EXTREME LOADING ANALYSIS OF PETROCHEMICAL PLANTS AND DESIGN OF METAMATERIAL-BASED SHIELDS FOR ENHANCED RESILIENCE

http://r.unitn.it/en/dicam/xp-resilience

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PROBABILISTIC SEISMIC RISK AND RESILIENCE ASSESSMENT FOR PROCESS PLANTS AND INFRASTRUCTURES

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Lecturers

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The seminar is organised by the XP-RESILIENCE research group
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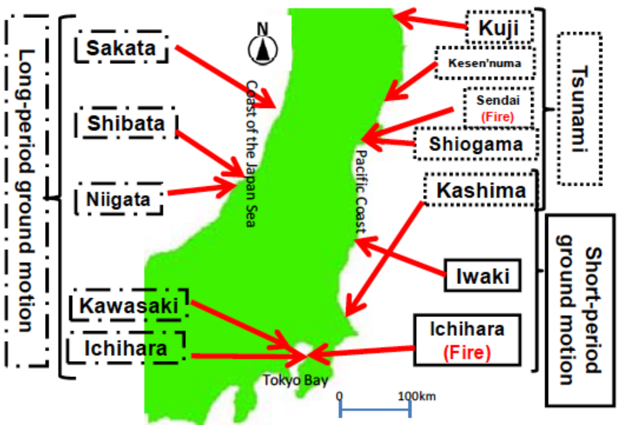
Premises



2011 Pacific Coast of Tohoku Earthquake (M_w 9.0), Japan

Seismic hazard of a site (H): the probability of a seismic event that induces a damage level, within a specific period of time and in a geographically defined zone.

Premises

The Kocaeli earthquake caused significant structural damages to the Tupras refinery itself and associated tank farm with crude oil and product jetties and triggered multiple fires in the refinery's naphtha tank farms.

Kocaeli earthquake (Turkey) -17 August 1999 - Magnitude 7.4

Tupras refinery

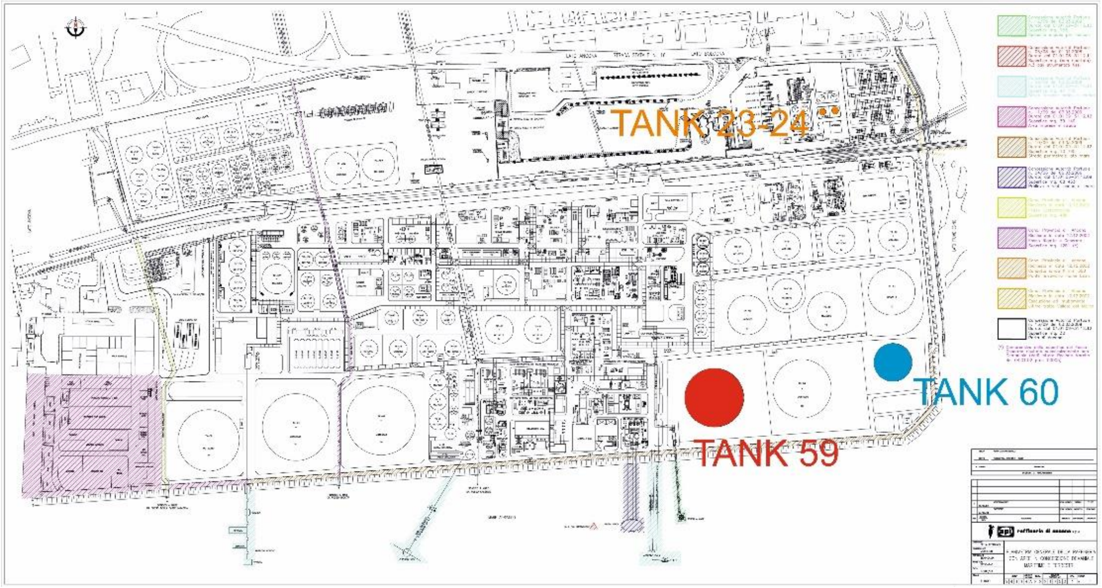
- The majority of the floating roof tanks (30 out of 45) were damaged;
- 250.000 m^3 crude oil and 100.000 m^3 oil product having been exposed to the atmosphere and partially pouring out of the tanks;
- Evacuation order was issued by the crisis centre for a zone of 5 km around the refinery;
- Considerable oil pollution occurred during the incident;
- Total damage is estimated to be around US$ 350 million

Lession from the past: Extreme vulnerability of the tank farm, importance of the domino effect, damaging of services and security systems.

Vulnerability of a structure (V): the level of loss induced to a structure subjected to risk of a seismic event characterized by a given damage level.

WP1 of INDUSE-2-SAFETY: Analysis of special risk petrochemical plants subjected to extreme loading.

Elements subjected to risk (Exposure: E): populations, structures, economic activities, public services, …, subjected to risk in a given site.



General overview of the plant and tanks position

Broad Tanks #59 and #60 contain crude oil

#59: steel, 85 m diameter, 22 m heigh, floating roof;

#60: steel, 55 m diameter, 15,6 m heigh, floating roof.

Slender Tanks #23 and #24 contain flammable liquids

#23, #24: steel, 8 m diameter, 14 m heigh, floating roof.

Premises

What about Europe?

SEVESO III

European Union Law: DIRECTIVE 2012/18/EU (amendments of 96/82/EC) *on the control of major-accident hazards involving dangerous substances*

Annex II: Minimum data and information to be considered in the safety report referred to in Article 10

4. Identification and accidental risks analysis and prevention methods:

(a) detailed description of the possible major-accident scenarios and their probability or the conditions under which they occur including a summary of the events which may play a role in triggering each of these scenarios, the causes being internal or external to the installation; including in particular:

(i) operational causes;

(ii) external causes, such as those related to domino effects, sites that fall outside the scope of this Directive, areas and developments that could be the source of, or increase the risk or consequences of a major accident;

(iii) natural causes, for example earthquakes or floods;

Premises

Lack of sustainability

Failures of a series of viaducts/overpasses

Fossano (Cuneo), 18 April, 2017

€6.8 Billion available to ANAS in 2016-2020

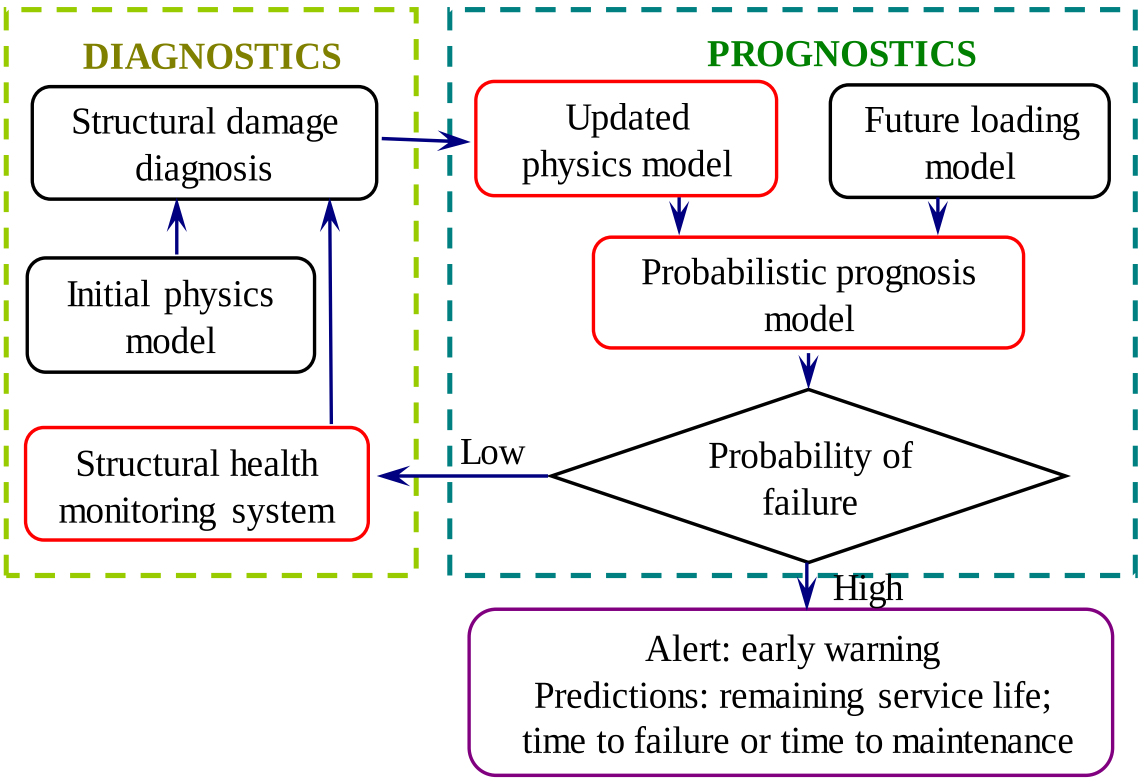
Events

- Agrigento, 7 July 2014
- Lecco, 28 October 2016
- Ancona, 9 March 2017

Action: Development of operational modal analysis for plants with early warning and rapid assessment damage capabilities

Objectives

The main aim of this work package is to develop an integrated procedure that addresses sensor network, data analysis, and damage assessment and to apply the procedure to effective decision-making systems for alert and EW.



Additive observational errors

$$\mathbf{d} = \mathbf{d}^t + \mathbf{e} = \mathbf{G}(\boldsymbol{\theta}) + \mathbf{e}$$

Bayesian approach for the posterior prob. density of $\boldsymbol{\theta}$

$$P(\boldsymbol{\theta}|\mathbf{d}) = \frac{P(\mathbf{d}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{\sum P(\mathbf{d}|\boldsymbol{\theta})P(\boldsymbol{\theta})}$$

Premises

What about USA?

Item	Current Funding	Projected need
Roads and bridges	$941 Billion	$1.1 Trillion
Ports and shipping	$22 Billion	$15 Billion
Water and wastewater	$45 Billion	$105 Billion
Electricity	$757 Billion	$177 Billion

Projection in 10 years. Source ASCE.

Outline

- Risk in Seismic Engineering
- PSRA for nuclear power plants
- PBEE approach
- PSHA and PSDA methods
- PSRA of process plants considering domino effects
- Loss evaluation in infrastructures
- A look at resilience
- Conclusions
- Outlooks

Figures on probabilities: annual probabilities of deaths

Gas Engineering

Cause of Death	Individual Level of Risk
Smoking 30 cigarettes per day	1 in 200 (5×10^{-2}) Per Year
Man aged 35-44 (general)	1 in 600 (1.7×10^{-2}) Per Year
Motor Vehicle Accident	1 in 10 000 (1×10^{-4}) Per Year
Accident at home	1 in 12 000 (8.3×10^{-5}) Per Year
Rail accident	1 in 420 000 (2.3×10^{-6}) Per Year
Airplane crash	1 in 3 500 000 (2.9×10^{-7}) Per Year
Hit by lightning strike	1 in 10 000 000 (1×10^{-7}) Per Year
Asteroid Impact	1 in 50 000 000 (2×10^{-8}) Per Year
For Reference:	
Win in the Lottery	1 in 14 000 000 (7.1×10^{-8}) Per Game

Daily/Ideal tool in gas industry Risk Matrix

(A = high vulnerability; F= small vulnerab.)

Gas Engineering

				SH	S0	S1	S2	S3	S4	SL
				Extreme	catastrophic	very severe	severe	moderate	slight	N eglegible
			Safety inside plant	-	More than 10 fatality	one or several fatalities	one or several serious injuries (disabilities)	one or several injuries (lost working days)	one or several minor injuries (first aid cases)	no impact
			Safety outside plant	More than one fatality	More than one fatality	One fatality	one or more injuries	severe inconvenience (irritation, need for evacuation)	slight inconvenience (smell, smoke, noise)	no impact
			Environment	-	irreversible impact	irreversible impact	serious reversible impact outside plant boundaries	slight reversible impact outside plant boundaries	slight reversible impact inside plant boundaries	no impact
			Asset Loss	-	TBD (by Client) e.g.: 100M €	TBD (by Client) e.g.: 10M €	TBD (by Client) e.g.: 1M €	TBD (by Client) e.g.: 250k€	TBD (by Client) e.g.: 50k €	TBD (by Client) e.g.: 1k €
			Severity Rating	100,000	10,000	1,000	0,100	0,010	0,001	0,000
			Acceptable Risk [Fatalities/yr]	1,00E-07	1,00E-07	1,00E-06	1,00E-06	1,00E-05	1,00E-05	1,00E-04
			Acceptable Risk [€/yr]	-	1	10	10	250	500	1000
FH	**Frequent Event:** Happened several times per year	several times a year	1,00E+01	A	A	A	A	B	C	E
F0	**Normal Event:** Happened once in several years	once a year	1,00E+00	A	A	A	A	C	D	F
F1	**Unusual Event:** Happened once in most plants	(1/10a)	1,00E-01	A	A	A	B	D	E	F
F2	**Unlikely Event:** Happened in some plant	(1/100a)	1,00E-02	A	A	B	C	E	F	F
F3	**Rare Event:** Nearly happened in some plant / Cannot be excluded	(1/1.000a)	1,00E-03	A	A	C	D	F	F	F
F4	**Very Rare Event:** Not to be expected reasonably	(1/10.000a)	1,00E-04	A	B	D	E	F	F	F
FL	**Extremely Rare Event:** Nearly impossible	(1/100.000a)	1,00E-05	X	C	E	F	F	F	F
Fx	**Intentional Acts:** Impossible to determine frequency	---	---	X	X	X	F	F	F	F

Annual probability figures for earthquakes
(D= demand o response; C=capacity)

- Gravity and seismic loading

Gravity loading: Pr (D>C) of the order of $1x10^{-6}$;

Seismic loading: Pr (D>C) of the order of $1x10^{-2}$ (for an economic structure);

For example, if the return period T_R of 500 years is the mean intensity for a design (and therefore the annual probability of exceeded intensity is $\lambda = 1 / T_R \approx 2x10^{-3}$) and if the likelihood of collapse accepted for that intensity is fixed at $1x10^{-2}$, then the probability of accepted annual collapse is approximately equal to $2x10^{-5}$.

- 3.2.1 LIMIT STATES AND EXCEEDING PROBABILITIES (Italian code)

Tabella 3.2.I – *Probabilità di superamento* P_{V_R} *al variare dello stato limite considerato*

Stato Limite		P_{V_R} : **Probabilità di superamento nella vita di riferimento** V_R
Stati limite di esercizio	*SLO*	81%
	SLD	63%
Stati limite ultimi	*SLU*	10%
	SLC	5%

Typically, we ignore ageing in seismic design, so we deal with random variables. The earthquake action clearly depends on time.

Monodimensional case:

Fragility function: probability of exceeding a given state of structural performance

$$P_f(im) = \int_0^{\infty} f_D(\alpha \mid im) F_C(\alpha) d\alpha$$

Risk: Unconditional probability of annually exceeding a given limit state

$$P_f = \int_0^{\infty} P_f(im) \left| \frac{dH}{\mathrm{d}\, im} \right| F_C(\alpha) d\alpha$$

Main assumption: time-integrated approach

Time does not explicitly appear in computations. In-time variations of quantities are absorbed in their extreme values

Temporal sequence of the seismic event.

- Appropriate interval of time: one year
- If failure is to occur in one year, it will do so under the seismic event of largest intensity
- A probabilistic model for the CDF of the yearly maxima is needed
- Independence among annual events and assumption of a Poissonian process

$$P_n(edp) = 1 - \left(1 - P(edp)\right)^n$$

Dynamic response of a structure during an event

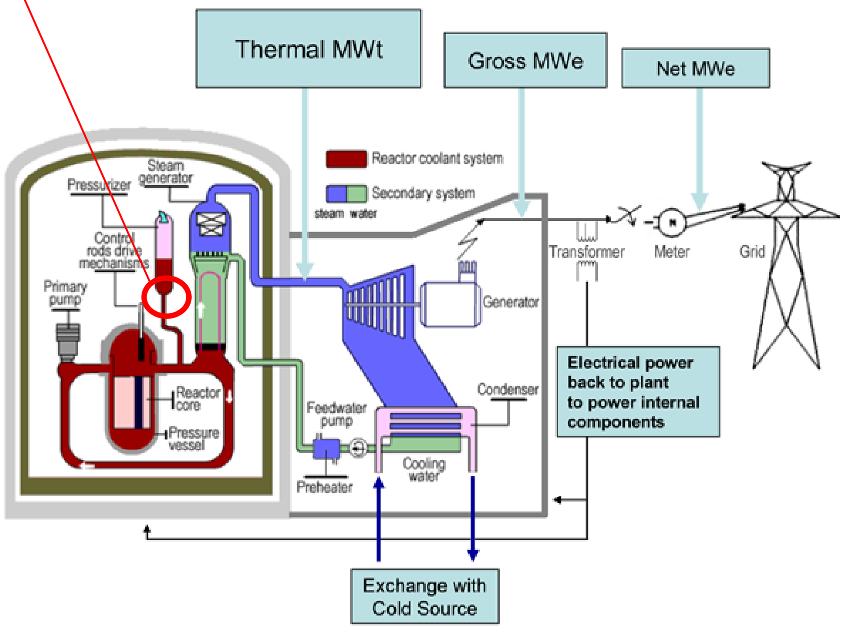
- In a structure subjected to ground acceleration, failure occurs when its response attains its maximum, i.e. $D(t)=D_{max}$. In general, $C[t, D(t)]-D(t)\leq 0$
- As for the case of a time-invariant problem, a vector of correlated random variables (maximum responses) will be compared with the corresponding random capacities

Heavily use of lognormal CDFs

- It deals with positvely valued variables. It assumes the least knowledge.

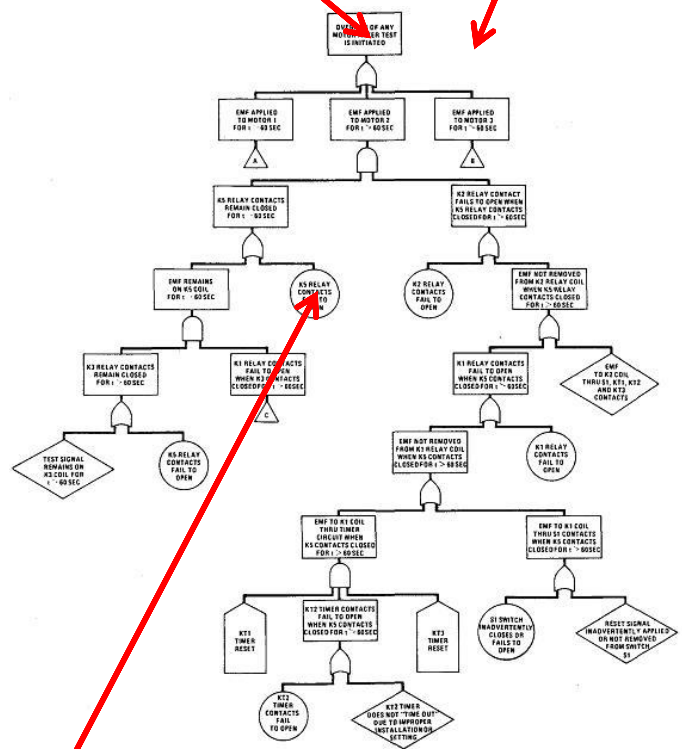
Probabilistic Seismic Response Assessment method derived from nuclear industry – One or a few faults

i.e. flange rupture derives from a structural stress and can be identified by a structural analysis



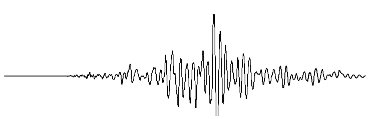
A single top event: core melt and release of radioactive material

Just one or few fault trees describe the risk scenario FT

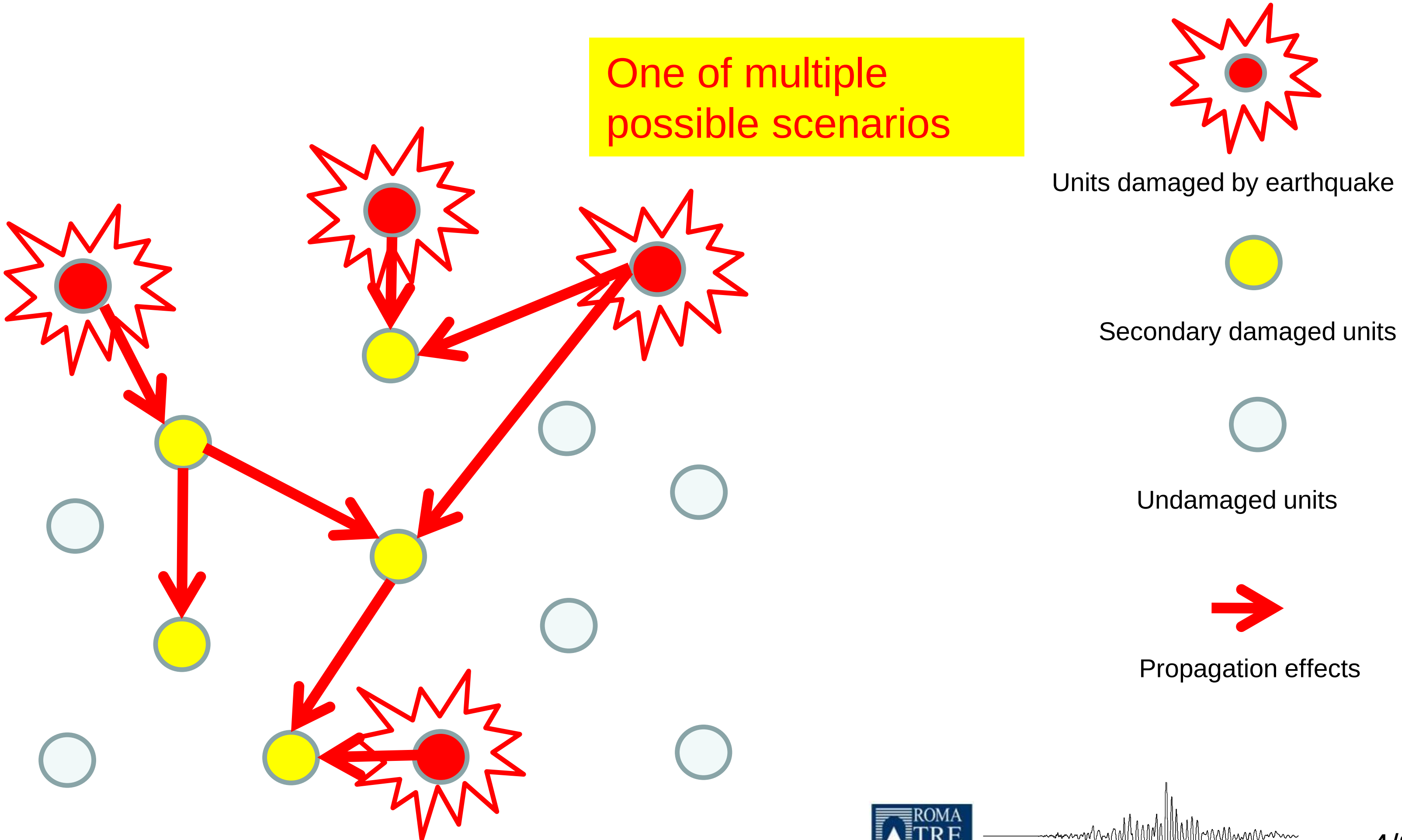


A Nuclear plant is a monolithic set of interconnected components integral to a unique physical structure (building).

Events probabilities can be computed from failure rate databases, from fragility curves or from structural analyses



WHAT MAY HAPPEN INSTEAD IN A PROCESS PLANT DURING EARTHQUAKE

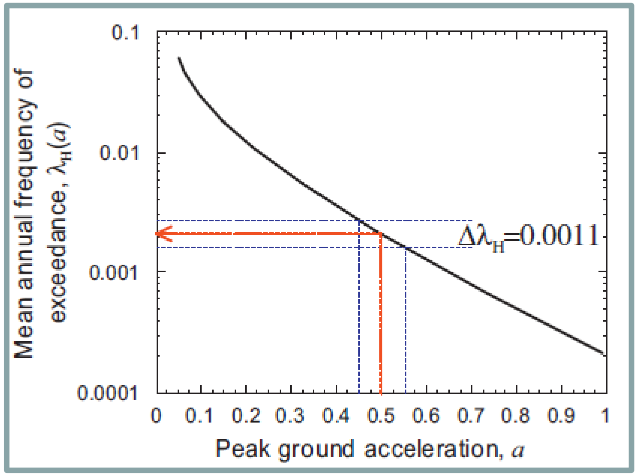


PSRA – Method…

The main tasks of this new methodology are: (1) Response based fragility curves, (2) non linear response history analysis to characterize the demand, (3) Monte Carlo simulations to consider the correlation between components in the damage analysis. The procedure estimates the mean annual frequency of unacceptable performance of a NPP.

DERIVATIVE OF SEISMIC HAZARD CURVE WITH RESPECT TO GROUND MOTION PARAMETER

$$\lambda_{UP} = \int G_{UP}(a) \boxed{\left| \frac{d\lambda_H(a)}{da} \right|} da$$



PSRA – Method…

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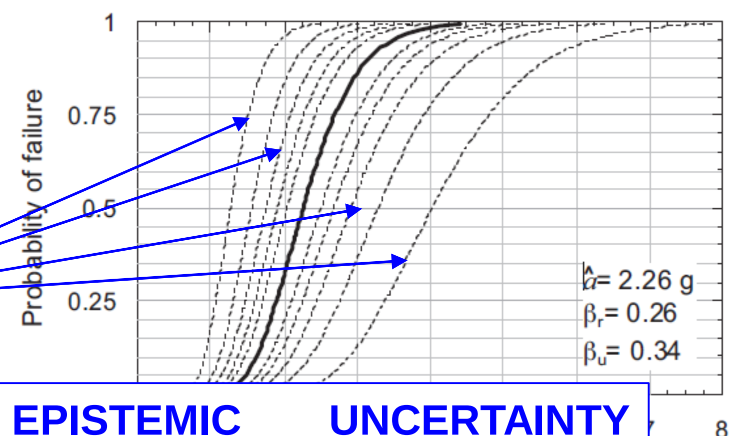
FRAGILIY FUNCTION/
FAMILY OF FRAGILITY FUNCTIONS

$$\lambda_{UP} = \int \boxed{G_{UP}(a)} \left| \frac{d\lambda_H(a)}{da} \right| da$$

$$G_C(a) = \Phi\left(\frac{\ln a/\hat{a} + \Phi^{-1}(Q)\beta_u}{\beta_r} \right)$$

$$\hat{a} = \mathrm{HCLPF} \cdot e^{1.65(\beta_r + \beta_u)}$$

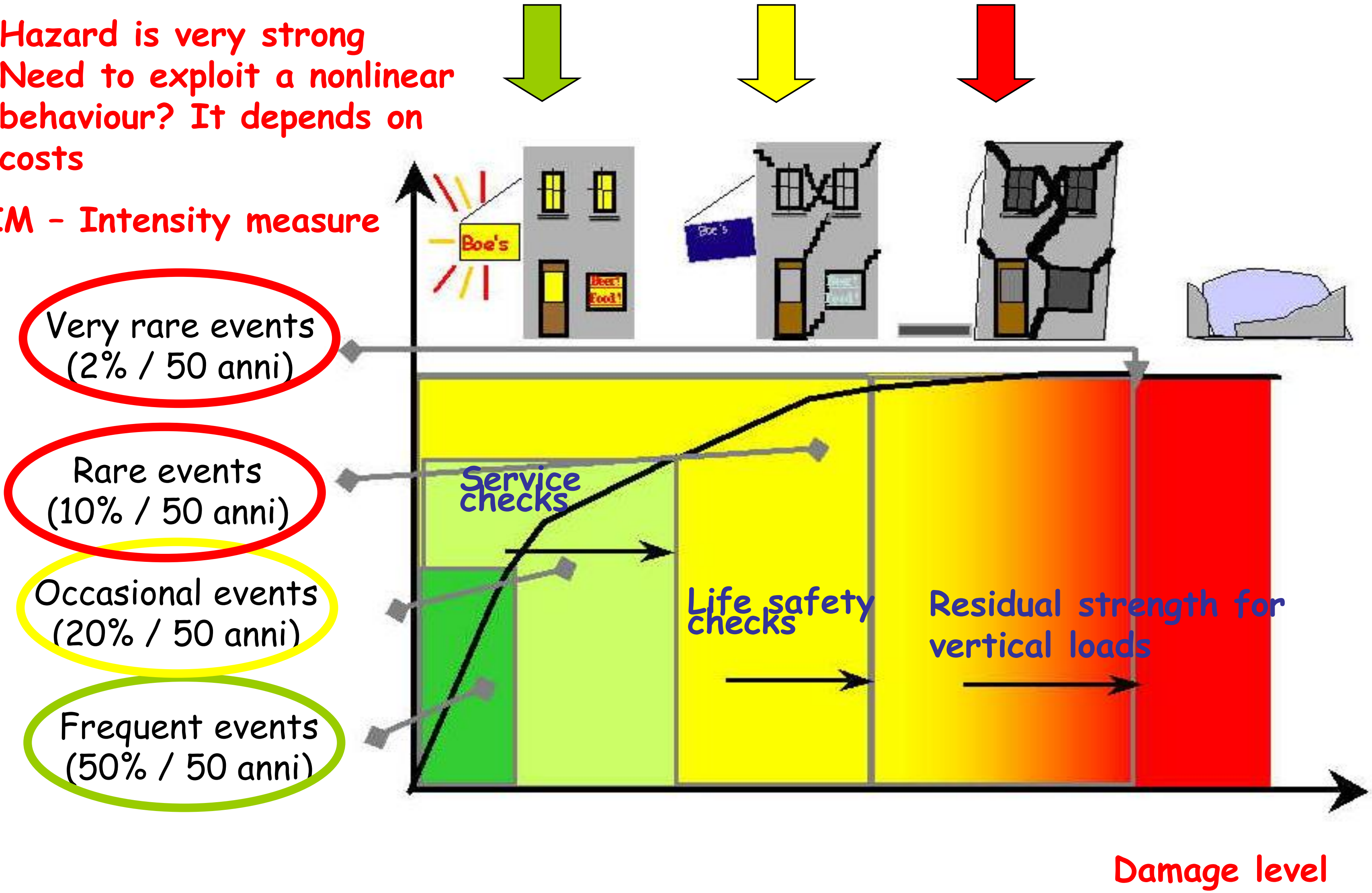


EPISTEMIC UNCERTAINTY CONSIDERED WITH a Q PARAMETER [Confidence interval 0-1]

PHYSICS: NONLINEAR RESPONSE IS NEEDED

- Hazard is very strong
- Need to exploit a nonlinear behaviour? It depends on costs

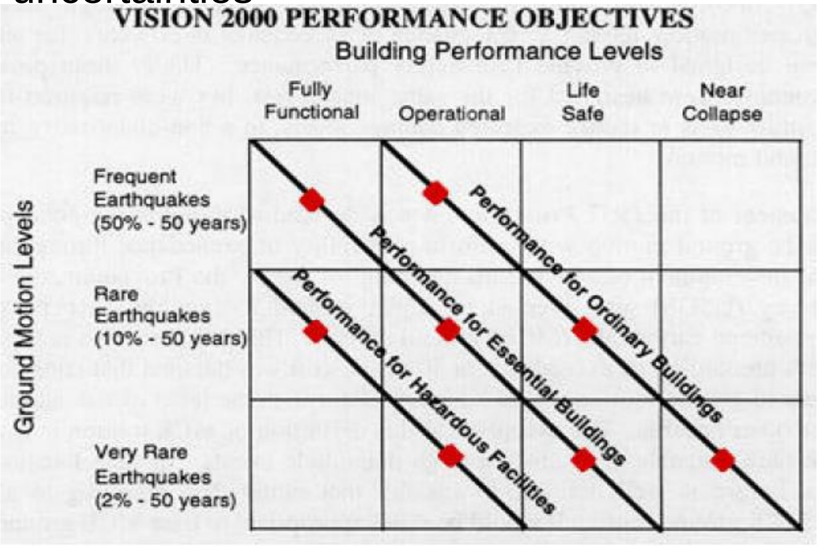
IM – Intensity measure



After Hamburger, R. O., Foutch, D. A. and Cornell, C. A. "Performance Basis of Guidelines for Evaluation, Upgrade and Design of Moment-Resisting Steel Frames." 12th WCEE. Auckland, 2000.

Measures of Performances: Performance-based Earthquake Engineering (PBEE)

- **Forces and deformation?**
  - Yes, but **only** for engineering calculations
  - Intermediate variables
  - Not for communication with clients and community
- **Communication in terms of the three D's:**
  - Dollars (direct economic loss)
  - Downtime (loss of operation/occupancy)
  - Death (injuries, fatalities, collapse)
- **Quantification**
  - Losses for a given shaking intensity
  - Losses for a specific scenario (M & R)
  - Annualized losses
  - With or without rigorous consideration of uncertainties

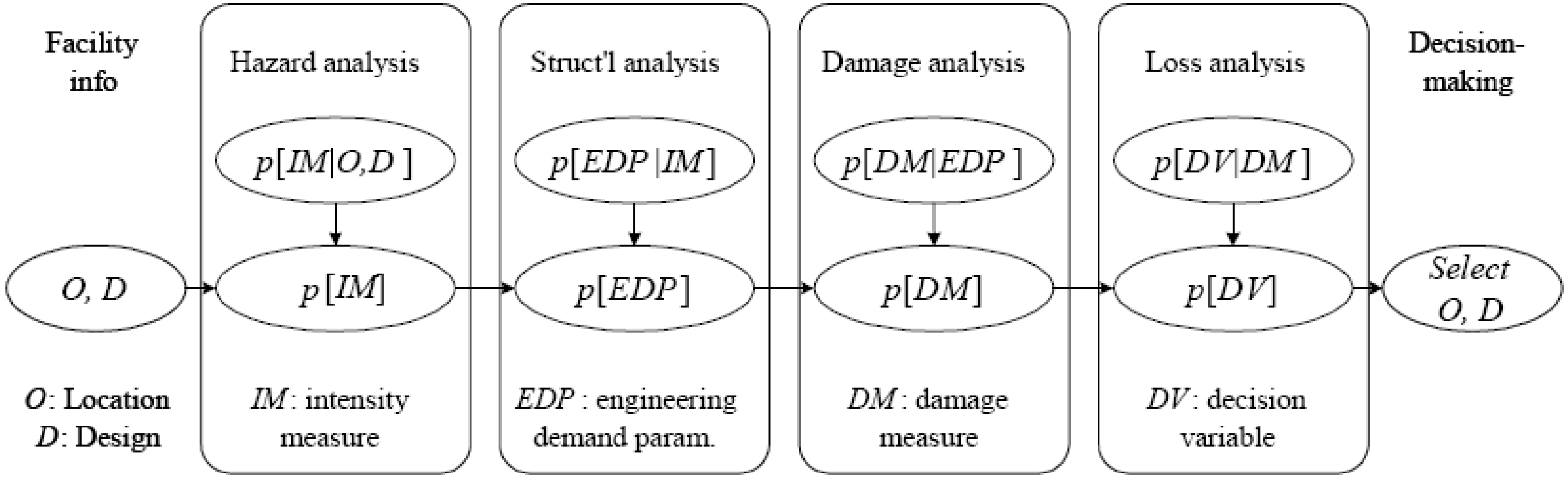


Performance-based earthquake methodology (PBEE) is based on the Law of Total Probability

- All randomnesses can be taken into account:
  - Randomness of seismic input (Hazard Analysis)
  - Randomness of structural response (Structural Analysis)
  - Randomness of Structural Capacity (Damage Analysis)
  - Randomness of Objective function (Loss analysis)

The procedure is concluded with a Decision Making Phase

$$\lambda(DV) = \int_0^\infty \int_0^\infty \int_0^\infty G(DV \mid DM)\,\left|dG(DM \mid EDP)\right|\,\left|dG(EDP \mid IM)\right|\,\left|d\lambda(IM)\right|$$

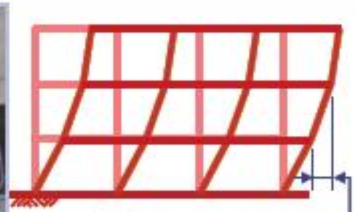


Performance-Based Framework: Buildings

- Collapse & Casualties
- Direct Financial Loss
- Downtime

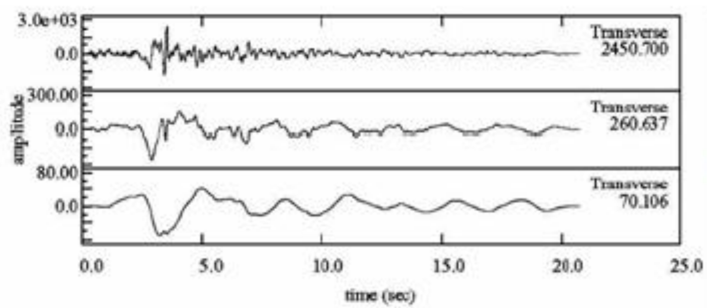
Decision Variable

Damage Measure



drift as an EDP

Engineering Demand Parameter



Intensity Measure

PBEE – Probabilistic Framework Equation by Allin Cornell

$$v\left(dv < DV\right) = \iiint G(dv\,|\,dm)\,dG(dm\,|\,edp)\,dG(edp\,|\,im)\,|\,d\lambda(im)\,|$$

Impact

Performance (Loss) Models and Simulation

Hazard

im – Intensity Measure

edp – Engineering Demand Parameter

dm – Damage Measure

dv – Decision Variable

$\lambda(im)$- mean annual frequency of exceedance of IM

ν(dv<DV) – Probabilistic Description of Decision Variable

(e.g., Mean Annual Probability $ Loss > 50% Replacement Cost)

PBEE – Main hypotheses

$$v(dv < DV) = \iiint_{im\ dm\ edp} G(dv \mid dm)\, dG(dm \mid edp)\, dG(edp \mid im)\, |d\lambda(im)|$$

Impact | Performance (Loss) Models and Simulation | Hazard

The main hypotheses behind this formulation are:

- $G(x|y) = Pr(x < X|Y = y)$, denotes the **conditional complementary cumulative distribution function** of a random variable X given a particular outcome Y =y of random variable Y.
- $dG(DM|EDP, IM) = dG(DM|EDP)$, so that, once an IM is selected, DM is ***statistically independent*** from it.
- $dG(DV|DM, EDP, IM) = dG(DV|DM)$, so that, once an EDP and an IM are selected, DV is ***statistically independent*** from them.

HAZARD ANALYSIS

PSHA methodology

How to calculate the $\lambda(im)$, - mean annual frequency of exceedance of the *IM* (*PGA, Sa(t), PGD, etc.*)?

The canonical approach is known as **Probabilistic Seismic Hazard Analysis (PSHA)** and consists in 5 steps

1. identification all earthquake sources capable of producing damaging ground motions;
2. characterization of the distribution of earthquake magnitudes;
3. characterization of the distribution of source-to-site distances associated with potential earthquakes;
4. prediction of the resulting distribution of ground motion intensity as a function of earthquake magnitude, distance, etc. (attenuation law);
5. combination of uncertainties in earthquake size, location and ground motion intensity, using the total probability theorem.

PBEE – Procedure

PSHA methodology

For one seismic source:

$$P(IM > x) = \int_{m_{\min}}^{m_{\max}} \int_{0}^{r_{\max}} P(IM > x \mid m, r) f_M(m) f_R(r) dr dm$$

For all the seismic sources:

$$\lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{\min}) \int_{m_{\min}}^{m_{\max}} \int_{0}^{r_{\max}} P(IM > x \mid m, r) f_{M_i}(m) f_{R_i}(r) dr\, dm$$

Where *m* and *r* are the **magnitude** and the **fault distance** respectively.

The main hypothesis that allows us to estimate the annual frequency of exceedance is that the **probability distribution of time between occurrences of earthquakes is assumed to be Poissonian.**

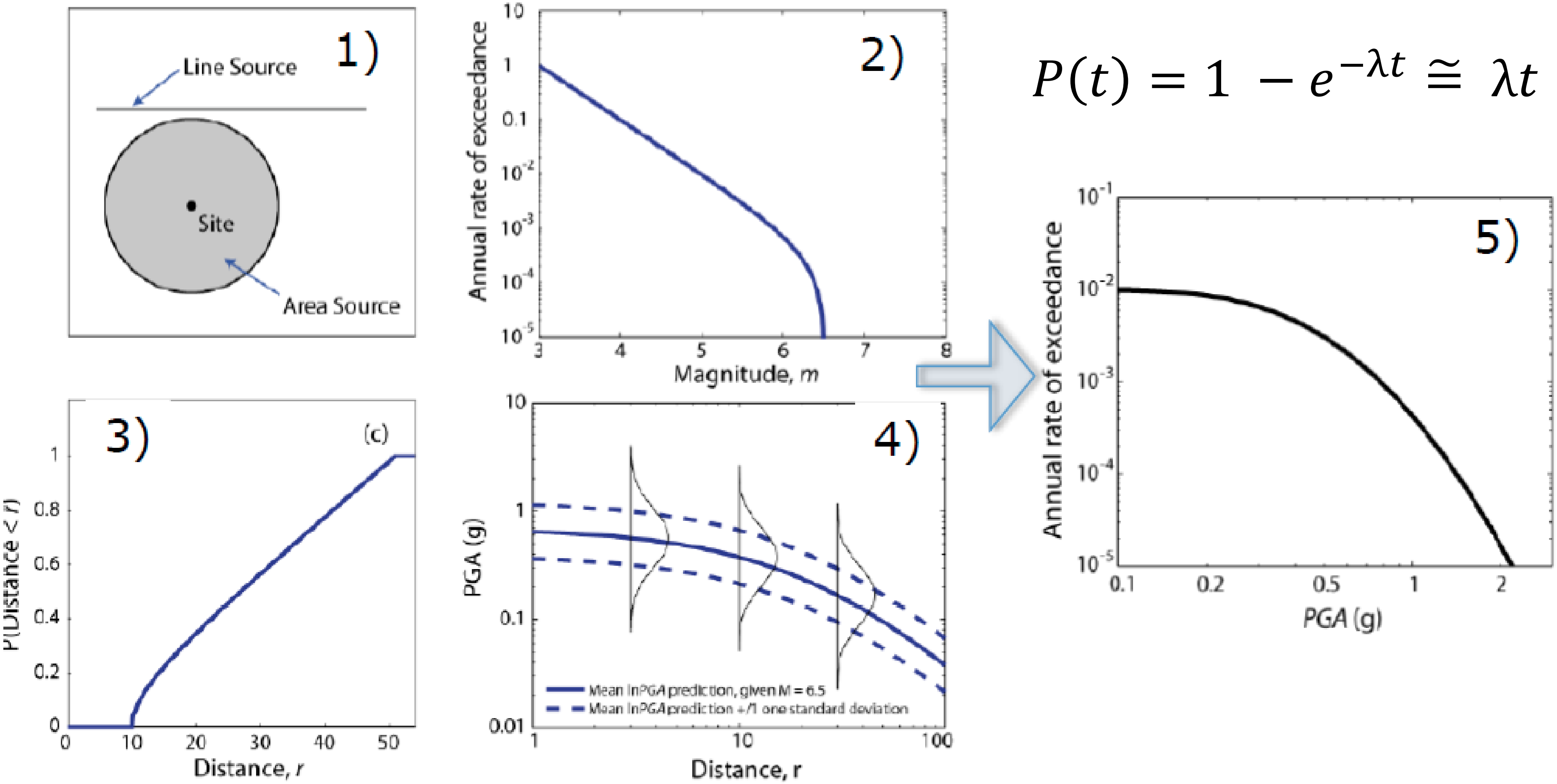
The Poisson model was found to be a reliable way to describe the earthquakes frequency.

$$P(t) = 1 - e^{-\lambda t} \cong \lambda t$$

PBEE – Procedure

PSHA methodology

$$P(t) = 1 - e^{-\lambda t} \cong \lambda t$$



PBEE – Procedure

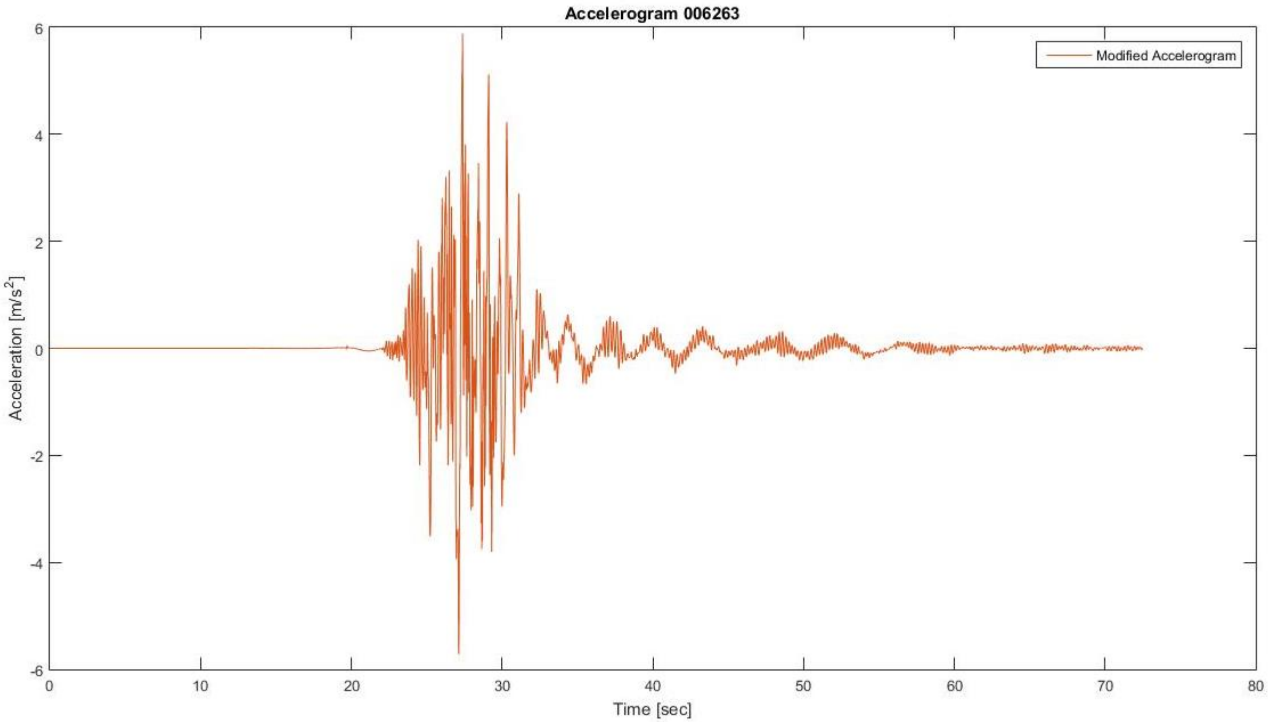
PSDA methods

How to calculate the $\underline{dG(EDP|IM)}$, the probability distribution of the EDP given the IM? Three main **Probabilistic Seismic Demand Analysis (PSDA)** methodologies, can be adopted.

.

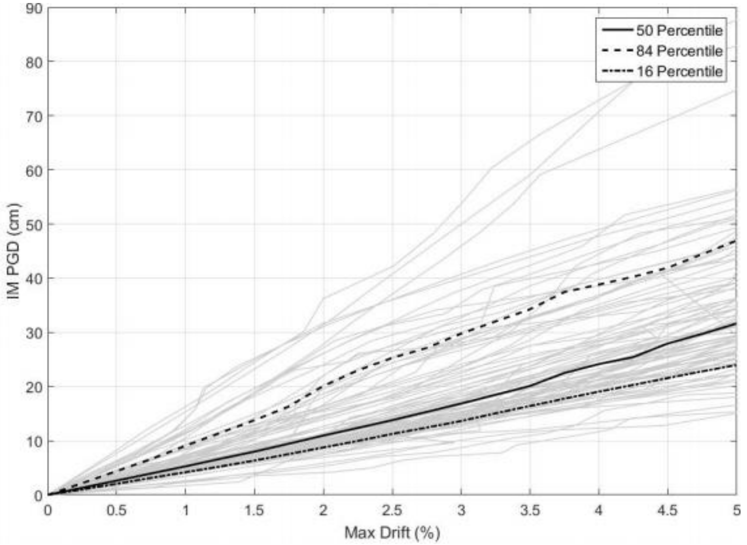
An **accelerogram** is the recording of the acceleration of the ground during an **earthquake**. It is used as input of a seismic dynamic analysis and can be derived from a **natural record** or from an **artificial seismic signal**.

Accelerogram of the 2000 Iceland Earthquake



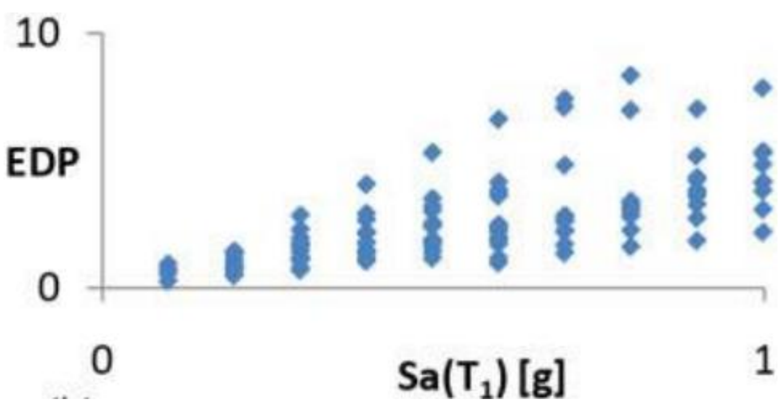
PBEE – Procedure

PSDA methods



1) Incremental Dynamic Analysis (IDA).

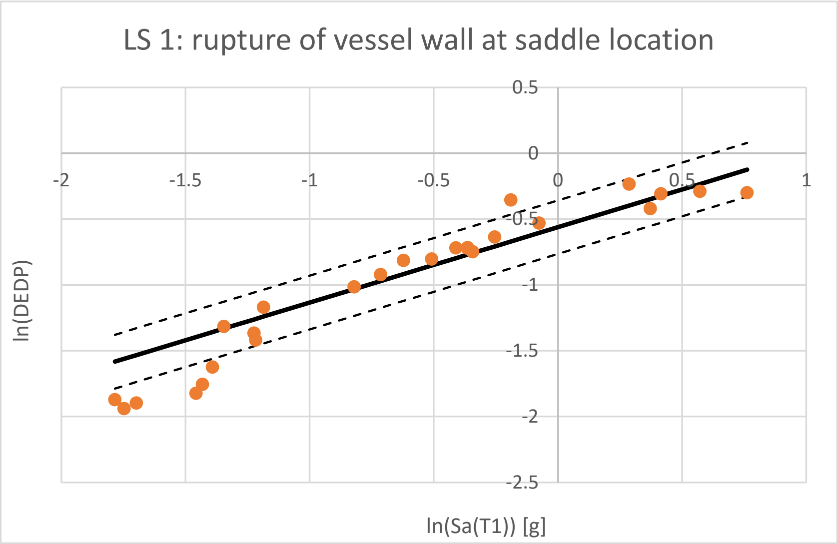
IDA adopts the same values of IMs for each of the accelerograms previously scaled.



2) Multiple-stripe Analysis (MSA).

MSA adopt the different intervals of IMs for each of the scaled accelerograms

PBEE – Procedure
PSDA methods



3) Cloud Method.

The **Cloud Method** adopts only the unscaled accelerograms.

For IDA and MSA:
IMs values that correspond, for each accelerograms, to the reaching point for the **limit state** are supposed to be part of a **lognormal distribution.** The estimation of the parameters of this distribution allows for the evaluation of the **CDF** which represents the **fragility function**.

For Cloud Method:
The estimation of a **linear relation, by regression, between the logarithm of EDP and the logarithm of the IM** provides the necessary parameters for the calculation of the **fragility function.**

PBEE – Procedure

Fragility Functions and Cloud Method

Cloud Method – Analytical Formulation

The expected EDP is modelled as a **linear relationship in the logarithmic space** of EDP versus the candidate *IM*

1) $E[lnEDP|IM] = a + bln(IM)$

The parameters *a* and *b* are regression coefficients estimated with the least square method. Then, *a* and *b* let us set the main parameters of the **probabilistic seismic demand model (PSDM).**

2) $\sigma_{lnEDP|IM} = \beta_{EDP|IM} = \sqrt{\dfrac{\sum_{i=1}^{n}[ln(EDP_i) - \ln(a(IM_i)^b)]^2}{n-2}}$

3) $m_{EDP} = \left(\dfrac{C_{LS}}{a}\right)^{1/b}$

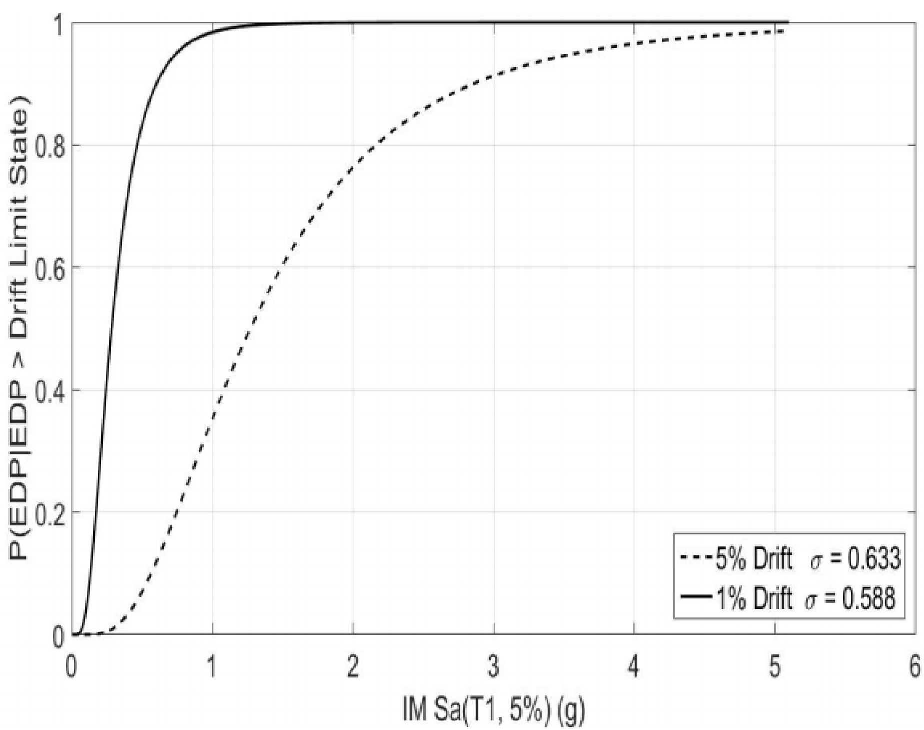
4) $\beta_{EDP} = \dfrac{1}{b}\beta_{EDP|IM}$

where β_D and m_D are the dispersion and the median of *EDP* values that exceed the **limit state level**, indicated as C_{LS}.

PBEE – Procedure
Cloud Method – Analytical Formulation

The conditional probability that the demand *EDP* exceeds the limit state capacity C_{LS}, which is known as **fragility function**, reads,

5) $P[EDP \geq C_{LS}|IM = im] = \Phi\left[\frac{ln(im/m_{EDP})}{\beta_{EDP}}\right]$



The **Fragility Functions** show the correlation between the **probability of exceeding a certain limit state** of a certain **EDP** (stresses, deformations, etc.) and the chosen **intensity measure (*IM*)** of the earthquake (Peak ground acceleration, Spectral acceleration, etc.)

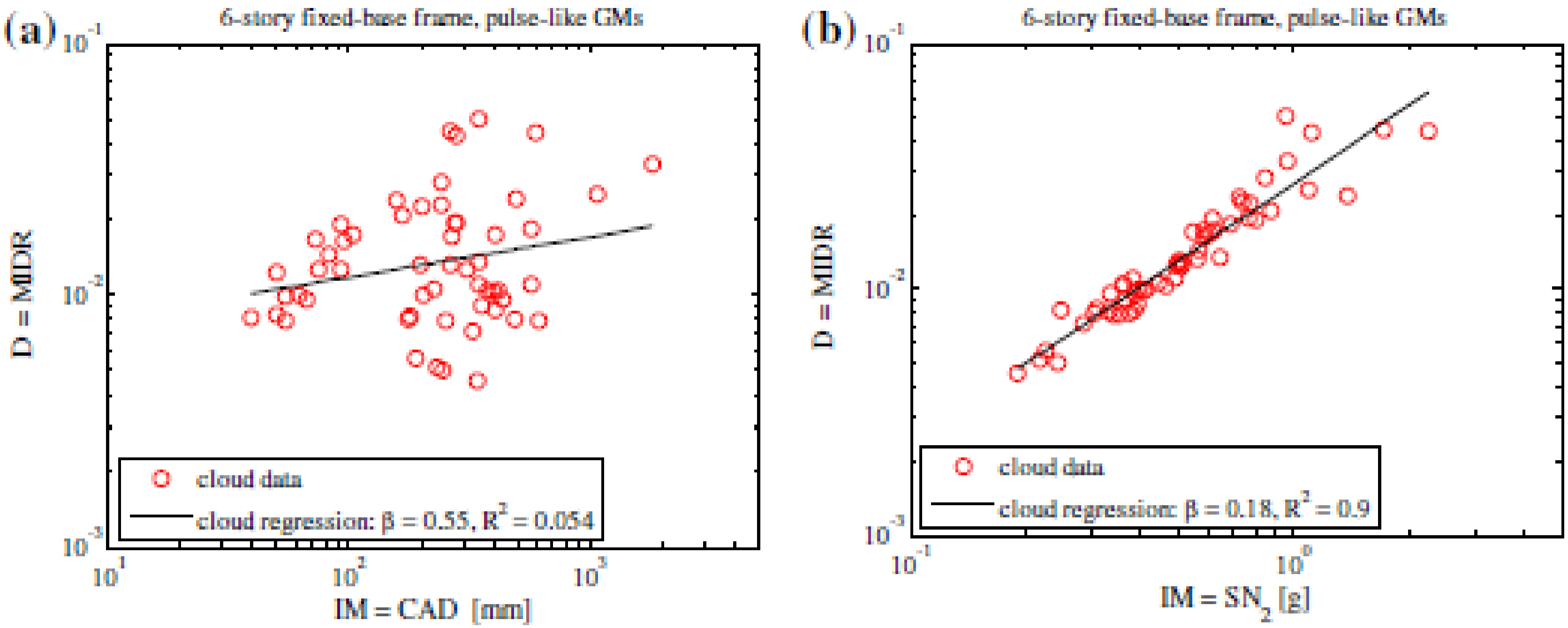
PBEE – Practical application

Efficiency of the IM

How to evaluate the *efficiency* of the IM and the relevant probabilistic seismic demand model (PSDM)?

According to Baker (2015), a PSDM is defined as efficient when the variance of the estimator, ln EDP, is low. According to Ebrahimian (2015), a PSDM is efficient when:

- The β_{EDP} (or COV) is lower than 0.4.
- The R^2 parameter of the linear regression is as near as possible to 1.



Baker JW, 2015. Efficient Analytical Fragility Function Fitting Using Dynamic Structural Analysis. Earthquake Spectra. Vol. 31, No. 1, pp. 579-599.
Ebrahimian H., Jalayer F., Lucchini A., Mollaioli F., Manfredi G., 2015. Preliminary ranking of alternative scalar and vector intensity measures of ground shaking. Bull Earthquake Eng 13, 2805–2840

PBEE – Procedure

Sufficiency of the IM

How to evaluate the *sufficiency* of the IM?

According to Ebrahimian et al. (2015), an IM is **sufficient** if and only if the probability distribution for demand parameter EDP given IM is independent of the accelerogram denoted as $a_{g.}$

$$P_{EDP|IM,a_g}\left(y|IM\left(a_g\right),a_g\right)=P_{EDP|IM}\left(y|IM\left(a_g\right)\right)$$

In other words, any other information about the accelerogram, so any different IMs, should not give additional information to the probability distribution

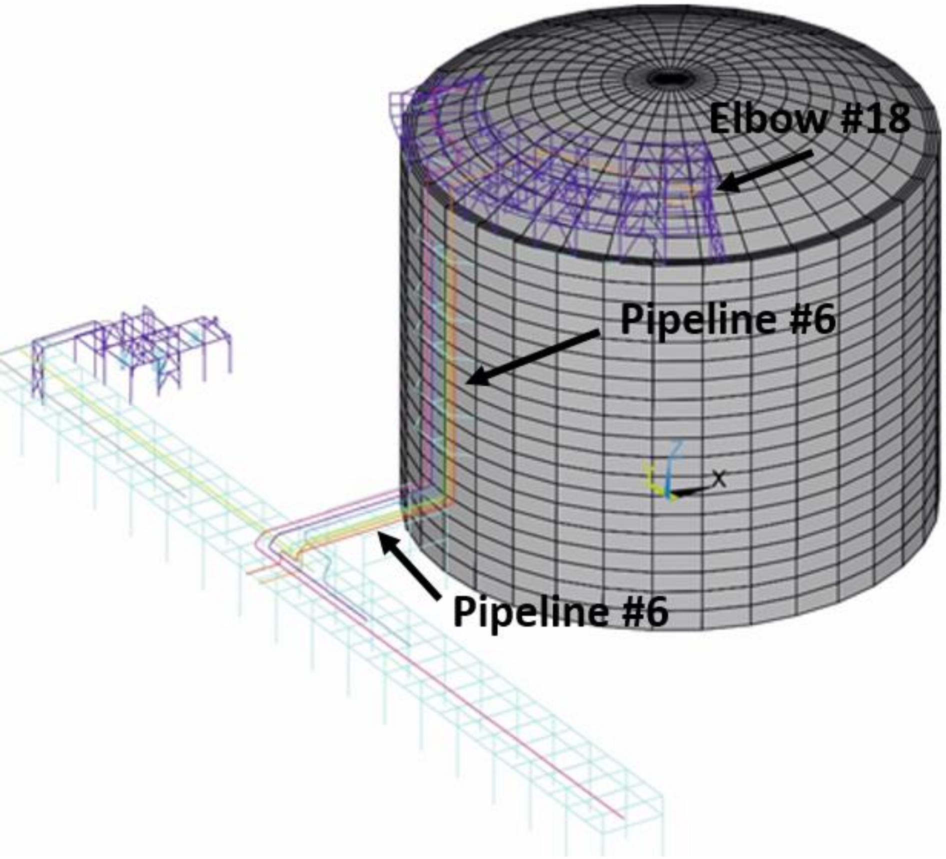
As explained by Jalayer et al. (2012), the grade of sufficiency can be estimated through the evaluation of the **relative entropies** (Kullback and Leilbler, 1951) between the probability density functions based on the different IMs.

Jalayer F, Beck J, Zareian F (2012) Analyzing the sufficiency of alternative scalar and vector intensity measures of ground shaking based on information theory. J Eng Mech 138(3):307–316

Kullback S, Leibler RA (1951) On information and sufficiency. Ann Math Stat 22(1):79–86

PBEE – Procedure
Real LNG Plant - PSDA

~= 20,000 degrees of freedom
- 1338 elements BEAM4
- 84 elements LINK180
- 159 elements PIPE289
- 95 elements ELBOW290
- 1122 elements SHELL181



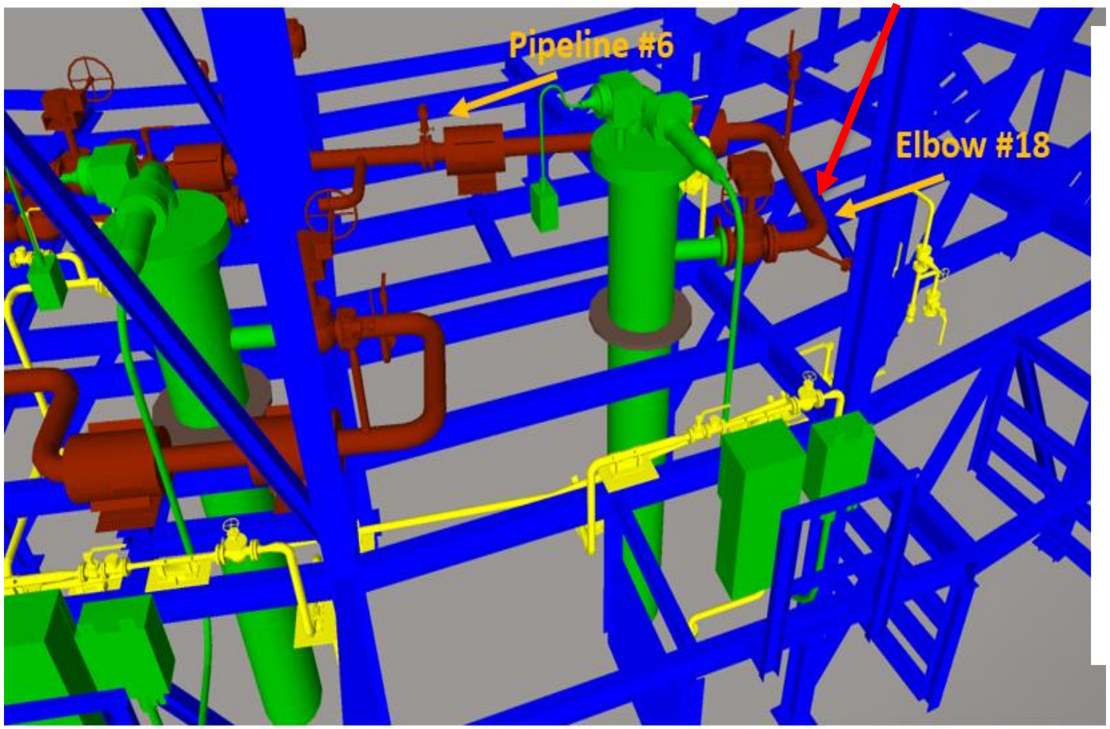
<u>It takes 3 days to run 1 seismic analysis</u>

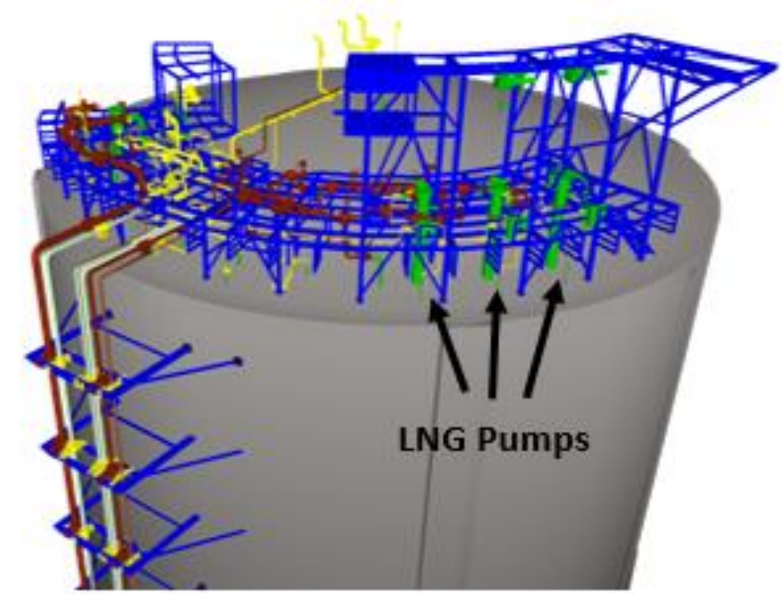
Bursi O.S., di Filippo R., La Salandra V., Pedot M., Reza Md S.,, Probabilistic Seismic Ananlysis of a Full Scale LNG Plant, (2017), Journal of Loss Prevention in the Process Industries. Submitted

Real LNG Plant – PSDA

Leakage Scenario

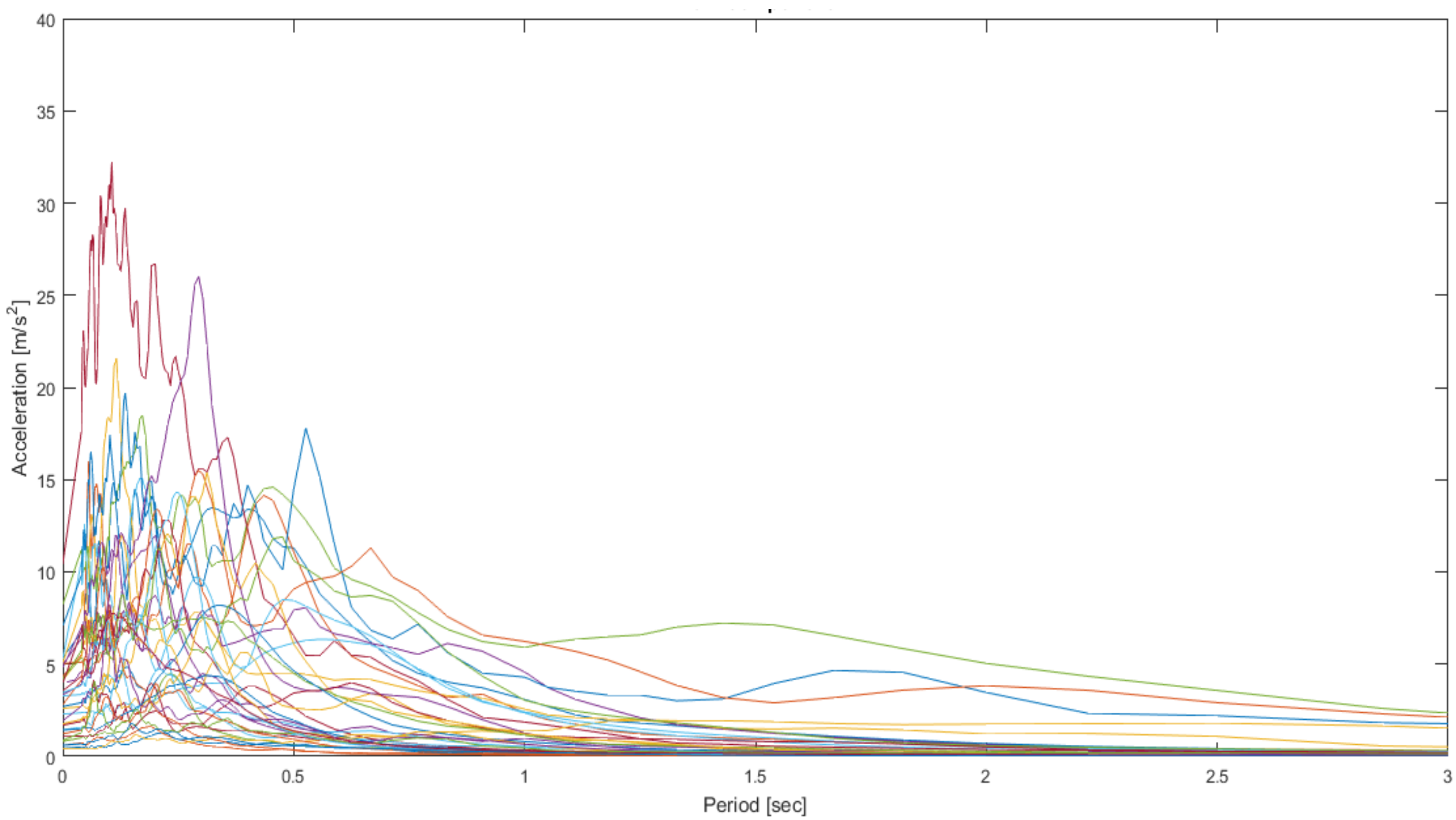
Leakage Location





Piping elbows were found to be the most vulnerable components. In particular, we registered very high **hoop strain values** (the selected **EDP**, directly correlated to **leakage events**) for the Elbow #18 attached to a LNG pump.

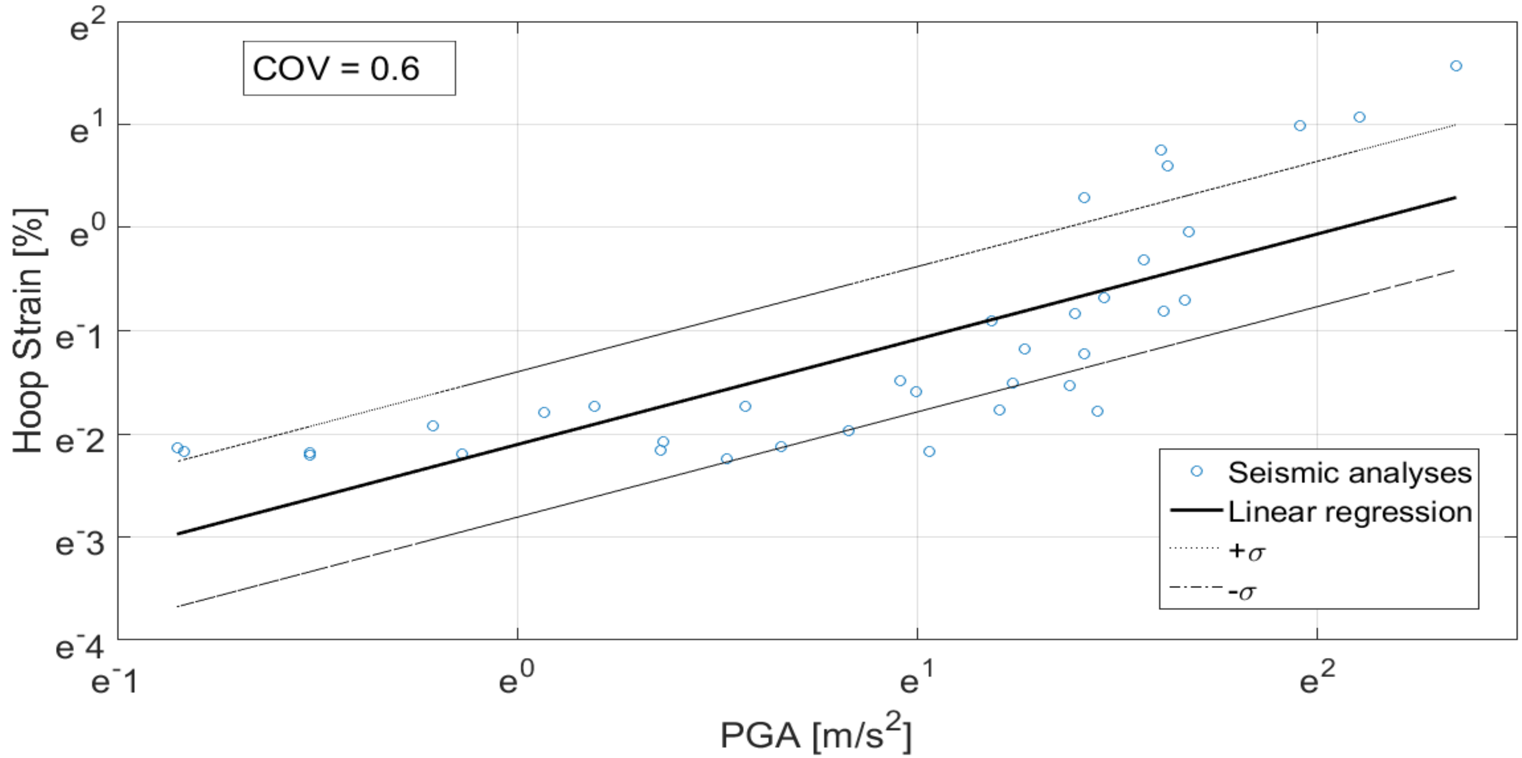
Real LNG Plant – PSDA Seismic Input



The **36 seismic signals** covered a wide range, from near zero to 3g. This wide range lets us **evaluate and improve the efficiency of the PSDM.**

PSDA – Cloud Method
Linear Regression

$$E[lnEDP|IM] = a + bln(IM)$$

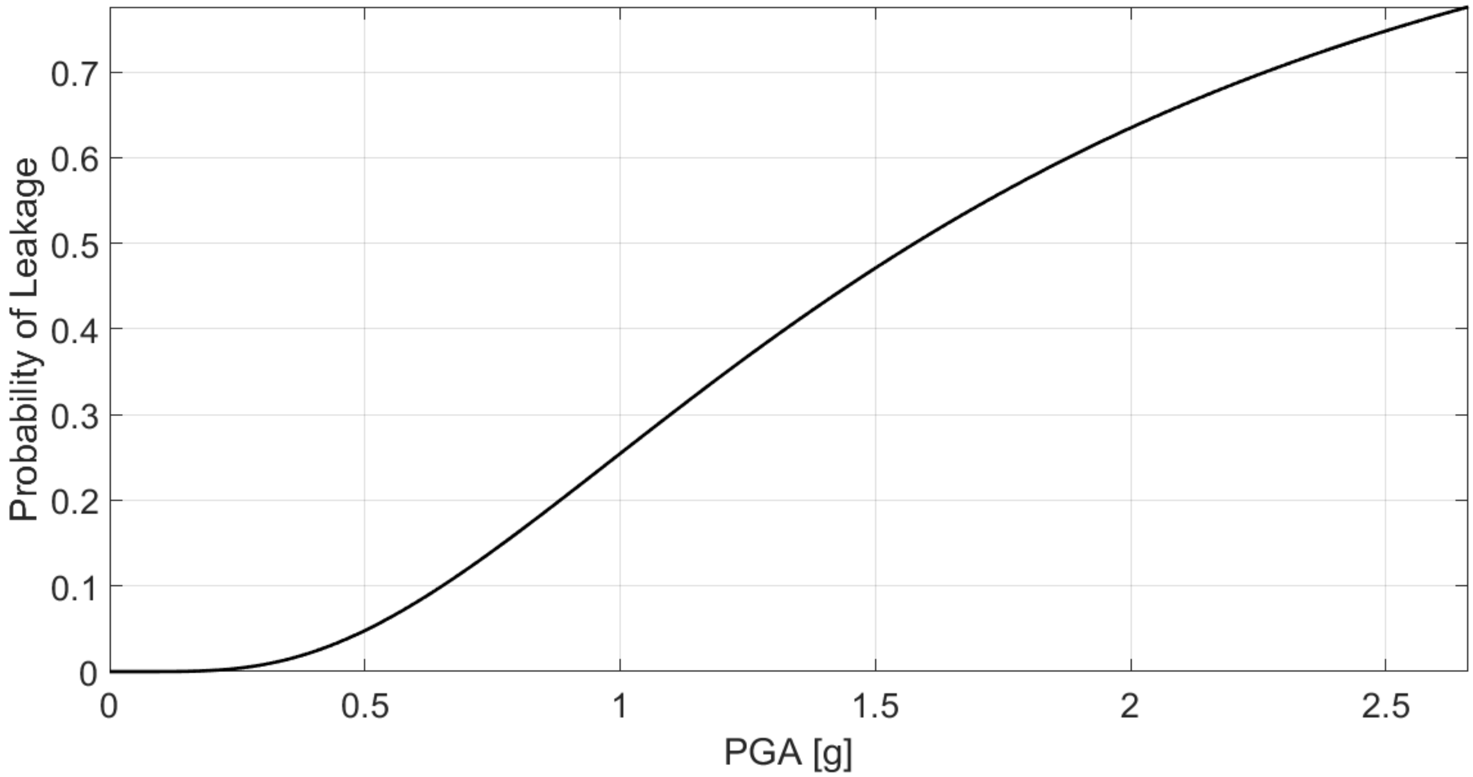


The **least squares** method was adopted and **the obtained COV resulted to be quite high but still acceptable.**

In order to reduce improve the **efficiency** of the PSDM, we will investigate the performance of **different IMs, like floor acceleration.**

PSDA – Elbow Leakage Fragility Curves

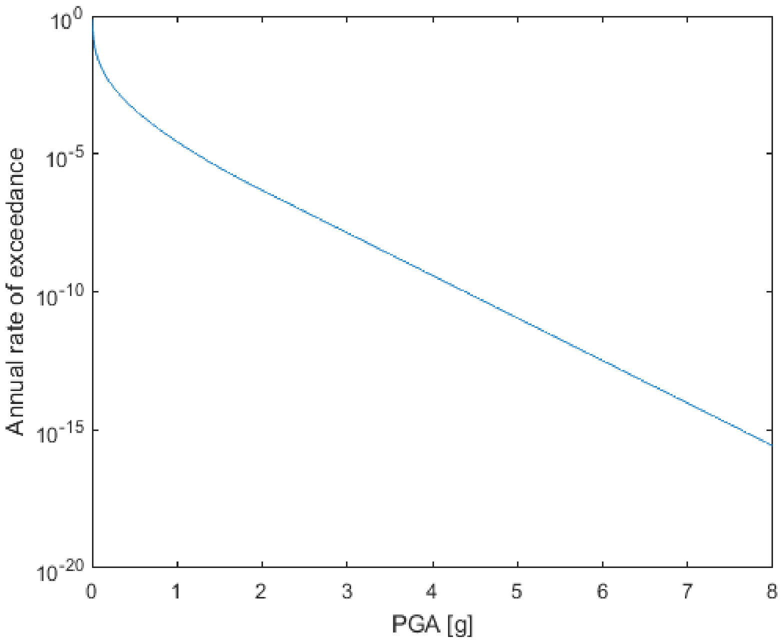
$$P[EDP \geq C_{LS}|IM = im] = \Phi\left[\frac{ln(im/m_{EDP})}{\beta_{EDP}}\right]$$



Lognormal distribution hypothesis

$\hat{\mu}$ [m/s^2]	$\hat{\sigma}$
15.46	**0.712**

PSDA - Probability of leakage over reference life



Hazard Curve of the high-seismic site of Priolo Gargallo (Sicily).

$$\mathrm{P(EDP)} = \int_{0}^{IM} P(EDP > EDP_{\mathrm{lim}} | IM)\lambda(\mathrm{IM})\mathrm{dIM}$$

Leakage Case	P(Leakage)
Elbow #18	$1.4\text{x}10^{-3}$

P(Leakage) is referred to a reference life of 100 years.

A simple formulation is used to compute the probability over different return periods

$$P_n(edp) = 1 - \left(1 - P(edp)\right)^n$$

Where $P(edp)$ is the annual probability while n defines the number of years of the target return period

PSDA – Issues and strategies for complex models

- **Non-ergodic random variables uncertainty.**

All the structural uncertainties (soil interaction, material characteristics, etc.) and the relevant FE model errors **are not statistically independent** in each of our seismic analyses or even **completely invariant in time**. For this reason, we cannot limit the uncertainties propagation by averaging the results of the highest possible number of different analyses. According to Der Kiureghan, 2005, **the total error in the probability computation can reach the 30%.**

- **Ergodic random variables uncertainty.**

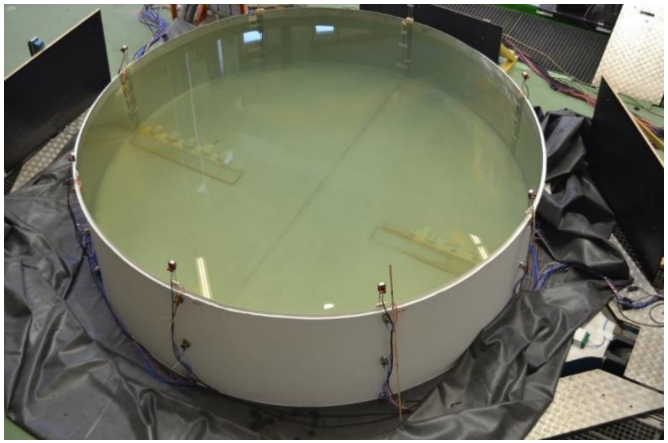
The variability of the seismic action and its characterization by the IM is a source of uncertainty and error in the PBEE approach. However, these ***intensity variables*** (Der Kiureghan, 2005) are ***ergodic (statistically independent in the time domain)*** and, for this reason, the more samples we have (e.g. natural records and relevant PSDAs) the more accuracy we will obtain. **Moreover, the probability distribution of this kind of random variables can be described by a Poissonian model.**

Der Kiureghian A. (2005). Non-ergodicity and PEER's framework formula, Earthquake Engng Struct. Dyn. 2005; 34:1643–1652

PSDA – Issues and strategies for complex models

Non-ergodic random variables uncertainty

Experimental tests are able to provide reference data that can be used to calibrate FE models in order to reduce the non-ergodic uncertainty.



Shaking table test of a **scaled broad tank** performed by CEA, France (INDUSE-2-SAFETY).

Experimental evaluation of leakage and strength capacity of **bolted flange joint** performed by UNITN (La Salandra et al., 2016).

V. La Salandra; R. Di Filippo; O.S. Bursi; F. Paolacci; S. Alessandri, "Cyclic Response of Enhanced Bolted Flange Joints for Piping Systems" in Proceedings of the ASME 2016 Pressure Vessels & Piping Conference, Vancouver, British Columbia, Canada, July 17-21, 2016

Reza, M. S., BURSI, O.S., Paolacci, F. and Kumar, A. "Performance of Seismically Enhanced Bolted Flange Joints for Petrochemical Piping Systems". Journal of Loss Prevention in the Process Industries , Vol. 30, 2014, 124-136.

BURSI, O.S., Reza, M.S., Abbiati, G. & Paolacci, F. "Performance-based earthquake evaluation of a full-scale petrochemical piping system". Journal of Loss Prevention in the Process Industries , Vol. 33, 2015, 10-22.

PSDA – Issues and strategies for complex models

Ergodic random variables uncertainty

Issues:

- scarcity of natural records, especially of those ones coherent with the seismic characteristics of the site.

- The amount of computational resources needed to run seismic non-linear dynamic analyses. The LNG plant FE model required 3 days for each run.

- The necessity for a high number of seismic analyses to evaluate the IM performances.

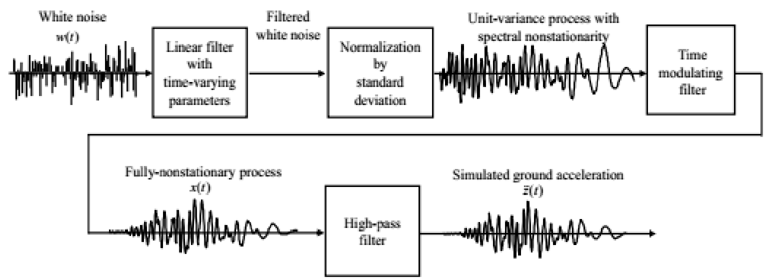
PSDA – Issues and strategies for complex models

The idea is to simulate **artificial seismic signals** with a set of predictive equations developed by Rezaeian and Der Kiureghian (2010), using **some of the site characteristics as inputs.**

The input parameters for the predictive equations are:

- F, the type of faulting
- M, the moment magnitude
- R_{rup} , the closest distance from the recording site to the ruptured area
- V_{s30} , represents the shear-wave velocity of the top meters of the site soil

Stochastic Ground Motion Model.



$$x(t) = q(t, \boldsymbol{\alpha}) \left\{ \frac{1}{\sigma_f(t)} \int_{-\infty}^{t} h[t-\tau, \boldsymbol{\lambda}(\tau)] w(\tau) \mathrm{d}\tau \right\}$$

The predictive equations give as outputs the distributions of the 6 parameters for the Stochastic Ground Motion Model.

- I_a, Arias intensity
- $D_{5\text{-}95}$, time interval of 95% of the I_a
- t_{mid}, time at which 45% of the I_a is reached
- ω_{mid}, filter frequency at t_{mid}
- ω', rate of change of the filter frequency with time
- ζ_f, filter damping ratio (constant).

Rezaeian S., Der Kiureghian A. (2010). Simulation of synthetic ground motions for specified earthquake and site characteristics, Earthquake Engng Struct. Dyn. 2010; 39:1155–1180

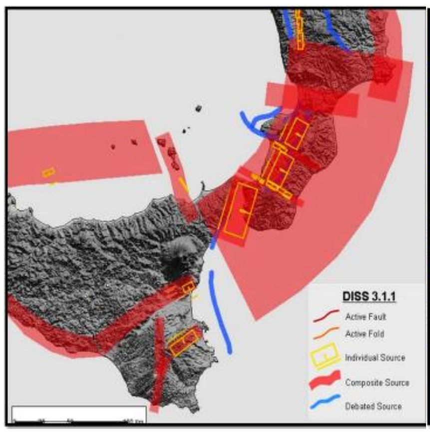
PSDA – Issues and strategies for complex models

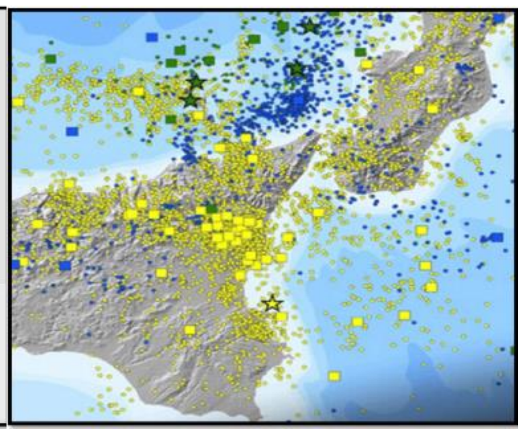
Our analysis is site-specific and for this reason we can fix the values of F and V_{s30}.

The other two parameters (M and R_{rup}) will be sampled in order to be statistically coherent.

Possible strategy:

1) *Sampling 7 values for M*
2) *Sampling 3 values for R_{rup} t*
3) *Generate the 21 combinations*
4) *Obtain 21 artificial seismic signals from the Stochastic Ground Motion Model*





FEM MODEL : ***EDPs = ANSYS(Artificial Seismic Signal)***

METAMODEL : ***EDPs = $f_{corr}(M, R_{rup})$***

The estimation of the **Correlation Function *$f_{corr}(M, R_{rup})$*** will allow for an **<u>outputs expansion.</u>**

In order to achieve this expansion, numerical methods like **<u>Truncated Polynomials Chaos Expansion (PCE)</u>** can be employed.

This approach will be first tested on smaller systems in order to validate its accuracy

PSDA – Issues and strategies for complex models

Truncated Polynomials Chaos Expansion (PCE)

Orthogonality Rule

$$< \pi_k \, , \, \pi_l >_w \stackrel{\text{def}}{=} \int_{D_X} \pi_k(x) \, \pi_l(x) \, w(x) \, dx = \gamma_k^2 \, \delta_{kl}$$

$$< \pi_k \, , \, \pi_l >_w = 0 \quad \text{if} \quad k \neq l$$

$$< \pi_k \, , \, \pi_k >_w = \| \, \pi_k \, \|_w^2 = \gamma_k^2$$

The method is based on multivariate polynomials bases, where the polynomials forms are chosen to be orthogonal with respect of the input distributions

The Polynomial Chaos expansion would allow for the ***calculation of the statistical characteristics of output distributions without computing the output results***

$$Y = \mathcal{M}(X) \approx \mathcal{M}_N^{\text{PC}}(X) = \sum_{k=0}^{N} y_k \, \tilde{\pi}_k(X)$$

Type of input distributions	**Orthogonal polynomials family**
Uniform	Legendre
Gaussian	Hermite
Exponential	Laguerre
Beta	Jacobi

- Y is the desired output
- X is the selected input
- M is the real model
- M^{PC} is the numerical meta-model obtained trough PCE
- N is the truncation order, corresponding to the maximum grade of the polynomials
- y_k are the polynomials coefficients
- π_k are the polynomials values

Quantitative Risk Analysis with domino effects

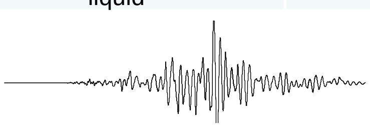
The procedure for the QSRA should include the following steps:

- Generation of initial damage scenarios and determination of LOC events for each seismically damaged component;
- Consequence analysis;
- Damage propagation and domino effect (level ≥ 1);
- Risk estimation and ranking scenarios.

The application of the procedure requires some preliminary steps performed once and for all at the beginning of the QRSA:

- Estimation of site-specific seismic hazard;
- Vulnerability assessment of the most critical units of the plant;
- Identification of LOC resulting from each LS (LS/LOC correlation matrix);
- Definition of the Probit functions;
- Definition of the Event Tree for the association of a physical effect to a LOC.

Damage State (DS)	Engineering Demand Parameter (EDP)	Limit State Threshold (LS)	LOC1 Continuous release from a 10mm hole	LOC2 Continuous release from a full bore of the pipe	LOC3 Instantaneous release of full content
Elephant Foot Buckling	Meridional Stress s_M	Buckling limit s_{EFB}	No	Yes	No
Diamond Shape buckling	Hoop Stress s_H	Buckling limit s_E	Yes	No	No
Sliding	Total Base Shear	$F_{sliding} = mW$	No	Yes	No
Overturning	Overturning Moment	Overturning Moment limit	No	No	Yes
Base plate fracture	Max local strain	Strain limit	No	No	No
Roof Damage	Max vertical displacement of liquid	Free-board height	No	No	No



Classification of equipment classes and structural limit states

Loss of Containment (LOC) events @ chapter 3 of the Purple Book.

Chapter 3 of the Purple Book provides:

- Various scenarios in terms of LOC events.
- Equipment type from where LOC takes place.
- Annual frequency of occurrence P_f for each scenario.

Example:

Stationary Atmospheric Tanks (Chapter 3) Scenario and annual occurrence frequency.

Three scenario's:

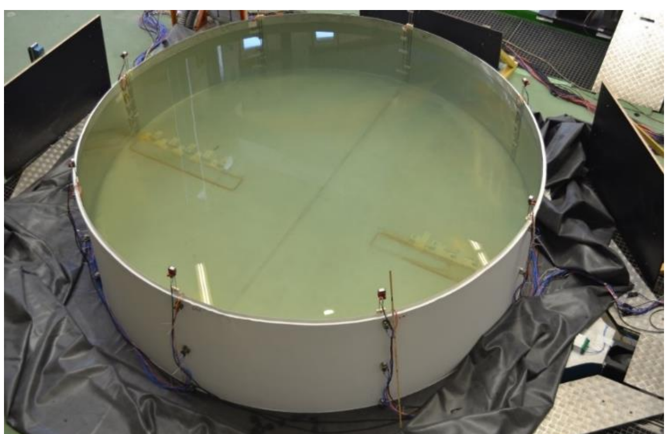
(1) Instantaneous release of the complete inventory; $P_f = 5 X 10^{-6}$ (for a single containment)

(2) Continuous release of the complete inventory in 10 min; $P_f = 5 x 10^{-6}$ (for a single containment)

(3) Continuous release from a hole with a diameter of 10 mm; $P_f = 10^{-4}$ (for a single containment)

Table 3.5 Frequencies of LOCs for atmospheric tanks

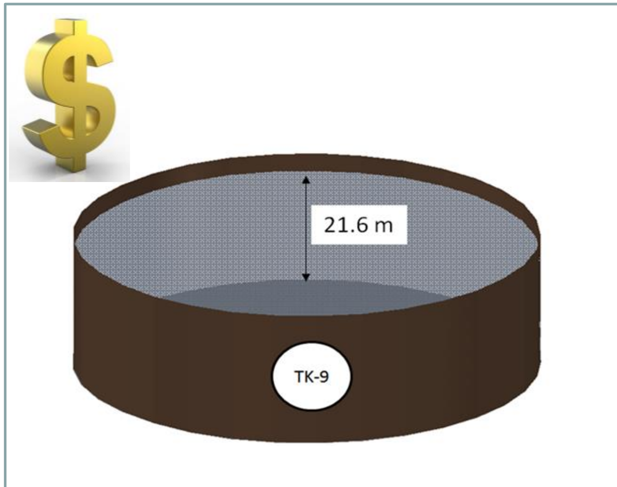
Installation (part)	G.1a Instantan. release to atmosphere	G.1b Instantan. release to secondary container	G.2a Continuous 10 min release to atmosphere	G.2b Continuous 10 min release to secondary container	G.3a Continuous Ø10 mm release to atmosphere	G.3b Continuous Ø10 mm release to secondary container
single-containment tank	$5 \times 10^{-6}\ y^{-1}$		$5 \times 10^{-6}\ y^{-1}$		$1 \times 10^{-4}\ y^{-1}$	
tank with a protective outer shell	$5 \times 10^{-7}\ y^{-1}$	$5 \times 10^{-7}\ y^{-1}$	$5 \times 10^{-7}\ y^{-1}$	$5 \times 10^{-7}\ y^{-1}$		$1 \times 10^{-4}\ y^{-1}$
double containment tank	$1.25 \times 10^{-8}\ y^{-1}$	$5 \times 10^{-8}\ y^{-1}$	$1.25 \times 10^{-8}\ y^{-1}$	$5 \times 10^{-8}\ y^{-1}$		$1 \times 10^{-4}\ y^{-1}$
full containment tank	$1 \times 10^{-8}\ y^{-1}$					
membrane tank	see note 7					
in-ground tank		$1 \times 10^{-8}\ y^{-1}$				
mounded tank	$1 \times 10^{-8}\ y^{-1}$					

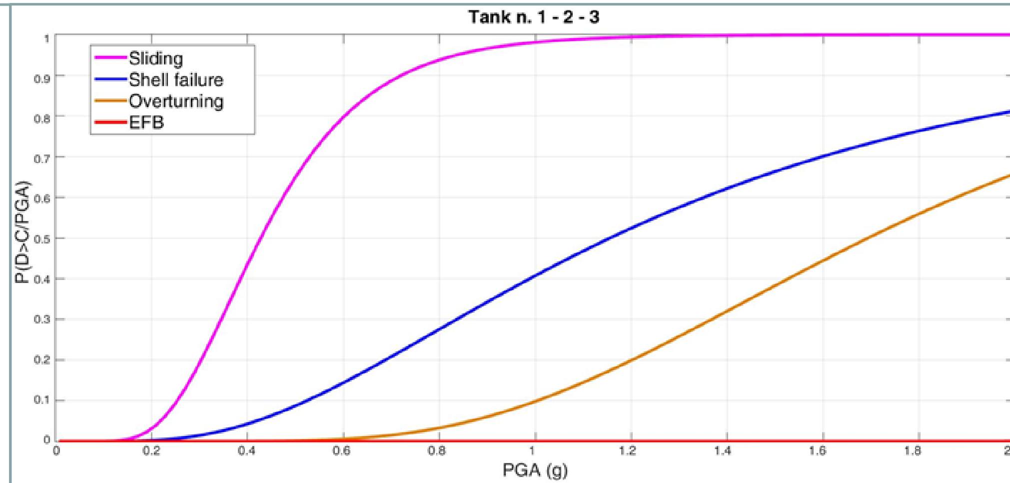


Shaking table test of a **scaled broad tank** performed by CEA, France (INDUSE-2-SAFETY).

QpsRA procedure

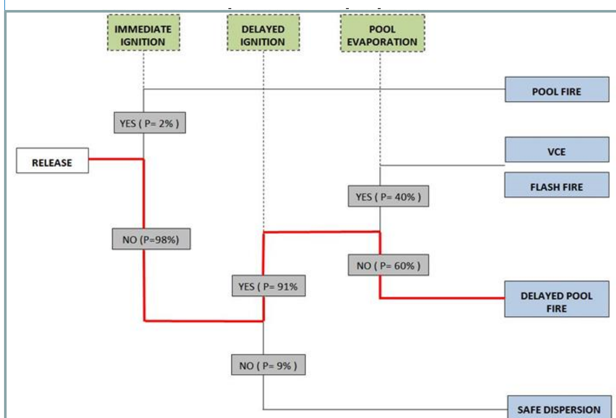
The procedure starts with the provision of input data.

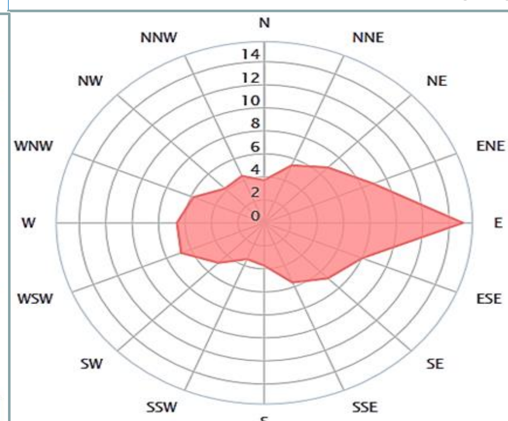




Geometrical and mechanical

Fragility curves





Event trees and probit functions

Atmospheric conditions

Chemical properties

ROMA TRE UNIVERSITÀ DEGLI STUDI

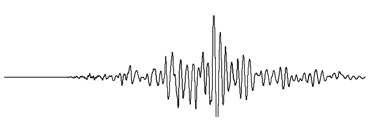
QpsRA procedure

The risk of the plant can be quantified by:

$$P_{tot} = \int_0^{+\infty} P(S \mid DE)\, P(DE \mid C)\, P(C|LOC)\, P(LOC|LS)\, P(LS|EDP)\, P(EDP|IM)\, dP(IM)$$

The proposed QSRA method has been numerically implemented by using the Monte Carlo Simulation Method (MCS):

- Samples of the random variables that govern the damage scenarios are generated.
- Each sample is generated according to assigned probability distribution functions.
- Each group of sample variables is used to generate an event.
- Repeated runs of the MCS allow to determine a frequency distribution of possible outcomes.



Assumptions

- In this preliminary version, only a storage tank farm can be considered;
- Peak Ground Acceleration (PGA) is considered as IM;
- The relationship between Limit State and Loss of Containment is considered deterministic (LS/LOC matrix)
- Two distinct series of event trees have to be defined to describe:
    - the events following a seismic damage,
    - the outcome physical effects when the unit is damaged by another source unit.
- An explosion or a thermal radiation model is applied to determine the overpressure or the impinging radiation intensity reached in the target units.

ROMA TRE
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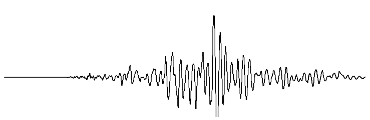
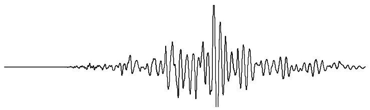


Assumptions

- When a tank is damaged by heat flux a tank fire is considered.
- When a tank is damaged by an overpressure, a total rupture of the tank is occurred with the instantaneous release of the full content and the immediate pool fire.
- Target unit is considered damaged by physical effects with the following probabilities:

Physical effect	Prob. of damage
Heat flux lower of 12.5 kW/m^2	0
Heat flux greater of 37.5 kW/m^2	1
Overpressure lower of 0.3 bar	0
Overpressure greater of 0.6 bar	1

- Intermediate values are calculated with a linear interpolation.



Ranking scenarios and losses evaluation

The procedure stops at level j-th if no other elements are damaged or if the total number of damaged elements coincides with the number of plant's components. The procedure restarts with a new simulation, until the convergence of the results is obtained.

Some Results

Economic losses

$$C\left[L \mid PGA\right] = \frac{\sum_{i=1}^{N}\sum_{j} C_{ij}\left(d_j\right)}{N}$$

$C_{ij}(d_j)$ indicates the reparing/substitution cost of the *j-th* unit of the plant that, at the *i-th* sampling, is subjected to the damage d_j

Expected economic losses

$$C = \frac{\sum_{i=1}^{N}\sum_{j} C_{ij}\left(d_j\right) w_{Ri} w_{Mi} w_{SZi}}{N}$$

Frequency of occurrence of a Damage Scenario

$$P\left[S \mid PGA\right] = \frac{\sum_{i=1}^{N} I_i\left(d\right)}{N}$$

I_i is the indicator function of the event i

Probability of occurrence of a Damage Scenario

$$p = \frac{\sum_{i=1}^{N} I\left(d\right) w_{Ri} w_{Mi} w_{SZi}}{N}$$

Convergence of the Results

Economic losses

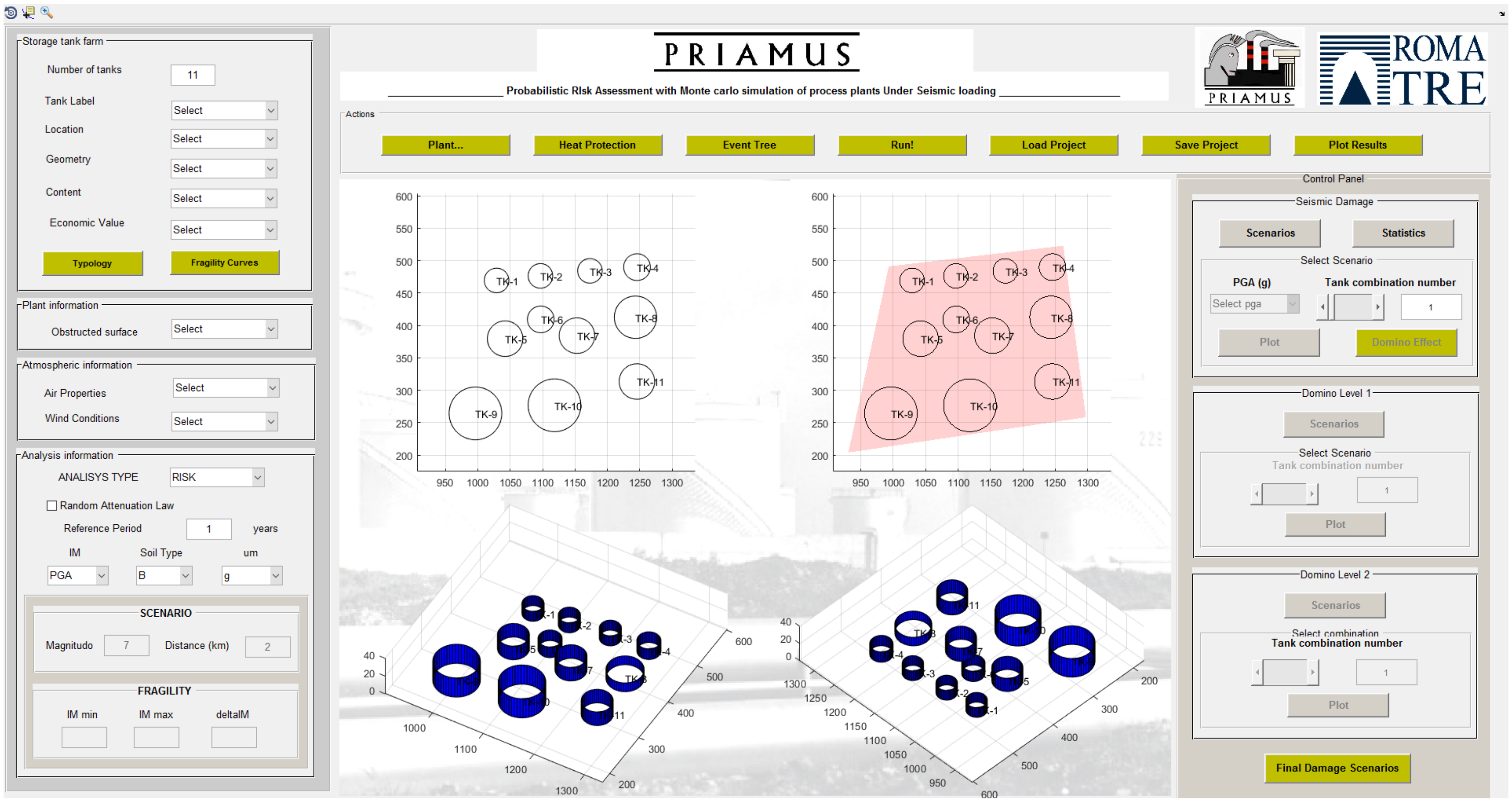
$$\Delta E = \frac{E_i - E_{i-1}}{E_{i-1}} \leq \delta$$

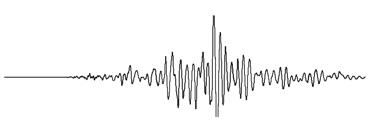
Probability of occurrence of a Damage Scenario

$$\Delta P = \frac{P_i - P_{i-1}}{P_{i-1}} \leq \delta$$

«PRIAMUS» software for QpsRA

PRIAMUS was developed in MATLAB environment, allows to define a quantitative probabilistic seismic risk analysis of petrochemicals plants with economic and domino effect evaluation.





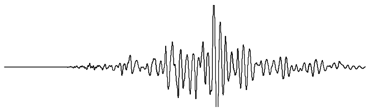
Example of application: seismic risk

RESULTS

it’s possible to assess the most likely damage scenario at the end of the domino effect and the seismic damage scenarios most likely to cause it.

Seismic damage scenarios causing the most likely scenario (all units damaged) at the end of domino effect

#	Damaged tanks	Probability
1	TK-9 TK-10	6.6624e-04
2	TK-9	1.5083e-04
3	TK-10	1.3358e-04
4	TK-5 TK-7 TK-9 TK-10 TK-11	4.2129e-06
5	TK-5 TK-7 TK-11	1.1871e-06



EXAMPLE ON INFRASRUCTURE
Loss (Cost-effective risk) Analysis

Earthquake demand → Local EDPs → Damage states → Associated damage/repair amounts → Repair costs and downtime

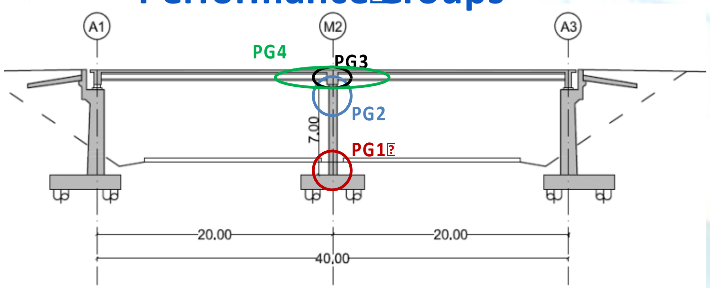
The global integrated probabilistic performance-based evaluation procedure used for the SEQBRI project

- The goal of Loss Analysis is the evaluation of the cumulative probability distribution function of the decision variable (DV) given a certain Seismic Intensity (IM): P (dv | im)
- The main DV adopted in this context is the repair/construction cost ratio (Direct cost). This choice comes from the goal to provide an immediate economic measure of earthquake performance of the assessed structure. Experimental tests helped in the selection of proper DMs for the CCB
- Costs database have been collected mainly from: SBRI project, PEER

Loss (Cost-effective risk) Analysis – Task 4.5

Earthquake demand → Local EDPs → Damage states → Associated damage/repair amounts → Repair costs and downtime

Performance Groups



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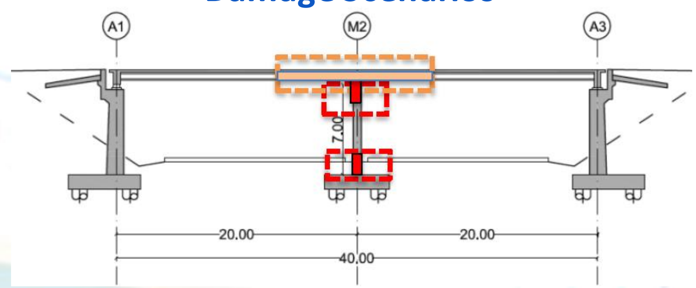
Damage Scenarios



Minor

Performance Group	Damage State	Description
PG1 (Pier at base)	DS1	Seal cracks and minor removal and patching of concrete
PG2 (Pier at top)	DS0	----
PG3	DS1	Seal cracks and minor removal and patching of concrete
PG4	DS2	Seal cracks, clean deck and apply methacrylate

Major

Performance Group	Damage State	Description
PG1 (Pier at base)	DS2	Seal cracks, major patching
PG2 (Pier at top)	DS1	Seal cracks and minor removal and patching of concrete
PG3 (CCB)	DS2	Replacement of CCB
PG4 (Deck)	DS2	Seal cracks, clean deck and apply methacrylate

EQBRI

Research Fund for Coal & Steel

Loss (Cost-effective risk) Analysis – Task 4.5

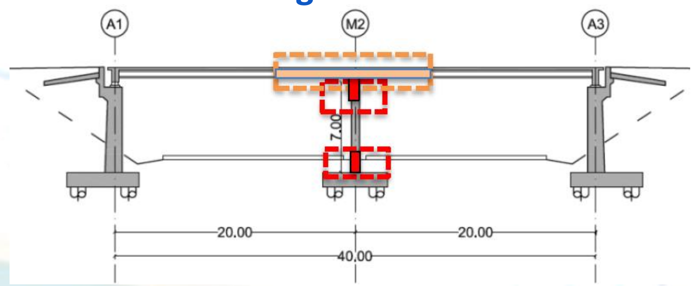
Earthquake demand → Local EDPs → Damage states → Associated damage/repair amounts → Repair costs and downtime

Performance Groups

	DS description	Repair Method	Repair Item	Unit Computation	Unit cost
DS0	Negligible damage with initial cracking	No repair	None	None	
DS1	Cover concrete spalling	Seal cracks and minor removal and patching of concrete	Epoxy inject cracks (m)	2 x column height	560 €
			Repair minor spalls (m2)	10% x surface area	407 €
DS2	Longitudinal reinforcing bar buckling	Seal cracks, major patching	Re-center pier (per pier)	Re-center pier (once max for PG1 and PG2)	790 €
			Epoxy inject cracks (m)	4 x column height	560 €
			Repair minor spalls (m2)	25% x surface area	407 €
DS3	Longitudinal reinforcing bar fracture	Replace half of column	Bridge removal, column (m^3)	Total column gross volume / 2	209 €
			Structural concrete, bridge (m^3)	Total column gross volume / 2	183 €
			Bar reinforcing steel, bridge (kg)	Total column gross volume / 2 x rebar weight ratio	1-6 €
			Temporary support, bridge (m^2)	Tributary length x tributary width (once max for both PG1 and PG2)	328 €
			Structure excavation (m^3) - only for PG1 (bottom)	0.9m embedment + 1.2m round the column	15-26€
			Structure backfill (m^3) - only for PG1 (bottom)	Same as structure excavation	15-35 €

+

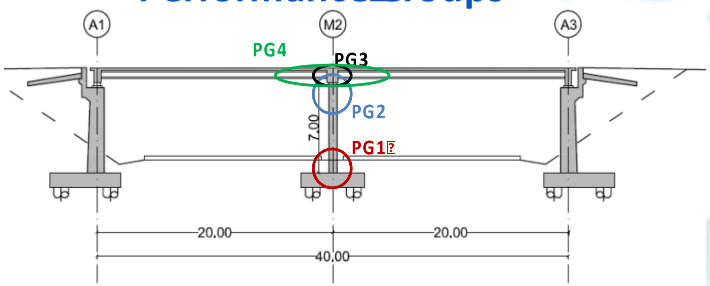
Damage Scenarios



Loss (Cost-effective risk) Analysis – Task 4.5

Earthquake demand → Local EDPs → Damage states → Associated damage/repair amounts → Repair costs and downtime

Performance Groups



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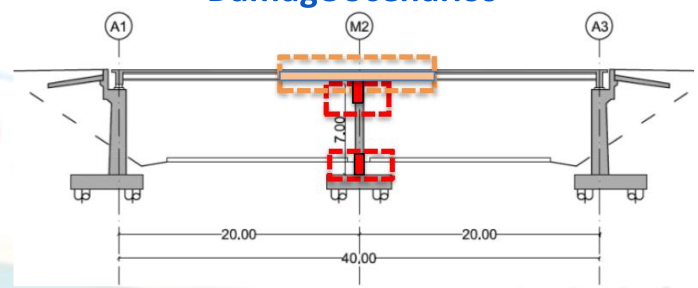
Damage Scenarios



$$C_{tot-scenario\_n/IM} = \sum_{l=1}^{N_{PG}} Q_{n,l} \cdot P(DS_{PG_l} / IM)$$

Mean expected repair cost conditioned to IM for each damage scenario

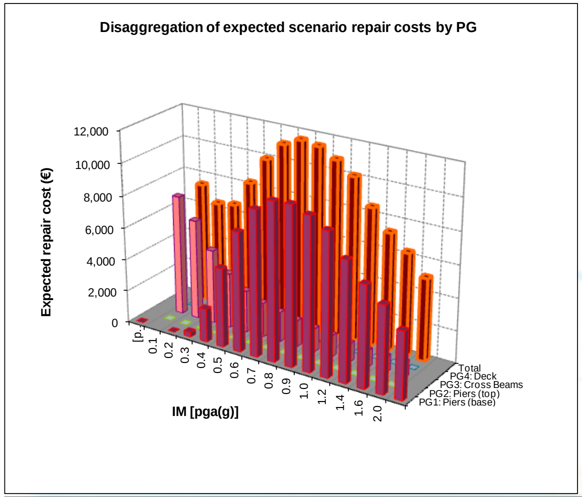
$$C_{tot-overall/IM} = \sum_{l=1}^{N_{PG}} \left[\sum_{n=1}^{DS} Q_{n,l} P(DS_{PG_l} / IM) \right]$$

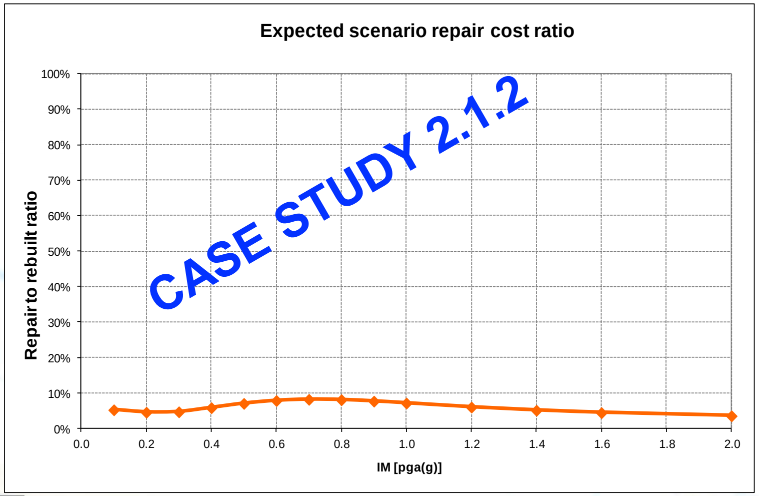
Overall expected (probable) repair cost conditioned to IM

$$P(Damage \geq Scenario \mid IM) = \prod_{l=1}^{N_{PG}} P(DS_{PG_l} \mid IM)$$

probability of exceeding a given damage scenario conditioned to IM (fragility curves)

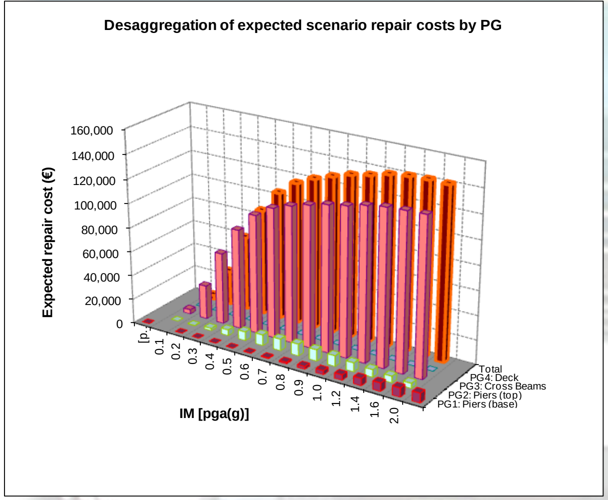
Loss (Cost-effective risk) Analysis – Task 4.5

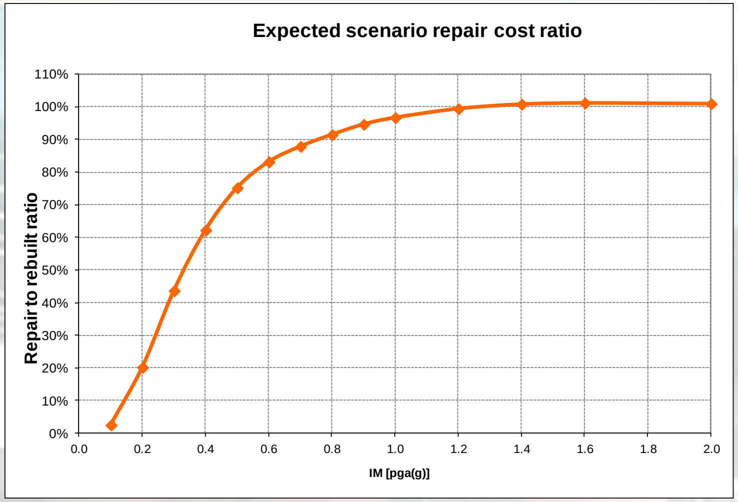




Mean expected repair cost conditioned to IM for each damage scenario

Minor Scenario





Major Scenario

EQBRI

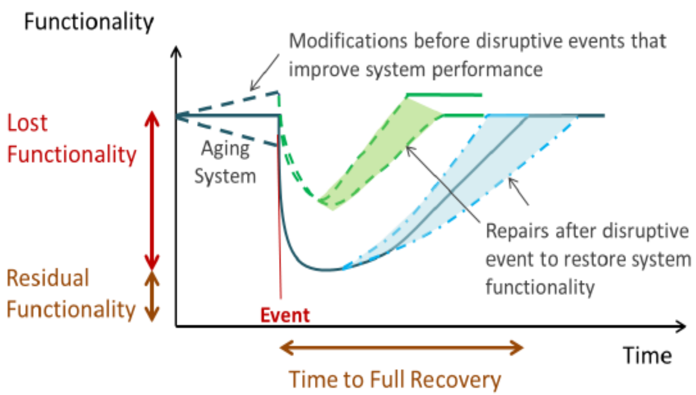
Research Fund for Coal & Steel

INDUSTRIAL PLANTS - RESILIENCE

Resilience is the result of a system

- *Preventing adverse consequences,*
- *Minimizing adverse consequences;*
- *Recovering quickly from adverse consequences;*

- Westrum R. A typology of resilience situations. Pp. 49–60 in Hollnagel E, Woods DD, Leveson N (eds). Resilience Engineering: Concepts and Precepts. Aldershot , UK : Ashgate Press, 2006. -



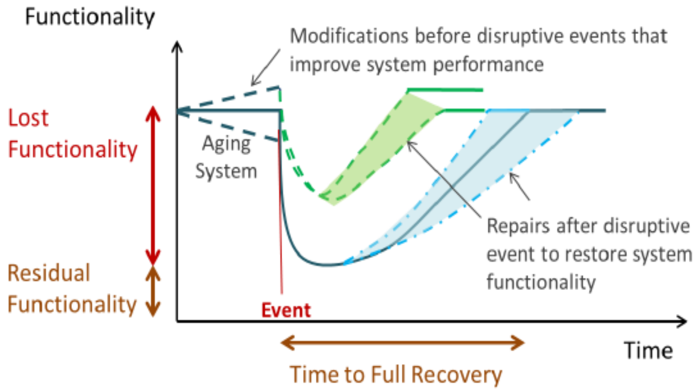
Adapted from Bruneau, 2003 and McDaniels, 2008

Integrated measures

- *Effects of Mitigation*
- *Effects of Preparadness*

WP7: Software tool development for risk-based analysis of plants and community disaster resilience.

Definitions of resilience R, in XP-RESILIENCE
R is the normalized integration of the functionality



Adapted from Bruneau, 2003 and McDaniels, 2008

$$R = R(HZ, TP, GM, t) = \left(\frac{1}{(t_f - t_0)} \right) \int_{t_0}^{t_f} Q(HZ, TP, GM, t)\, dt$$

Quantify resilience purely in terms of consequences because of hazard effects

$$R(T) \propto \frac{1}{CM(T)} = RRI(T)$$

The likely magnitude of consequences v(CM) based on topology, geometry and hazards -where adaptation and recovery are excluded- can be estimated as

$$\upsilon(CM) = \int \iiint G(CM \mid DM)\, p(DM \mid ERP)\, p(ERP \mid IM)\, p(IM \mid T)\, p(T)\ dDM\ dERP\ dIM\ dT$$

Cimellaro G.P., Reinhorn, A.M. and Bruneau, M., (2010), Framework for analytical quantification of disaster resilience, Engineering Structures, 32, 11, 3639-3649.

Quiel, S.E., Marjanishvili, S.M., Katz, B. P., (2015), Performance-based framework for quantifying structural resilience to blast-induced damage, Journal of Structural Engineerig, 5, 1-12.

WP7: Software tool development for risk-based analysis of plants and community disaster resilience.

Performance Indicators for Infrastructure Networks

- Ghosn, Duenas Osorio, Frangopol, McAllister, Bocchini, Manuel, Ellingwood, Arangio, Bontempi, Shah, Akiyama, Biondini, Hernandez, Tsiatas -

Based on topology or functionality of networks

Graph theory provides mathematical tools for assessing networks based on their layout

Topology-Based Performance Metrics

Flow Based Functional Performance Metrics

Power Distribution Performance Metrics

Transportation Networks Performance Metrics

Ability of a network to keep its connectivity after being subjected to hazard events

Flow capacity after a disruptive event

Concluding Remarks

- Performance-based (earthquake) engineering enforces a probabilistic transparent design/assessment approach
- More emphasis should be placed on $ losses and loss of function (downtime)
- More emphasis should be placed on resilience
- As a result, key words in structural engineering are becoming: SUSTAINABILITY, RESILIENCE, INFRASTRUCTURE NETWORKS, COMPLEX SYSTEMS

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Other EU Projects on Resilience

- Founded by Horizon 2020 -

RESOLUTE PROJECT → **RES**ilience management guidelines and **O**perationalization app**L**ied to **U**rban **T**ransport **E**nvironment;

IMPROVER PROJECT → Improved risk evaluation and implementation of resilience concepts to Critical Infrastructure;

RESILENS PROJECT → Realising European Resilience for Critical Infrastructure

DARWIN PROJECT → Expect the unexpected and know how to respond;

SMR PROJECT→ Smart mature resilience for more resilient cities in Europe

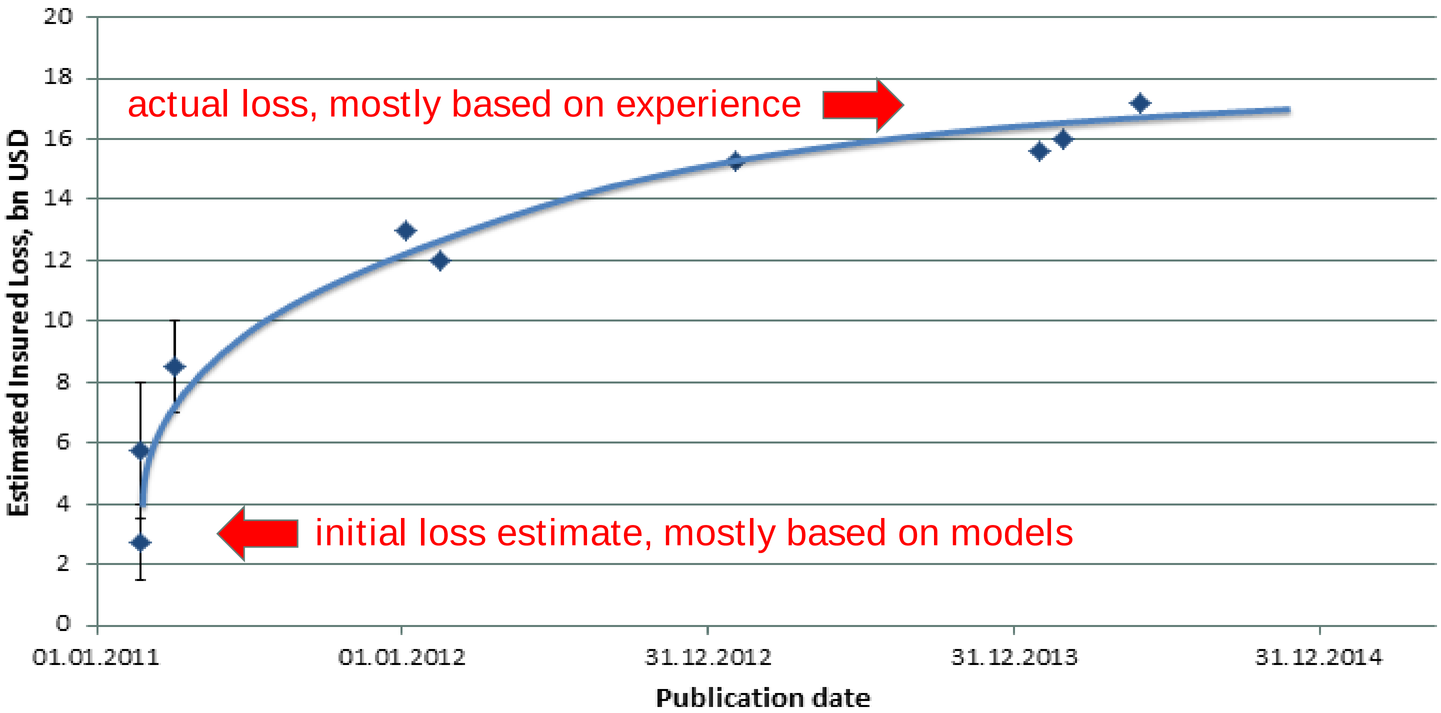
Three major recent earthquake events

	Chile 27 February 2010	New Zealand 22 February 2011	Japan 11 March 2011
Magnitude	8.8	6.3	9.0
Energy released[1]	5'600	1	11'200
Victims[2]	562	185	18'520
Damage % GDP[2] **Insured share**[2]	15% 27%	13% 85%	4% 17%

[1] Energy release of New Zealand event is set to 1
[2] Swiss Re Sigma, World Bank

same scale for all maps

A (drastic) example:
Almost sixfold increase of insured loss estimates for Christchurch earthquake



Outlooks

- Improve the PBEE formulation
- Reduce the computation time for the analysis of complex structural systems
- Remain anchored to physics/mechanics
- No work for free

- Focus on the outcomes/impacts. Will a project reduce risk, promote economic development, create jobs and support commerce?
- Favour accountability to improve the permitting process and eliminate decision paralysis
- Attract more private sector funding

Thank you very much for your attention !

Any question ?

2017/4/21

Premises

Distinction between Safety and Security

A way forward?

- **A systemic and synergic approach to safety and security in industrial installations may be extremely important**

SAFETY RISKS	SECURITY RISKS
Accidental nature, due to inherently random failures	Intentionality, involving adaptation on the part of the adversary
Analyzed in terms of:	Analyzed in terms of:
	Risk source
(Hazard)	**Threats**
Consequences	**Consequences** *Risk*
Probabilities / frequencies	**Target Attractiveness/ Vulnerability**

Direction: Holistic framework to risk assessment is desiderable

Open issues: mainly qualitative analysis tools available for security risks

PROBABILISTIC SEISMIC RISK ASSESSMENT

This method modifies the current PSRA (Probabilistic Seismic Risk Assessment) procedure (NUREG - 1407) by using innovative tools developed for the performance based engineering methodology (ATC-58) applied to buildings. The main criticisms of existent procedures are:

1. Spectral acceleration at a representative period (typically the fundamental period) of the structure is a much better indicator of demand and damage than PGA;

2. Although the failure of each basic component at the lowest level of a fault tree may be independent, the responses between the components are not. For this reason the assumption of PSRA method could be improved with Monte Carlo simulations for the evaluation of NPP components failure.

Reference:

Huang Y.N., Whittaker A.S., Luco N. (2011), *A probabilistic seismic risk assessment procedure for nuclear power plants: (I) Methodology*. Nuclear Engineering and Design, No. 241, pages 3996-4003.

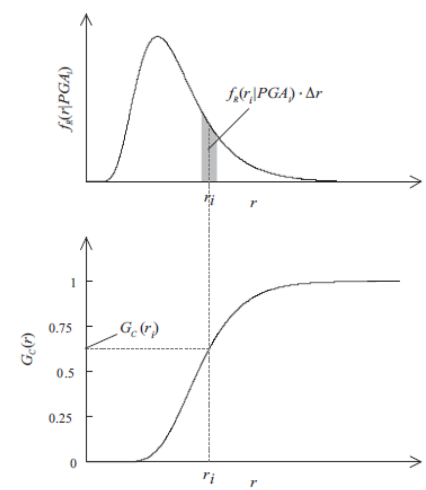
Huang Y.N., Whittaker A.S., Luco N. (2011), *A probabilistic seismic risk assessment procedure for nuclear power plants: (II) Application*. Nuclear Engineering and Design, No. 241, pages 3985-3995.

PSRA – Method…

The main tasks of this new methodology are: (1) Response based fragility curves, (2) non linear response history analysis to characterize the demand, (3) Monte Carlo simulations to consider the correlation between components in the damage analysis. The procedure estimates the mean annual frequency of unacceptable performance of a NPP.

$$P_C(PGA_i) = \int_0^{\infty} G_C(r) f_R(r|PGA_i)\, dr$$

$$\lambda_{UP} = \int \boxed{G_{UP}(a)} \left| \frac{d\lambda_H(a)}{da} \right| da$$



PBEE – Probabilistic Framework Equation by Allin Cornell

$$v\left(dv < DV\right) = \iiint G(dv \mid dm)\,dG(dm \mid edp)\,dG(edp \mid im)\,|\,d\lambda(im)\,|$$

Impact

Performance (Loss) Models and Simulation

Hazard

im – Intensity Measure

edp – Engineering Demand Parameter

dm – Damage Measure

dv – Decision Variable

$\lambda(im)$- mean annual frequency of exceedance of IM

ν(dv<DV) – Probabilistic Description of Decision Variable

(e.g., Mean Annual Probability $ Loss > 50% Replacement Cost)

Classification of LOC events and correlation between LS and LOC events

Table 2.6-3. Classification of process plant equipment types.

LOC Classes	**Source**
For vessels and storage tanks LOC_1 = instantaneous release of the complete inventory; LOC_2 = continuous release of the complete inventory in 10 min at a constant rate of release; LOC_3 = continuous release from a hole with an effective diameter of 10 mm *For pipes* LOC_1 = Rupture (whole diameter hole) LOC_2 = Leak with an effective diameter of 10% of the nominal diameter, up to a maximum of 50 mm *For other equipment* LOC_1 = Catastrophic failure LOC_2 = Outflow at the maximum outflow rate LOC_3 = Leak (10% diameter)	Purple Book (Uijt De Haag and Ale, 2005)

Classification of Loss of Containement

Approach #1 based on a LS/LOC matrix

Table 2.6-4. Example of storage tanks LS/LOC matrix.

LIMIT STATE	LOC_1 = instantaneous release of the complete inventory	LOC_2 = continuous release of the complete inventory in 10 min	LOC_3 = continuous release from a hole with an effective diameter of 10 mm
EFB with tank collapse	1		
EFB with flange rupture		1	1
EFB with crack			1
DSB			1
Overtopping		1	
Overturning	1		
Sliding		1	1
Uplifting without overturning			1
Base plate fracture	1		
Roof damage		1	1

$\underline{\Delta}$ =1 in case the *l-th* LS may cause the *m-th* class of LOC

$P_{fA,i,l}$ (PGA, $LS_{i,l}$) = f_{PGA} $P_{f,i,l}$ ($LS_{i,l}$, PGA)

$$P_{fA,i,m}(PGA)=P\left(\bigcup_{l=1}^{l=LS_i} LOC_{l,m}\right)=\sum_{l=1}^{LS_i} P\left(LOC_{l,m}\right)-\sum_{l<j} P\left(LOC_{l,m}\cap LOC_{j,m}\right)+\sum_{l<j<k} P\left(LOC_{l,m}\cap LOC_{j,m}\cap LOC_{k,m}\right)-\cdots+(-1)^{LS_i-1}P\left(\bigcap_{l=1}^{l=LS_i} LOC_{l,m}\right)$$

ANNUAL PROBABILITY FIGURES

Recommended Probability of Failure Levels for Ultimate Limit States (CEB-FIP 1978)

Population At Risk	Economic Consequences		
	Insignificant	High	Very High
Small (1<)	10^{-3}	10^{-4}	10^{-5}
Medium	10^{-4} ($\beta = 3$)	10^{-5}	10^{-6} ($\beta = 4.5$)
Large (>10)	10^{-5}	10^{-6}	10^{-7}

After Aktan et al (2007)