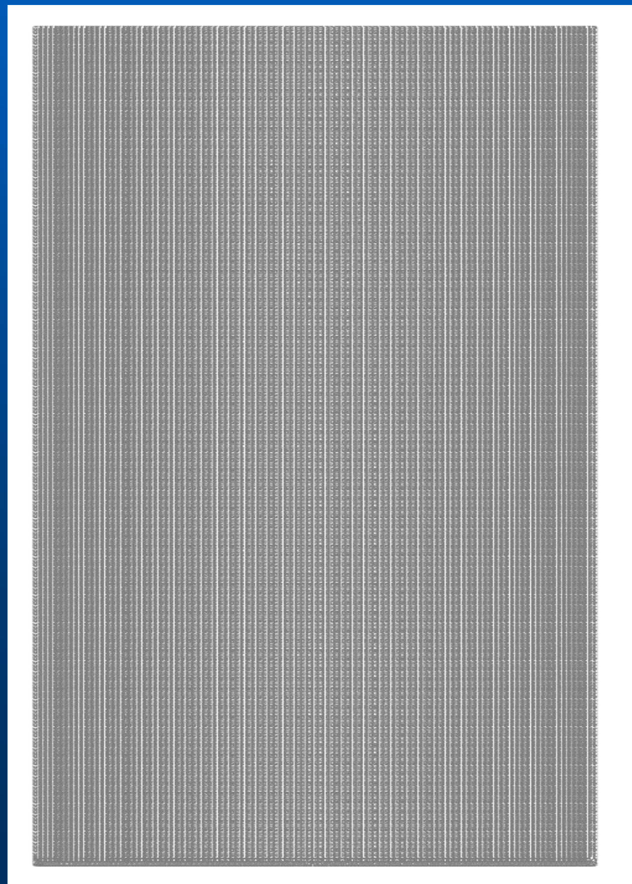
FEM model of Tarapur NNP containment building (India)



Model Uncertainty

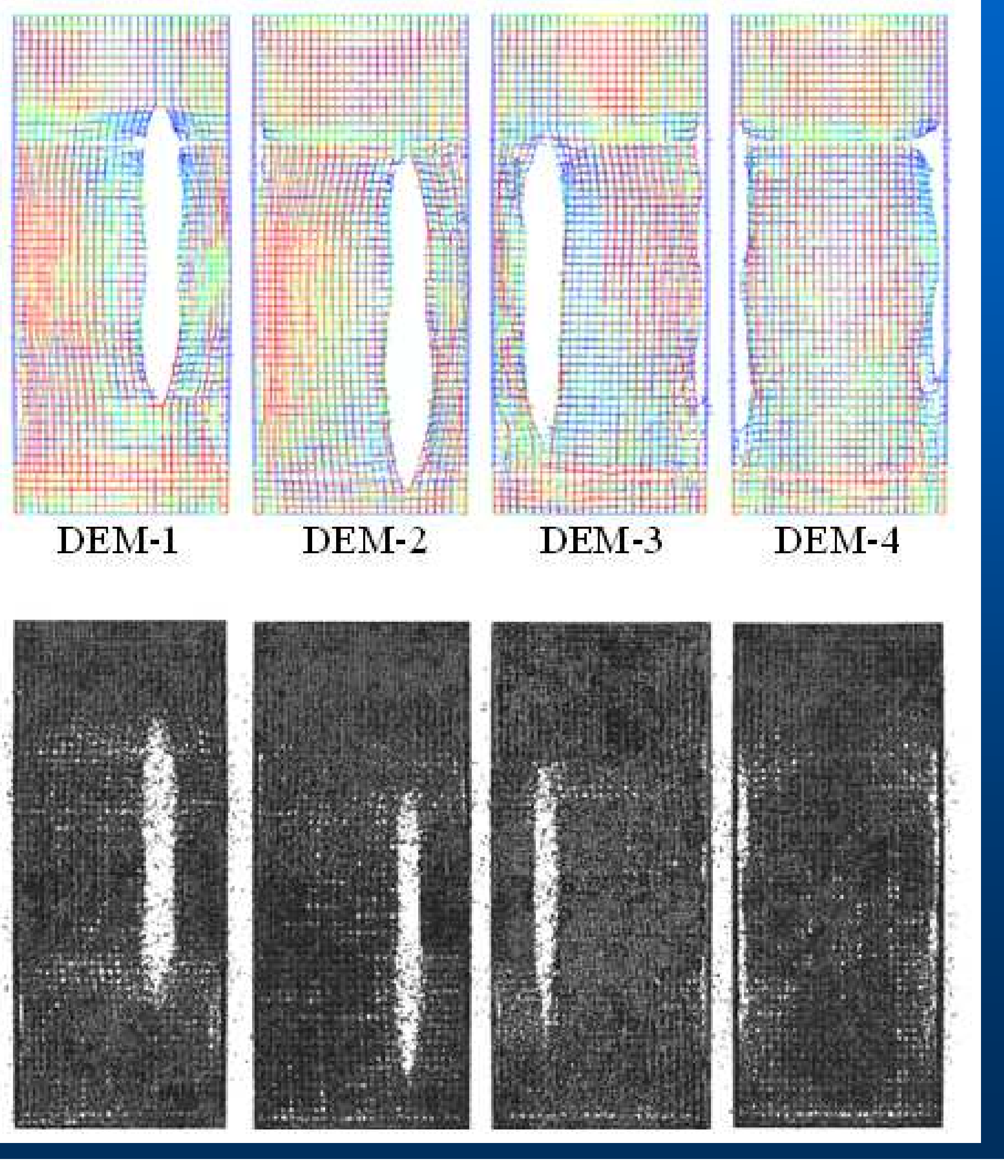
Tarapur NPP DEM model of containment building cylindrical panel





Model Uncertainty

Failure patterns in four DEM simulations of cylindrical containment wall



Model Uncertainty

- One of the objectives of the study was to determine the influence of physical uncertainty, which led to similar rupture configurations, and close values of the corresponding ultimate pressures. In fact, the CV of the internal pressure that causes failure of the containment (0.448 Mpa) predicted by simulations was only 2%.

- The CV of the nine predictions of the ultimate pressure of the BARCOM containment equals 18%, value that is within the range observed in the estimation of the loading capacity of engineering structures.

Phenomenological Uncertainty

- The reliability assessment of complex systems requires, as a basic step, *the identification of all relevant failure modes*. Its final objective consists of an avaluation of the proneness to failure, which is necessarily conditioned on the assumption that all meaningful failure modes have been duly considered. Nevertheless, there is always a *nonzero likelihood* that physical phenomena that may lead to relevant failure modes be unknown when the system enters into operation.

- This is known as *phenomenological or epistemic uncertainty*, being particularly relevant in connection with new technologies

Phenomenological Uncertainty

Let's assume that the system under consideration was designed considering n failure modes and that the proneness to failure $P_f\,(t)$ and associated reliabilty $R\,(t) = 1 - P_f\,(t)$ were determined. Now let L_{n+1} denote the likelihood that a relevant (n+1) failure mode exists, while $P_f^*\,(t)$ denotes the proneness to failure *if failure mode* (n+1) *exists*. The derivation of the updated reliability may be found in Riera and Rocha (1998). According to the total probability theorem, an improved reliability estimator $R'\,(t)$ is now given by:

$$R'\,(t) = [1 - L'_{n+1}\,] \,/\, R\,(t) + L'_{n+1}\,R^*\,(t)$$

A correction factor of the initial reliability may be defined as:

$$\rho(t\,) = R'\,(t) \;/\, R\,(t)$$

Phenomenological Uncertainty

It may be shown that the correction factor $\rho(t)$ presents a minimum value, which for small likelihood of the existence of an unknown failure mode ($L_{n+1} < 0.02$) is given by:

$$\rho_{\min} = 1 - 0.24\, L_{n+1}$$

The previous equation is applicable to any engineering system with a nonzero likelihood of being vulnerable to an unknown failure mode. It should be noted than unless L_{n+1} is negligibly small, theoretically determined reliabilities may greatly overestimate their *true* values.

Phenomenological Uncertainty

Riera and Rocha (1998) derived an expression to update the reliability estimate after M units of the engineering system under consideration operate during a time T_{past} without failure.

There is no question that only through continuous long time operation very high Reliabilities can be achieved.

Human Error

- There is no general agreement on which aspects of human participation must be taken into consideration in an assessment of structural reliability. Elms and Turkstra (1992), for instance, argue that human action cannot be modelled as a technical matter and that studies on one individual cannot be transferred to predict the performance of others.

- Other authors, such as Melchers (1987), sustain that human errors are susceptible of analytical treatment within the bounds of the Theory of Probability.

Human Error

The author coincides with the last position, *i.e.* with the belief that the intrinsic variability in human performance can be usually measured and explicitly considered in reliability assessments.

In fact, the results presented on Phenomenological Uncertainty seem to be equally valid if the cause of the (not considered) relevant failure mode ($n + 1$) is Human Error, rather than Phenomenological Uncertainty. In such case L_{n+1} would represent the likelihood that the analyst did not consider a possible cause of failure, and may provide a basis for a comprehensive assessment of the risk posed by inexperienced or poorly qualified design teams.

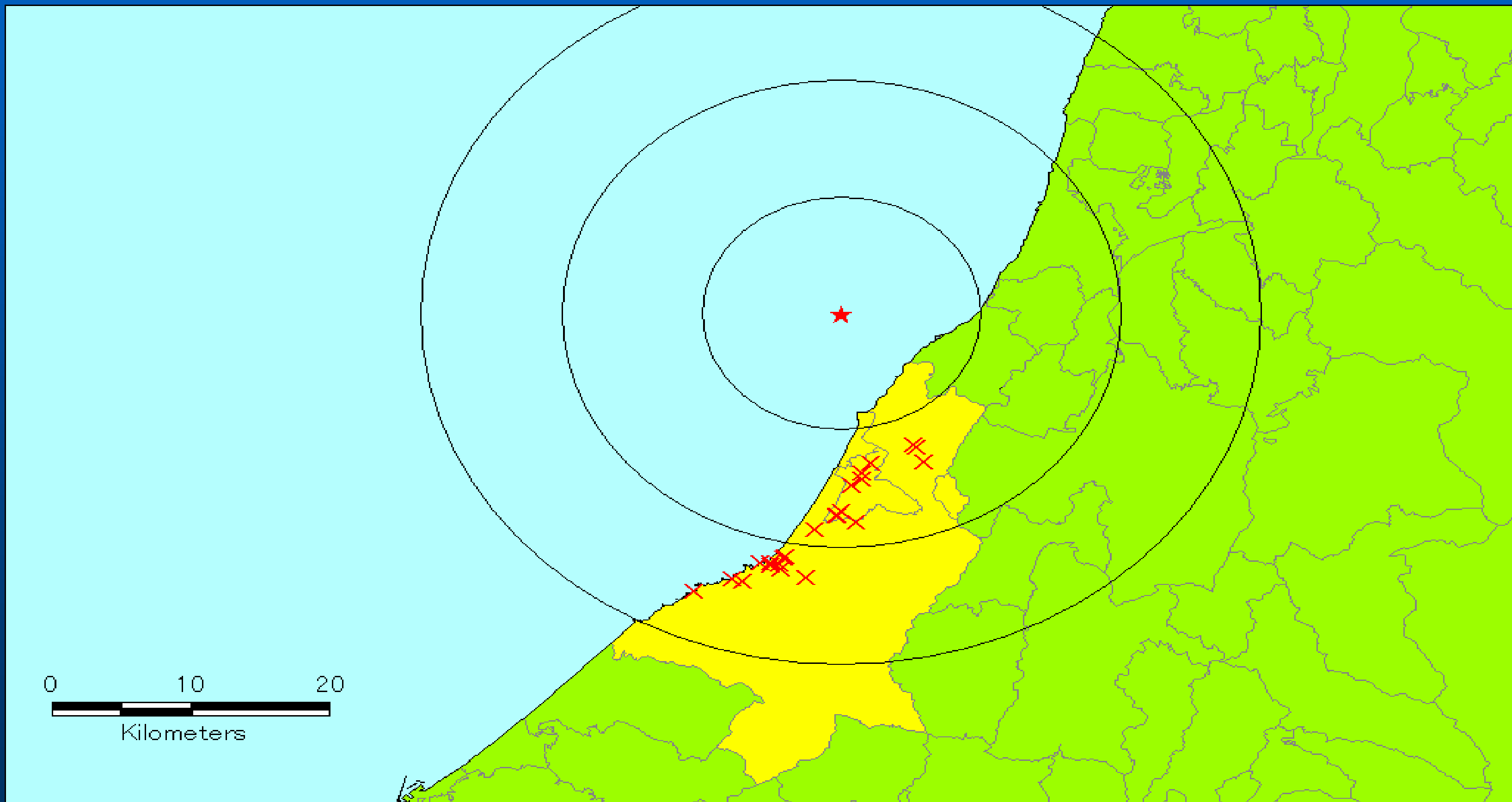
Kashiwasaki-Kariwa NPP

Kashiwasaki-Kariwa NPP

- The seven NPP units at TEPCO´s nuclear complex were subjected to strong seismic excitation on July 16, 2007, by the Niigataken Chuetsuo-Oki earthquake.

- The magnitude of this earthquake was reported as M_w = *6.7 (NIED)*, with epicentral distance equal to 16km and focal depth of 23 km.

Kashiwasaki-Kariwa NPP



Kashiwasaki-Kariwa NPP

Table 1-1 Maximum seismic acceleration (gals) at the Kashiwazaki-Kariwa NPP (observed on the foundation of the reactor buildings)

	North-south	East-west	Vertical
Unit 1	311 (274)	680 (273)	408 (235)
Unit 2	304 (167)	606 (167)	282 (235)
Unit 3	308 (192)	384 (193)	311 (235)
Unit 4	310 (193)	492 (194)	337 (235)
Unit 5	277 (249)	442 (254)	205 (235)
Unit 6	271 (263)	322 (263)	488 (235)
Unit 7	267 (263)	356 (263)	355 (235)

* Design values shown between parenthesis

Kashiwasaki-Kariwa NPP

- The preceding table shows that the design PGA was largely exceeded in most units, the ratio between observed and design values being in most units larger than 2.

- Thanks to the inherent conservatism of the structural design, in spite of the rather gross underestimation of the seismic excitation, damage to the Kashiwasaki-Kariwa NPP structures and components was minor and confined to non critical systems, such as vent stacks and oil tanks.

Kashiwasaki-Kariwa NPP

- The reasons behind the gross underestimation mentioned above had to be explained. Large R&D projects were launched both in Japan and abroad to answer a number of relevant questions.

- We will briefly examine one possible defficiency in the seismic risk studies upon which the KK-NPP PGA coefficients had been selected: the attenuation equations.

Kashiwasaki-Kariwa NPP

- Attenuation equations are used to predict parameters needed to define the seismic excitation, such as the PGA, in terms of the distance to the seismogenic source.

- These equations depend on the *size* of the earthquake, typically quantified by a *single parameter*, the magnitude *M* of the event.

- Hence, the risk analysis is formulated in terms of *M*. When the seismogenic source may be idealized as a *point*, located at the epicenter, no objections can be formulated against the approach.

Kashiwasaki-Kariwa NPP

- The last condition requires that the distance to the source be larger than the source dimensions, condition that is never satisfied in the epicentral region, in which at least two parameters would be needed to describe the seismic event. Examples of attenuation equations in terms of *A* and $\Delta\sigma$ are given below (Riera *et al*, 1986):

- for inter-plate earthquakes ($\Delta\sigma = 60\ bar$)

$$(PGA)_o = 59{,}93\ A^{0{,}34}\ r^{-1} / (1 + 0{,}408\ A^{0{,}29} \ln r)$$

- for intra-plate earthquakes ($\Delta\sigma = 150\ bar$)

$$(PGA)_o = 44{,}32\ A^{0{,}25}\ r^{-1} / (1 + 0{,}314\ A^{0{,}21} \ln r)$$

Kashiwasaki-Kariwa NPP

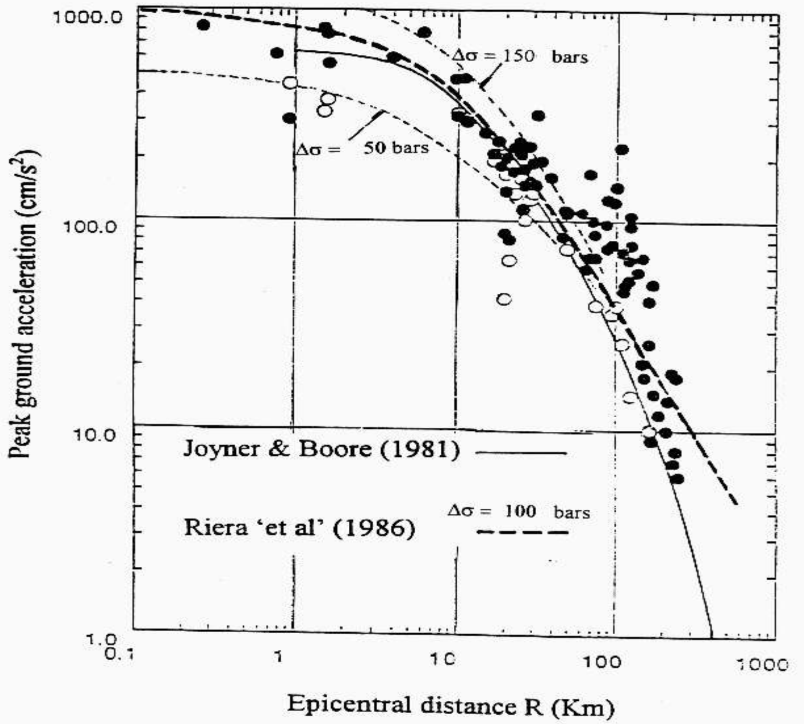


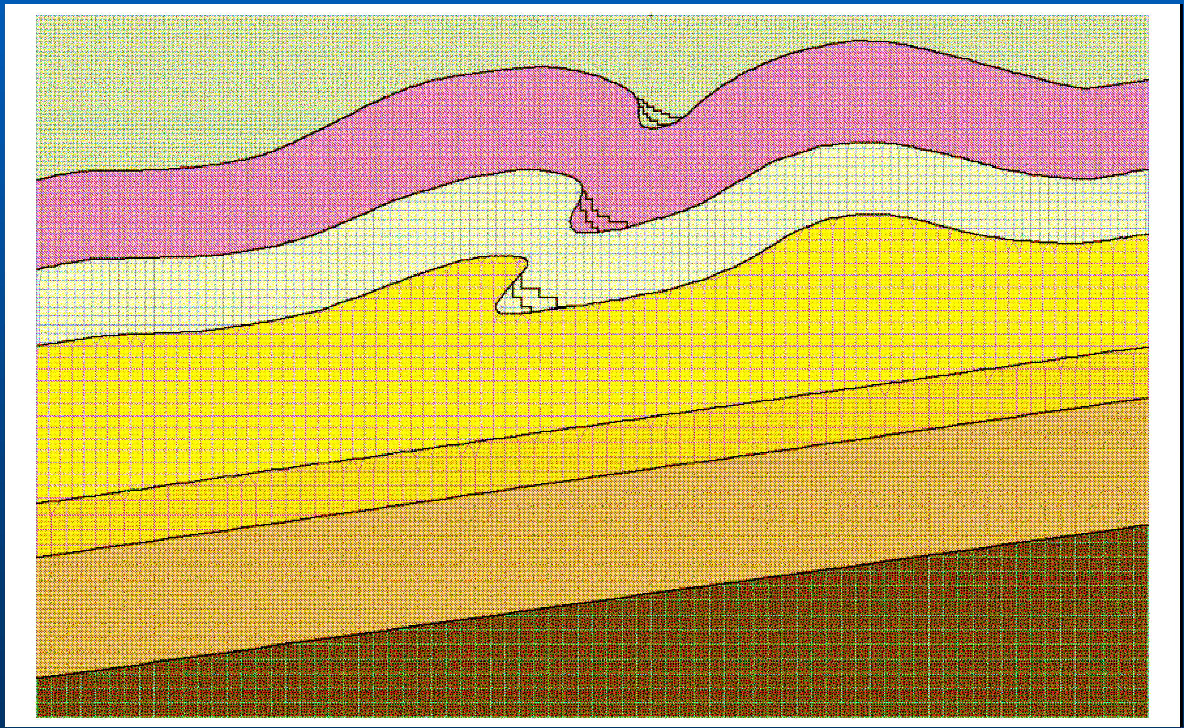
Fig. 6. Attenuation of peak ground acceleration for Great Hanshin Earthquake of 1995 (Measured values furnished by Shibata, 1995)

Kashiwasaki-Kariwa NPP

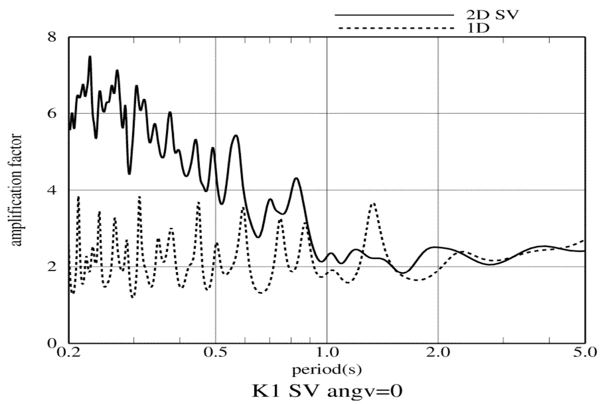
- Preliminary studies with the proposed two parameters attenuation equations, conducted immediately after the Niigataken Chuetsuo-Oki earthquake, although leading to PGA values at the KK NPP site slighly higher than the design values, were unable to explain the amplitudes measured on July 17, 2007.

- Satisfactory explanations were only acknowledged two years later after the folds in the underlying rock shown in next figure were mapped, thanks to additonal geomorphological studies, and subsequent numerical analyses completed.

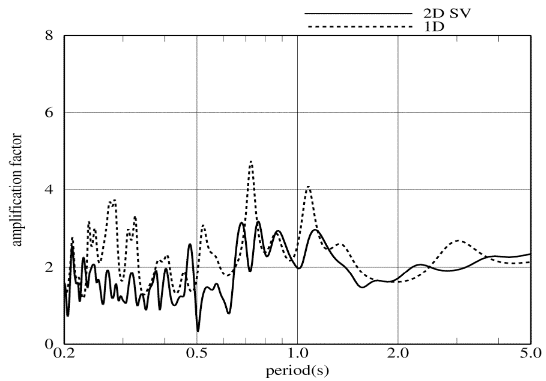
Kashiwasaki-Kariwa NPP



Kashiwasaki-Kariwa NPP



Kashiwasaki-Kariwa NPP



K5 SV angv=0

Kashiwasaki-Kariwa NPP

- It is now clear that the underestimation of seismic excitation at the KK NPP site was a direct result of model uncertainty, which was not duly accounted for when the design criteria was established.

- Fortunately, inherent conservatism in the ensuing structural analysis and design prevented the occurrence of serious effects as a consequence of the earthquake.

- The design criteria and structures at KK have since been upgraded.

Fukushima-Dai-ichi NPP

Fukushima-Dai-ichi NPP

Fukushima-Dai-ichi NPP

- The Great East Japan Earthquake on 11 March 2011, a magnitude 9 earthquake, generated a series of large tsunami waves that struck the east coast of Japan, the highest being 38.9 meters at Aneyoshi, Miyako.

- The earthquake and tsunami waves caused widespread devastation along the north-east coast of Japan, with more than 14,000 lives lost. At least 10,000 people remain missing, with many more being displaced from their homes as towns and villages were swept away.

Fukushima-Dai-ichi NPP

- The operational units at NPP along the coast were successfully shutdown by the automatic systems installed as part of their seismic design. However, the large tsunami waves affected these facilities to varying degrees, with the most serious consequences occurring at TEPCO`s Fukushima Dai-ichi.

Fukushima-Dai-ichi NPP

Fukushima-Dai-ichi NPP

- Although all off-site power was lost when the earthquake occurred*, the automatic systems at TEPCO`s Fukushima Dai-ichi successfully inserted all the control rods into its three operational reactors, and all available emergency diesel generator power systems entered into operation, as designed.

* In terms of damage to the external power supply at the Fukushima NPPs, a total of six external power supply sources were connected to the Dai-ichi Power Station. However, all power supplied from these six lines was cut-off due to damage to breakers, etc. and the collapse of transmission line towers due to the earthquake.

Fukushima-Dai-ichi NPP

- The first of a series of large tsunami waves reached the TEPCO`s Fukushima Dai-ichi site about 46 minutes after the earthquake.
- These tsunami waves overwhelmed the defences of TEPCO`s Fukushima Dai-ichi facility, which were designed to withstand 5.7m high high tsunami waves. The largest wave that impacted this facility was estimated to be around 14 meters high.
- The tsunami waves reached areas deep within the plant causing the loss of all power sources except for one emergency diesel generator (6B).

Fukushima-Dai-ichi NPP

- Impact of the tsunami rendered the loss of all instrumentation and control systems at reactors 1-4, with emergency diesel 6B providing emergency power to be shared between Units 5 and 6. The tsunami and associated large debris caused widespread destruction of buildings, doors, roads, tanks and other site infrastructure at TEPCO`s Fukushima Dai-ichi, including loss of heat sinks.

- The operators were faced with a catastrophic, unprecedented emergency scenario with no power, reactor control or instrumentation and, in addition, severely affected communications systems both within and external to the site.

Fukushima-Dai-ichi NPP

- With no means to control or cool the reactor units, the three reactor units that were operational up to the time of the earthquake quickly heated up due to reactor decay heating. Despite the attempts to restore control and cool the reactors and spent fuel, severe damage of the fuel and a series of explosions occurred.

- These explosions caused further destruction at the site, making the scene faced by the operators even more demanding and dangerous. Moreover, radiological contamination spread into the environment. These events were determined to be of the highest rating on the International Nuclear Event Scale.

- However, until June 2011 no health effects had been reported in any person as a result of radiation exposure from the nuclear accident.

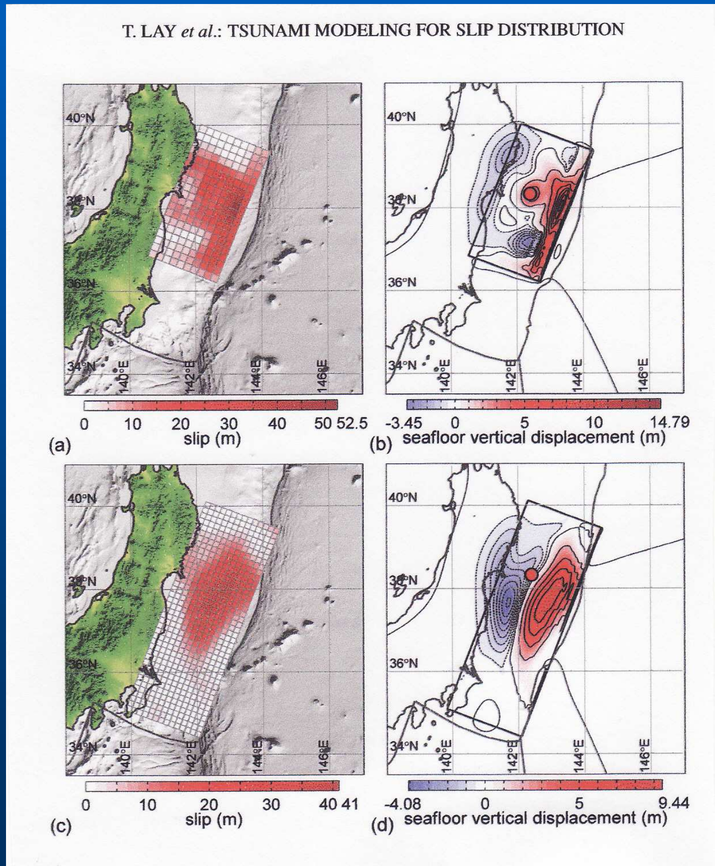
Fukushima-Dai-ichi NPP

- It is obvious that the primary cause of the nuclear accident at Fukushima-Daí-ichi NPPs was due to a gross exceedance of the seismic and tsunami design specifications.

- It is important to determine whether this exceedance was the consequence of a very unlikely chain of events, of a really unexpected event – *i.e.* to phenomenological uncertainty (the black swan) – of human error or of a combinations of uncertainties and errors.

- Within this context, the relevance and current neglect of model uncertainty in risk assessments and practice codes will be briefly examined in connection with these events.

Fukushima-Dai-ichi NPP



Fukushima-Dai-ichi NPP

- According to NASA (April 2012), the massive earthquake off the coast of Japan caused a rare ‘merging tsunami’, in which two waves combined to amplify the destruction after landfall.

- For the first time ever, US and European radar satellites captured images of the two wave fronts of the tsunami, confirming the existence of the long-hypothesised process, which forms a single, double-high wave far out at sea.

- Close to shore, bird-eye views show up to three waves aproaching the coast with different velocities and hinting at the possibility of wave superposition.

Fukushima-Dai-ichi NPP

- John Ritch, Director General of the *World Nuclear Association*, contends that a starting point is to define Fukushima. Although the terms “nuclear disaster” and “nuclear tragedy” are commonly applied, there is reason to resist such usage. When 24,000 Japanese citizens have been killed by an enormous earthquake and a resulting tsunami which combined into one of the great calamities in that nation’s history, does it not seem a gross abuse of language to label as a disaster an occurrence *incidental to that calamity* which has not in itself produced a single fatality?

Fukushima-Dai-ichi NPP

- According to J. M. Acton & M. Gibbs (*Why Fukushima was preventable*, © 2012 Carnegie Endowment for International Peace), had the plant's owner, Tokyo Electric Power Company (TEPCO), and Japan's regulator, the Nuclear and Industrial Safety Agency (NISA), followed international best practice and standards, it is conceivable that they would have predicted the possibility of the plant being struck by a massive tsunami.

- The plant would have withstood the tsunami had its design been previously upgraded in accordance with state-of-the-art safety approaches.

Fukushima-Dai-ichi NPP

- The methods used by TEPCO and NISA to assess the risk from tsunamis lagged behind international standards in at least three important respects:

  • Insufficient attention was paid to evidence of large tsunamis inundating the region surrounding the plant about once every thousand years.

  • Computer modeling of the tsunami threat was inadequate. In fact, preliminary simulations conducted in 2008 that suggested the tsunami risk to the plant had been seriously underestimated were not followed up and were only reported to NISA on March 7, 2011.

  • NISA failed to review simulations conducted by TEPCO and to foster the development of appropriate computer modeling tools.

Fukushima-Dai-ichi NPP

Steps that could have prevented a major accident in the event that the plant was inundated by a massive tsunami, such as the one that struck the plant in March 2011, include:

• Protecting emergency power supplies, including diesel generators and batteries, by moving them to higher ground or by placing them in watertight bunkers as well as establishing watertight connections between emergency power supplies and key safety systems; and

• Enhancing the protection of seawater pumps (which were used to transfer heat from the plant to the ocean and to cool diesel generators) and / or constructing a backup means to dissipate heat.

Fukushima-Dai-ichi NPP

- Though there is no single reason for TEPCO and NISA's failure to follow international best practice and standards, a number of potential underlying causes can be identified.

- In the final analysis, the Fukushima accident does not reveal a previously unknown fatal flaw associated with nuclear power. Rather, it underscores the importance of periodically reevaluating plant safety in light of dynamic external threats and of evolving best practices, as well as the need for an effective regulator to oversee this process.