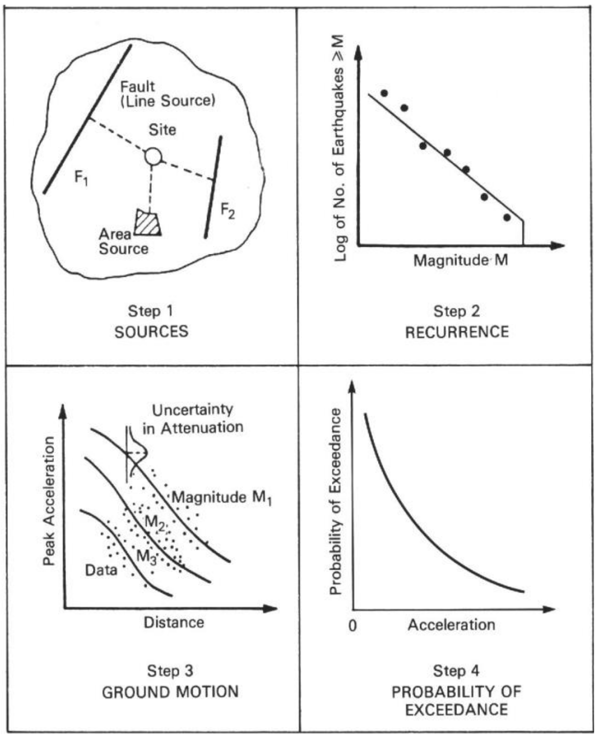
DIPARTIMENTO DI INGEGNERIA DELL'UNIVERSITA' DEGLI STUDI ROMA III

Laurea magistrale in Ingegneria Civile per la Protezione dai Rischi Naturali (Dm 270)

Corso di Costruzioni in zona simica
Modulo di Determinazione della pericolosità sismica



F.Sabetta.

8. Pericolosità deterministica e probabilistica
Approccio di Cornell
Dati di input

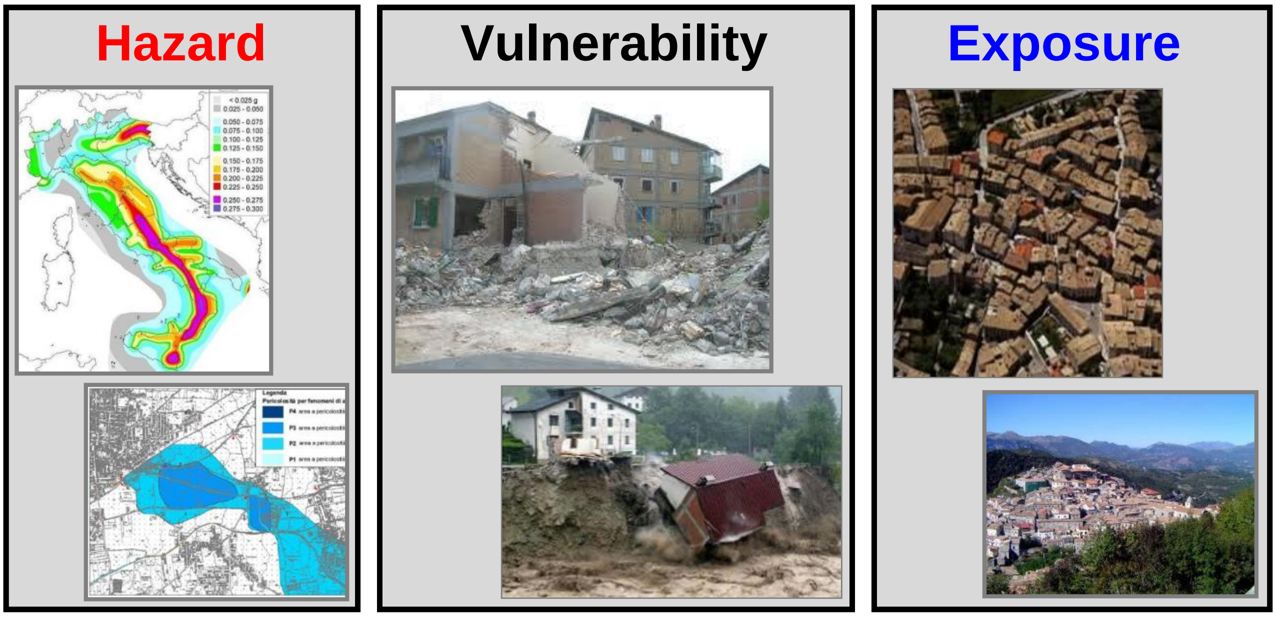
Anno accademico 2023/23

SUMMARY

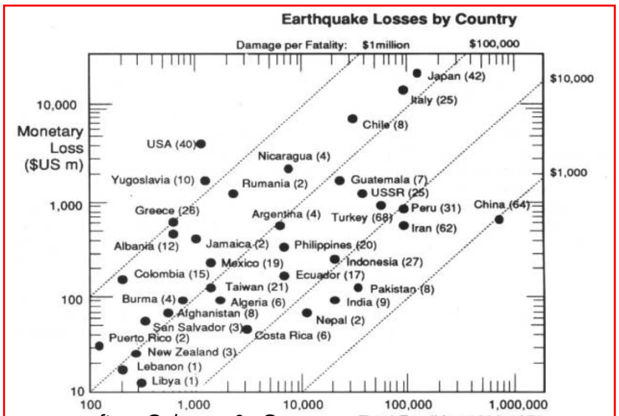
Seismic Hazard and Seismic Risk

Seismic risk can be defined as the possibility or probability of losses due to earthquake, whether these losses are human, social or economic.

Seismic Risk = Seismic Hazard * Vulnerability * Exposure



The **seismic hazard** represents the expected earthquake ground motion at the site of a structure or other engineering project. The **vulnerability** of a structure represents its attitude to be damaged by a given intensity earthquake. The **exposure** refers to the human activity located in the zones of seismic hazard and represents the quantity and quality of the "goods" (population, facilities, lifelines, etc.) exposed to risk.



after Coburn & Spence,

It could be stated very simply that **the objective of earthquake engineering is to reduce seismic risk.** Since generally **hazard and exposure can't be reduced** (it's not possible to avoid the occurrence of the earthquakes or eliminate the presence of the man), the only way in which engineers can bring about a reduction in risk is to **reduce the vulnerability of buildings and lifelines**.

Seismic risk is increasing in the World and this is mainly due to an increase in exposure. About 2 billions people are nowadays living in areas exposed to earthquake hazard.
Bilham (1988) predicted that by the year 2000 there would be more than 100 "super-cities" (population greater than 2 million) in the world, with **41 of these located in zones of high seismic hazard**.
The total population of these exposed cities has grown from 153 million in 1975 to more than **300 million now**, with **80% of the people at risk living in the Third World**.
Any comparison of earthquakes in the Third World with those in the developed world immediately reveals the critical influence of vulnerability and exposure in determining risk.
after Bommer, 2001a

Seismic Risk Reduction Policies

PHASE 1 – PREVENTION
- Hazard assessment
- Seismic classification and building code
- Vulnerability assessment
- Risk assessment
- Vulnerability reduction
- Information and preparedness
- Technical training

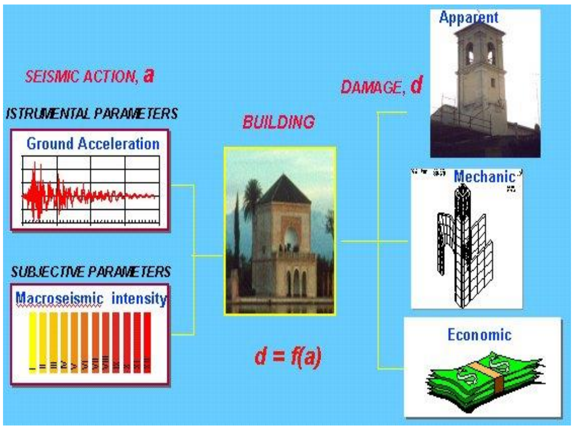
PHASE 2 – EVENT
- Emergency management: Loss scenarios
- Emergency management: Search and Rescue
- Emergency management: People assistance

PHASE 3 – POST-EVENT
- Damage survey and safety assessment
- Microzonation and land use planning

From this point onwards, the course is entirely focused on the seismic hazard assessment (SHA) in terms of strong ground-motion. The SHA must always be viewed as an integral part of the assessment of seismic risk, otherwise SHA is nothing more than an interesting academic amusement. Consider the following examples:
- Defining the earthquake loads to be considered in the earthquake-resistant design of standard occupancy structures according to a code of practice.
- Assessing the seismic safety of a nuclear power plant.
- Formulating an emergency response plan for a large city in the event of a major earthquake.
- Assessing the capacity of a hospital to continue to operate and provide medical attention following a major earthquake in the city where it is located.
- Designing a retrofit scheme for a national monument in an earthquake area.

There is no one single approach suitable for application in all of these situations, indeed the SHAs in each case may differ significantly in the way they are carried out.

In each engineering project, the actual approach adopted should be determined according to the tectonic setting and the level of seismicity, the nature and cost of the project, the consequences of failure under seismic shaking, the conditions of the owner, the requirements of the law and the perceptions of the public.



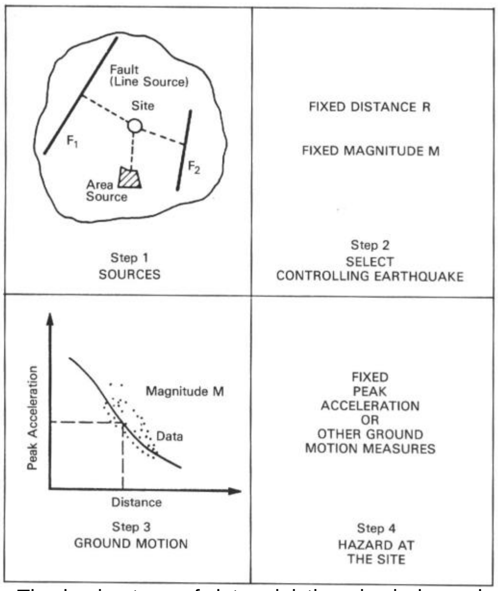
after Bommer, 2001a

Deterministic Seismic Hazard Assessment (DSHA)

Similar to the analysis of other natural hazards, SHA consists of two parts:

- Characterizing the sources of hazard (size and spatial location of earthquakes)
- Characterizing the effect these sources would have at a particular location (earthquake ground motion)

The 2 fundamental types of analysis are probabilistic and deterministic.
In the early years of earthquake engineering the use of **Deterministic Seismic Hazard Analysis (DSHA)** was prevalent. A DSHA involves the development of a particular **seismic scenario** upon which a ground motion hazard evaluation is based.

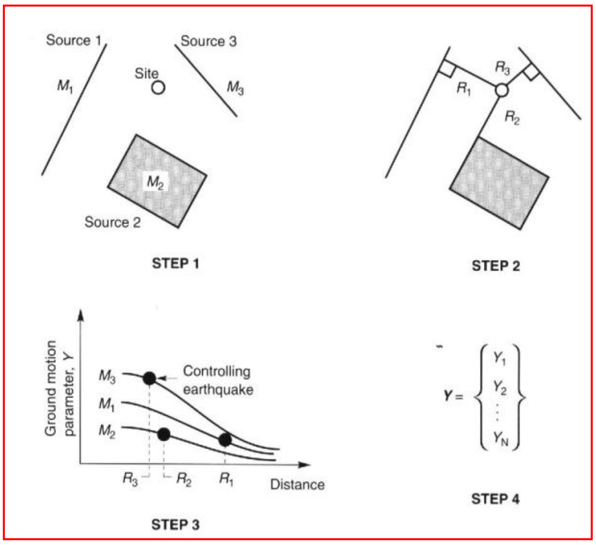


The basic steps of deterministic seismic hazard assessment (Reiter, 1990).

A simple example of a deterministic statement of hazard could be: the earthquake hazard at site **X** is a **PGA of 0.5 g** resulting from the occurrence of a **M=6.5** earthquake on fault **Y** at a distance of **10 km**.

after Reiter, 1990 and Kramer, 1996.

1. **Identification and characterization of all earthquake sources** capable of producing significant ground motion at the site. Source characterization includes definition of each source's geometry and earthquake potential. Source may range from clearly understood faults, to less well defined geological structures, to hypothetical seismotectonic provinces or zones.
2. Selection of a source-to-site distance parameter for each source zone. In most DSHAs **the shortest distance between the source and the site** is selected.
3. Selection of the ***controlling earthquake***, i.e. the **earthquake that is expecting to produce the strongest level of shaking**, generally described in terms of magnitude and distance from the site



The basic steps of deterministic seismic hazard assessment (Kramer, 1996)

4. The hazard at the site is usually defined in terms of the ground motion produced by the controlling earthquake. **The ground motion is usually estimated using attenuation relations (PGA, PGV, PSA median or 84% values), but is sometimes estimated using seismological simulations of the ground motion.**

When applied to structures for which failure could have catastrophic consequences, such as nuclear power plants and large dams, **DSHA provides a straightforward framework for evaluation of worst-case (?) ground motions**.

However it provides no information on the likelihood of the controlling earthquake, the level of shaking expected during a finite period of time (structure lifetime), or the effects of uncertainties.
Over the years there have been many terms used to describe earthquake potential:
Maximum Credible Earthquake (*MCE*), Design Basis Earthquake (*DBE*), Safe Shutdown Earthquake (*SSE*), Maximum Probable Earthquake (*MPE*), and Operating Basis Earthquake (*OBE*). The *MCE*, for example, is defined as the maximum earthquake that appears capable of occurring under the known tectonic framework. The *DBE* and *SSE* are usually defined essentially in the same way. *MPE* has been defined as the maximum historical earthquake, etc.
However there are many who argue for this terminology to be abandoned and the *EERI* Committee on Seismic Risk stated that terms such as *MCE* and *MPE* "are misleading and their use is discouraged".
The criticism most commonly levelled at DSHA is that it provides an estimate of ground motion without assessing the level of conservatism. For critical structures it is perhaps unimportant how conservative the resulting ground motions are, since the important point is to design against the most severe ground motion that can reasonably be expected to occur at the site.
However, it is precisely on this point that one of the main weaknesses in current approaches to DSHA is encountered. If the ground motion amplitudes are calculated as the median (50-percentile) values from the attenuation equations, although the design earthquake, in terms of magnitude and location, may be a worst-case scenario, the resulting ground motions represent the average expected levels for such an event.
Others have proposed using the mean-plus-one-standard-deviation level of motion, but in probabilistic terms **<u>this is the 84-percentile level, which although more severe is still not a worst-case scenario</u>**.

after Kramer, 1996 and Bommer, 2001a

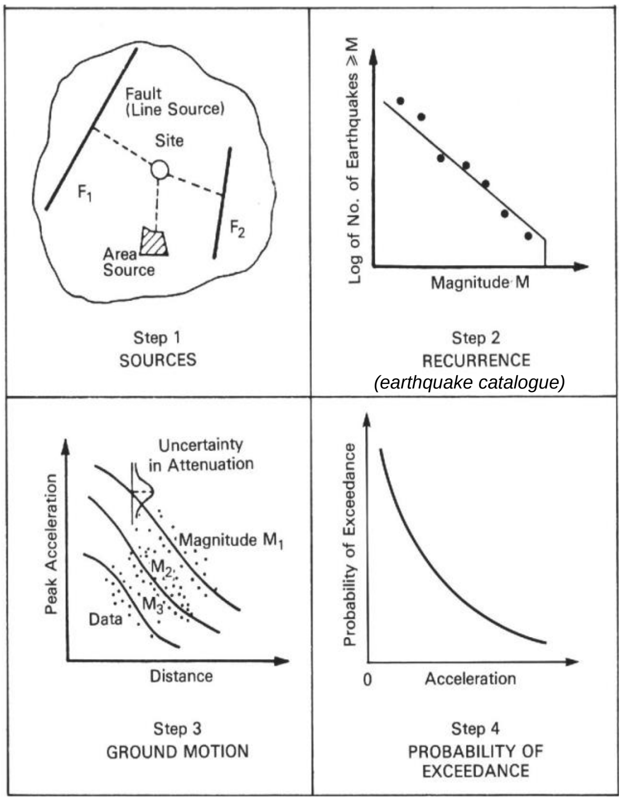
Probabilistic Seismic Hazard Assessment (PSHA)

In the past 20 t0 30 years the use of probabilistic concepts has allowed uncertainties in the size, location and rate of occurrence of earthquakes and in the variation of ground motion characteristics to be explicitly considered in the evaluation of seismic hazards. **Probabilistic Seismic Hazard Assessment (PSHA) provides a framework in which these uncertainties can be identified, quantified and combined in a rational manner**.
Hazard descriptions are not restricted to scenario-like statements; they incorporates the effects of all earthquakes capable of affecting the site in question. Competing models and their uncertainties can be taken into account and **the probability of different magnitude (or intensity) earthquakes occurring, is included in the analysis**.
An advantage of PSHA is that it results in an estimate of the likelihood of earthquake ground motion. **This allows the incorporation of PSHA into seismic risk estimates and the quantitative comparison of different options in making decisions**.
The basic procedure of PSHA was first defined by **Cornell (1968)** and although numerous modifications have been made to the process, the basic elements of the calculations remain unchanged.
The Cornell method is based on three specific assumptions:

- earthquake recurrence times follow a Poisson process (events are independent and stationary in time)
- event magnitude is exponentially distributed (log(N) = a -bM)
- seismicity is uniformly distributed inside each seismogenic zone

The basic steps of the Cornell methodology are analogous to those of DSHA with some major differences:

1. Similar to DSHA except that the sources are explicitly defined as being of uniform earthquake potential, that is, **the earthquakes have an equal probability of occurring at any point within the seismic source zone**.
2. Different from DSHA; instead of picking a single controlling earthquake, each source is characterized by an earthquake probability distribution or **recurrence relationship**, which specifies the average rate at which a given size earthquake will be exceeded.
3. Similar to DSHA except that **uncertainty inherent in the attenuation relation is included in PSHA.**
4. Different uncertainties are combined to obtain the **probability that the ground motion parameter will be exceeded during a particular time period.**

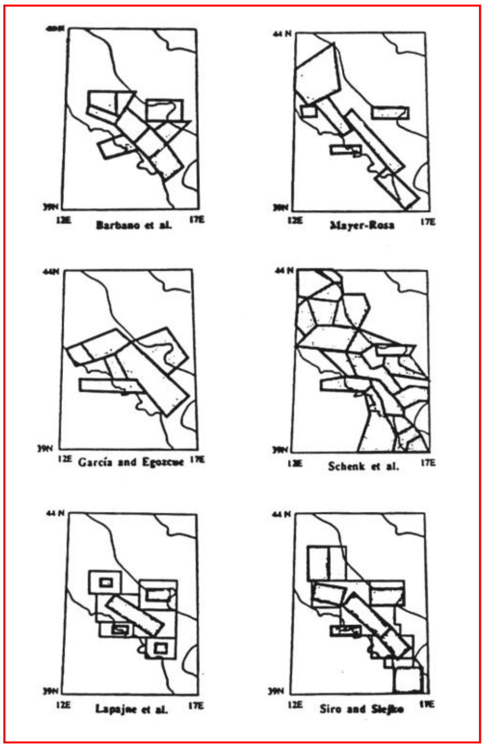


Basic steps of probabilistic seismic hazard assessment (Reiter, 1990).

To develop a PSHA we need: **seismic source zones, earthquake catalogues** (historical and/or instrumental), **attenuation relationships.**

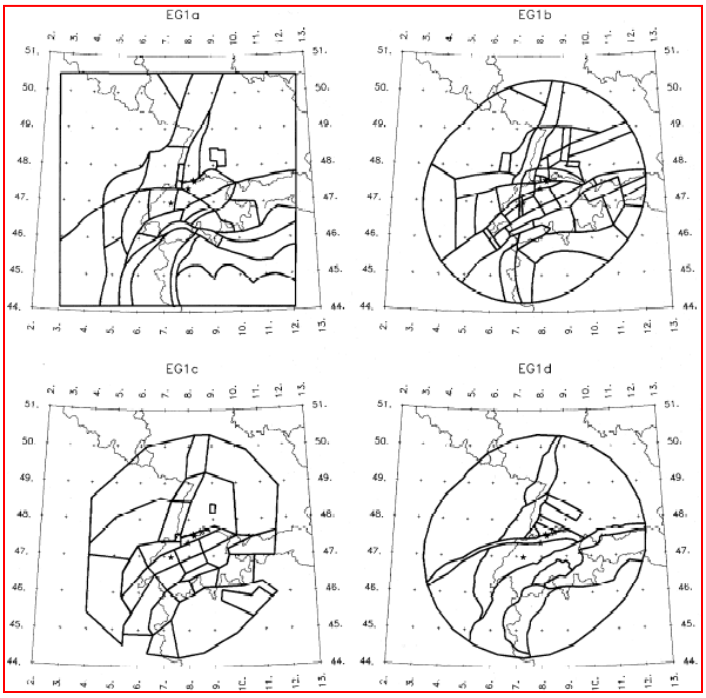
after Reiter, 1990 and Kramer, 1996

Seismic source zones



Seismic source zones defined by different groups of researchers for the Sannio-Matese region of southern Italy (Barbano *et al*., 1989).

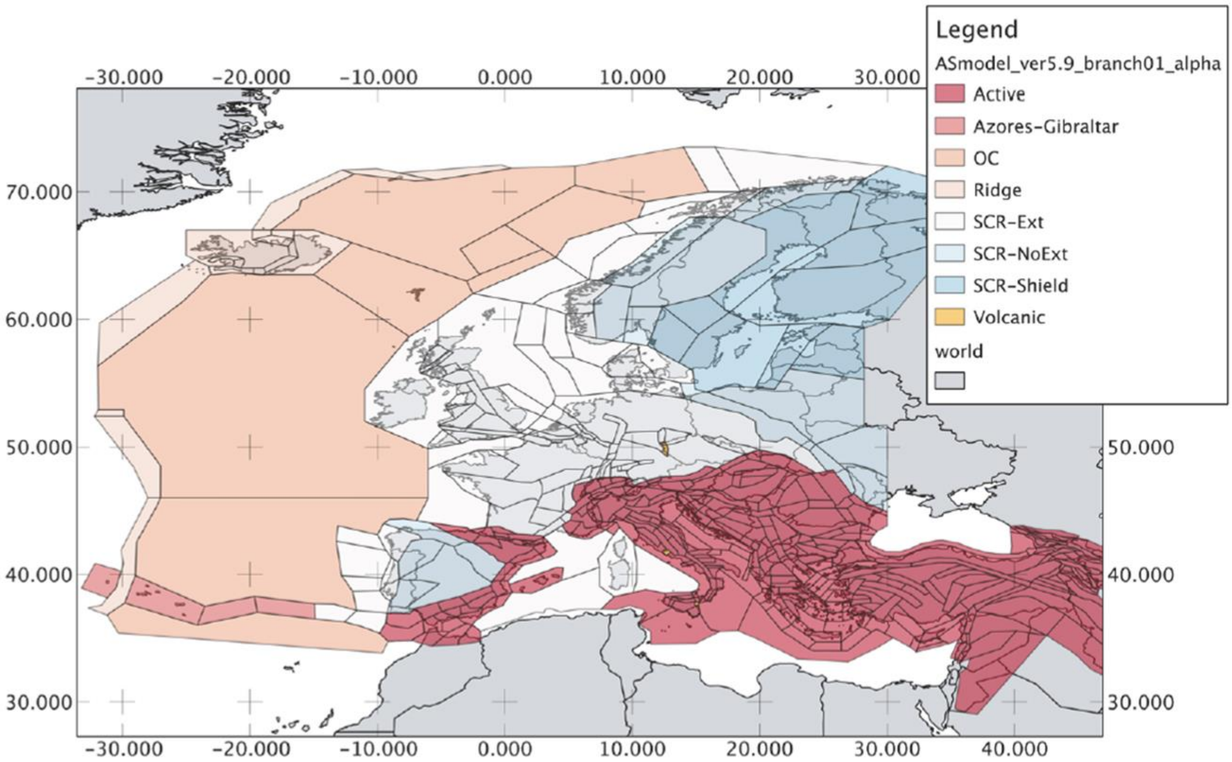
The first step is to **define seismic source zones**. These are regions defined by polygons within which it is assumed that seismicity is uniform in terms of the type and distribution of earthquakes.
The criteria for determining the boundaries of the seismic zones include the **distribution of instrumental and historical seismicity, the tectonic configuration and the location of known active faults**.
It is almost impossible to prescribe a standard procedure for the definition of seismic source zones, since the **process involves a high degree of subjective judgement.**



Example of seismic source zones adopted for Switzerland by different experts groups in the frame of PEGASOS project (Coppersmith, 2004).

The most encouraging lesson that can be provided for a student of engineering seismology is proof that even renowned experts in the field will rarely agree on the limits of appropriate source zones: **there will generally be as many answers as there are scientists working on the problem**.

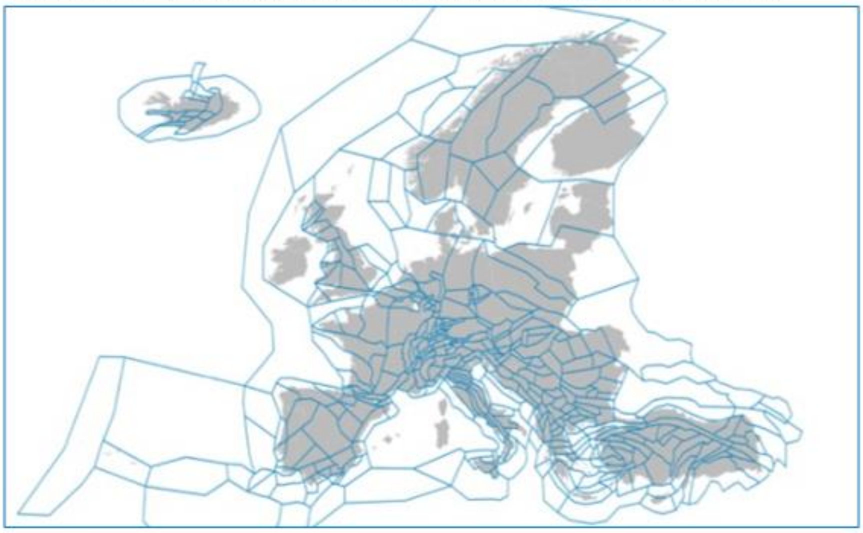
Seismogenic source model of Europe (EHSM13-EHSM20)



EHSM20 Area sources model

European Facilities for Earthquake Hazard and Risk - EFEHR
http://efehrcms.ethz.ch/en/home/

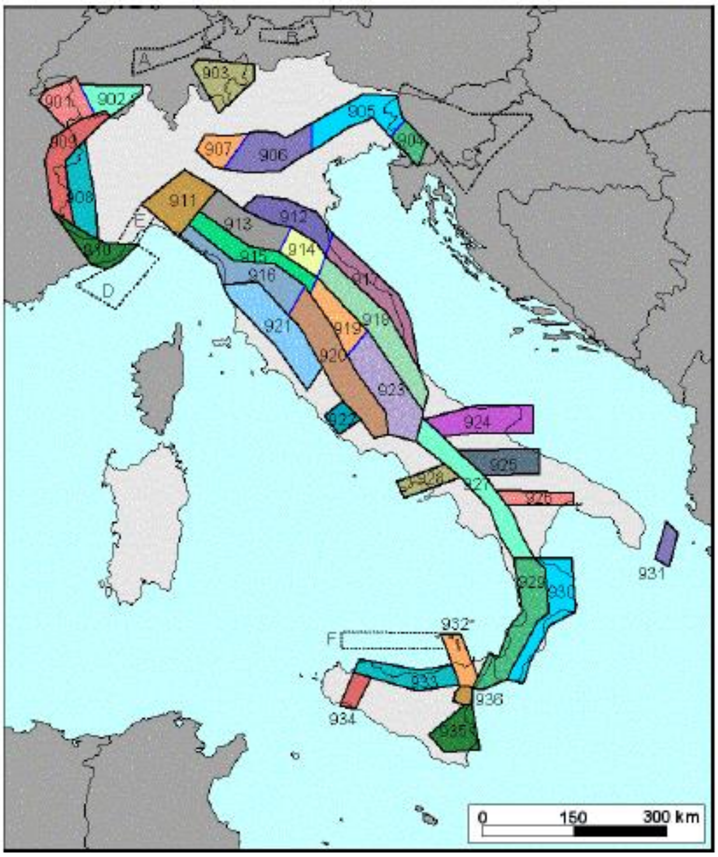
To reduce discrepancies between the national and regional models, a **consensus area source model** was adopted, based on tectonic information, geological evidence, and seismicity patterns



(Danciu et al. 2021) https://doi.org/10.12686/a15
http://efehrcms.ethz.ch/en/Documentation/specific-hazard-models/europe/eshm2020-overview/eshm20-seismogenic-sources/

http://efehrcms.ethz.ch/en/home/

Seismogenic source model of Italy



2- ZS9- 2004
(Stucchi et al., 2004)
http://zonesismiche.mi.ingv.it/

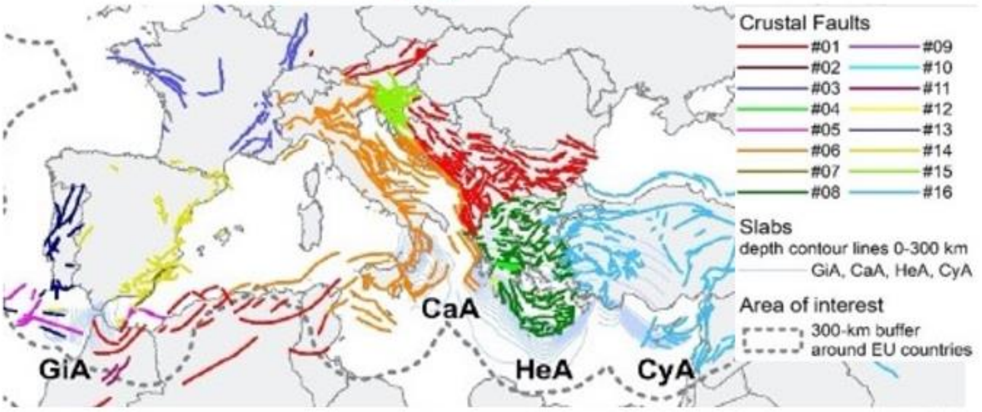
It represent an updating of the previous (ZS4) zoning, based on the most recent knowledge of active tectonics.
The number of zones is reduced at 35

It's the seismogenic zoning used for the implementation of the seismic hazard map of Italy (MPS04) adopted in the Italian seismic building code (NTC08)

Faults and zones

European Fault-Source Model 2020 (EFSM20)

SERA EFEHR INGV



Map of collated fault datasets for the development of the European Fault -Source Model 2020 (EFSM20). From west to east, the subduction systems are: Gibraltar Arc (GiA); Calabrian Arc (CaA); Hellenic Arc (HeA); and Cyprus Arc (CyA).

(Danciu et al. 2021) https://doi.org/10.12686/a15
http://efehrcms.ethz.ch/en/Documentation/specific-hazard-models/europe/eshm2020-overview/eshm20-active-faults-and-subduction-sources/

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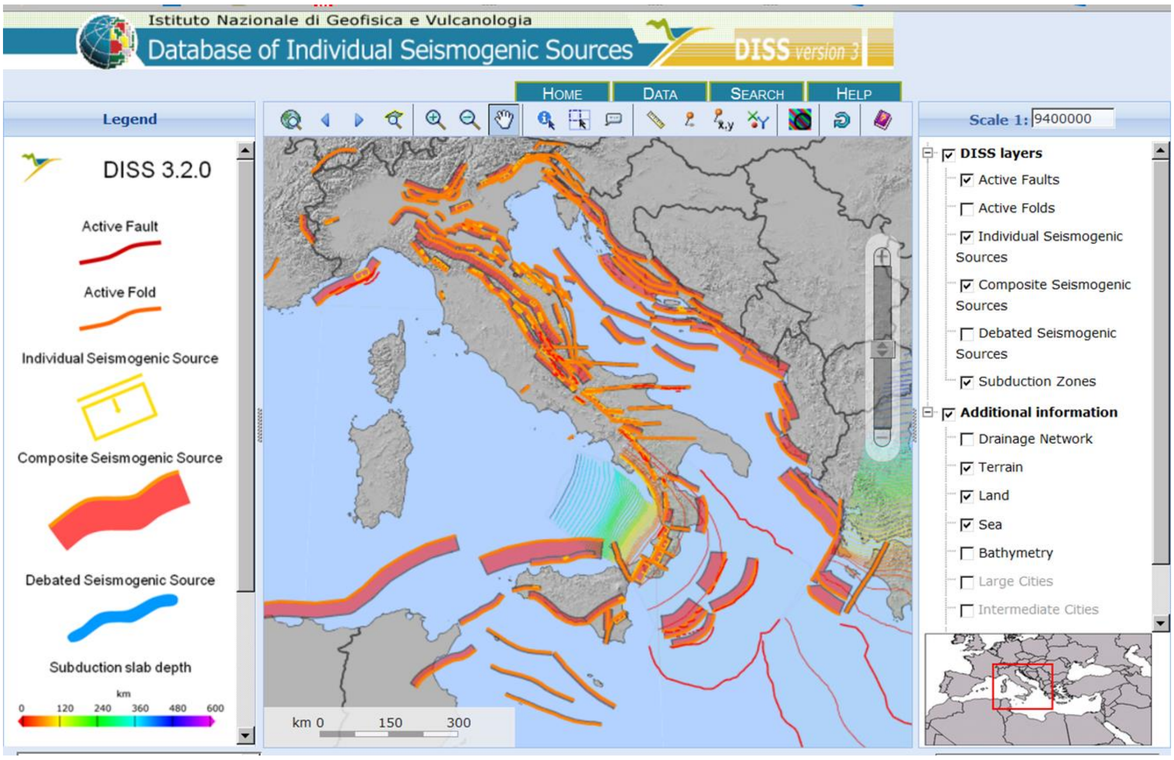
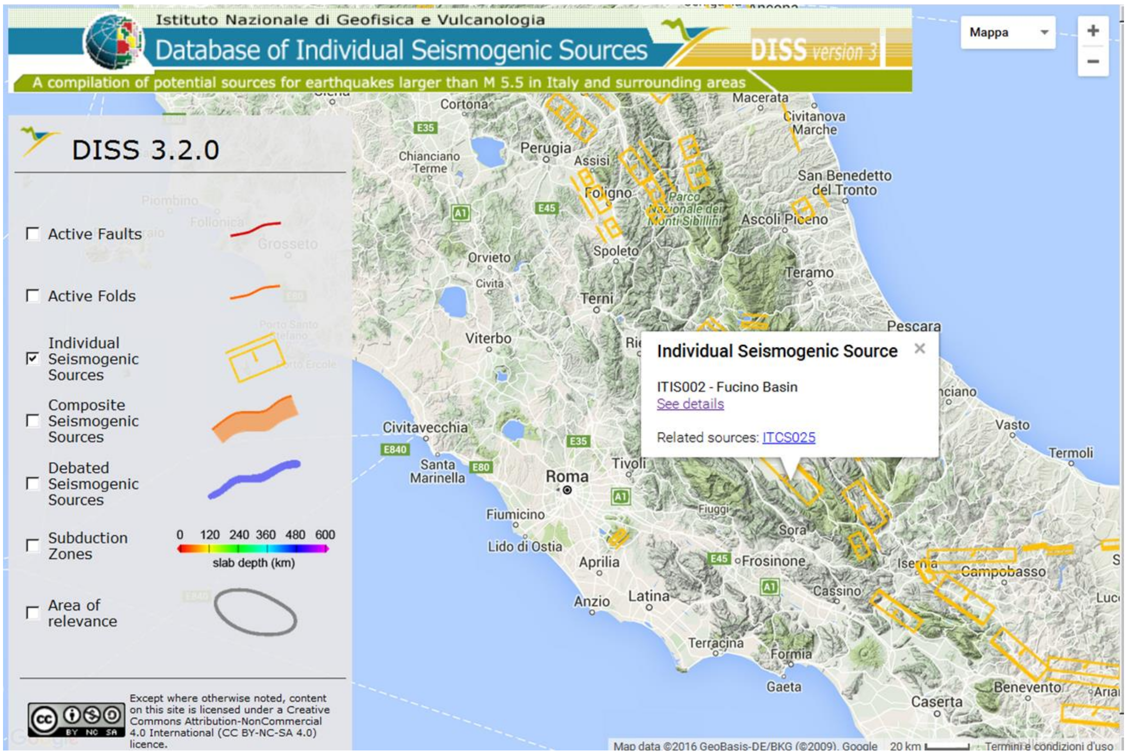
http://efehrcms.ethz.ch/en/Documentation/specific-hazard-models/europe/eshm2020-overview/eshm20-active-faults-and-subduction-sources/

https://diss.ingv.it/diss330/dissmap.html





http://diss.rm.ingv.it/dissnet/

Geological Geophysical Sources
Individual Seismogenic Sources
Composite Seismogenic Sources
Debated Seismogenic Sources
Subduction Zones
User Comments

Commentary ▼ Pictures ▼ References ▼ User Comments ▼

General Information

DISS–ID	ITCS025
Name	Salto Lake-Ovindoli-Barrea
Compiler(s)	Barba S.(1), Basili R.(1), Burrato P.(1), Fracassi U.(1), Kastelic V.(1), Tiberti M.M.(1), Valensise G.(1), Vannoli P.(1)
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Affiliation(s)	1) Istituto Nazionale di Geofisica e Vulcanologia; Sismologia e Tettonofisica; Via di Vigna Murata, 605, 00143 Roma, Italy
Created	08-Jan-2005
Updated	23-Dec-2011
Display map ...	
Related sources	ITIS002 ITIS028

Parametric Information

Parameter		Quality	Evidence
Min depth [km]	1.0	LD	Based on data of instrumental seismicity.
Max depth [km]	14.5	LD	Based on data of instrumental seismicity.
Strike [deg] min... max	130...150	LD	Based on geological data from various authors.
Dip [deg] min... max	40...65	LD	Based on geological data from various authors.
Rake [deg] min... max	260...280	LD	Based on geological data from various authors.
Slip Rate [mm/y] min... max	0.1...1.7	LD	Based on paleoseismology and long-term geological markers.

Faults and zones

However, in spite of the increased availability of geological, paleosismological, geodetic and seismometric data, it's very rare that in Europe (complex seismotectonics, buried faults) PSHA could be based purely on active faults, as e.g. in California (S. Andreas fault).

The most recent seismogenic source **model of Europe (ESHM20)** consists of four distinct source models :

- The **area sources model** is assumed to be the pan-European consensus model, incorporating the national area sources provided by local experts and fully cross-border harmonisation.
- **Active faults and background smoothed seismicity**, a hybrid seismicity model that combines the updated active faults datasets with the background seismicity in regions where faults are identified. The kernel smoothed seismicity model represents an alternative to the area sources model in regions without active faults.
- **Subduction sources** depicting both the subduction interface and in-slab of the Hellenic, Cyprian, Calabrian and Gibraltar Arcs.
- **Non-subducting deep seismicity sources** describe the nested seismicity with depth in Vrancea, Romania, and the cluster of deep seismicity in the southern Iberia Peninsula.

http://efehrcms.ethz.ch/en/Documentation/specific-hazard-models/europe/eshm2020-overview/eshm20-seismogenic-sources/

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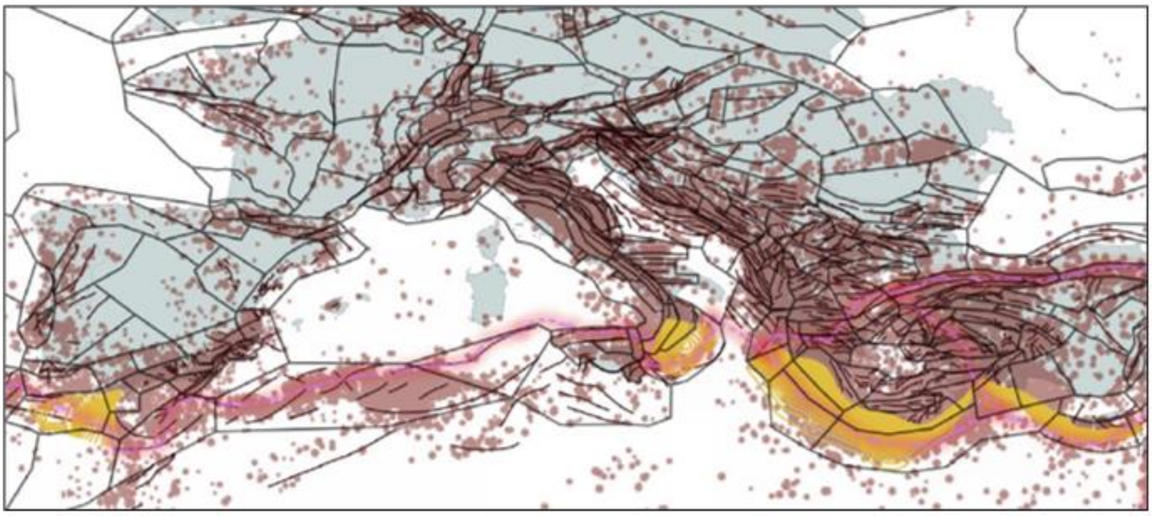
ESHM20 seismogenic source model



Schematic illustration of the ESHM20 seismogenic source model overlaying the area source (black polygons) active faults (black lines) and subduction sources (orange polylines) with the tectonic plate boundaries (red lines) and the earthquakes (red dots) of the unified earthquake catalogue.

Danciu et - The 2020 European Seismic Hazard Model: Milestones and Lessons Learned - Third European Conference on Earthquake Engineering and Seismology – Bucharest, 2022

Earthquake catalogues

Earthquake catalogues: Instrumental

The first step in a seismic hazard assessment is to compile an earthquake catalogue for the region under study. **This catalogue must give the origin time, location (epicentral co-ordinates and focal depth) and magnitude of earthquakes** that have occurred in or near to the region of interest. **Catalogues may be instrumental, historical or mixture of both types**.

Instrumental earthquake catalogues covering most of the twentieth century are easily obtainable for any part of the world from a number of national and international agencies, such as those listed below:

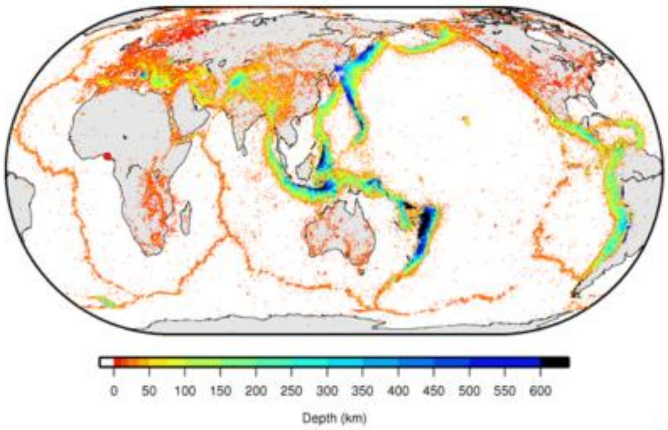
International Seismological Centre (ISC)
http://www.isc.ac.uk/

National Geophysical Data Center (NGDC)
http://www.ngdc.noaa.gov/

National Earthquake
Information Center (NEIC)
http://earthquake.usgs.gov/regional/neic/

Istituto Nazionale di Geofisica (INGV) –
http://cnt.rm.ingv.it/

ISC locations: 1964 to present



ta 8.23

It is often tempting to obtain an earthquake catalogue for the region of interest and then to proceed directly to the hazard calculations, but **it is always necessary to first assess the reliability of the data in the catalogue**. Agencies such as those listed above are producing routine earthquake locations that may easily carry an error of 5-10 km in the epicentral location and more in the focal depth.

Earthquake catalogues: historical sources

It was pointed out that the era of instrumental seismicity is considered to have begun around 1898, meaning that **the instrumental record of earthquake activity is at very best just over 100 years in length**. Compared with the time-scale of the geological processes underlying earthquake generation, this is an extremely short period of observation.


RELAZIONE
DE' DANNI FATTI
DALL'INNONDAZIONI,
E TERREMOTO
NELLA CITTA'
DELL'AQUILA,
Ed in altri luoghi Circonvicini
Dalli 14. del Mese di Gennaro
fino alli 8. del Mese di
Febraro 1703.
In ROMA, MDCCIII. Si vendono nella Stamperia del Zenobj
presso la Gran CURIA INNOCENZIANA.
CON LICENZA DE SUPERIORI.

Historical seismicity is the term given to the study of earthquakes that occurred before the end of the nineteenth century. The key to this study is the collection of contemporary reports of earthquakes and earthquake effects in **newspapers, diaries, church records, etc.**

Italy has one of the most extended and complete historical catalogues. A great effort for a revised and improved global (historical + instrumental) catalogue for Italy has been made, with the help of a **well experienced team of historians** for an accurate historical interpretation of the ancient descriptions, by Camassi and Stucchi (1996),

F. Sabetta 8.24

Italian catalogues: CPTI11-15

Catalogo Parametrico dei Terremoti Italiani

https://emidius.mi.ingv.it/CPTI15-DBMI15

Dati macrosismici e strumentali, di terremoti con intensità massima ≥ 5 o magnitudo ≥ 4.0 nel periodo 1000-2020.

versione CPTI11 2985 terremoti dall'anno 1005 al 2006

versione CPTI15 release 4 4895 terremoti dall'anno 1005 al 2020

a cura di
A. Rovida, R. Camassi, P. Gasperini e M. Stucchi

La versione 2011 del catalogo CPTI rappresenta una evoluzione significativa rispetto alla versione 2004, con particolare riferimento a contenuti e struttura.

Innanzitutto il catalogo si riferisce a un database macrosismico (DBMI11; Locati et al., 2011) e su una base di dati strumentali molto più ampia e aggiornata. In aggiunta, sviluppando quanto già avviato con le versioni CPTI08 (1900-2006) e CPTI08aq, il catalogo contiene anche un certo numero di record relativi a foreshock e repliche per cui sono disponibili dati macrosismici e/o strumentali.

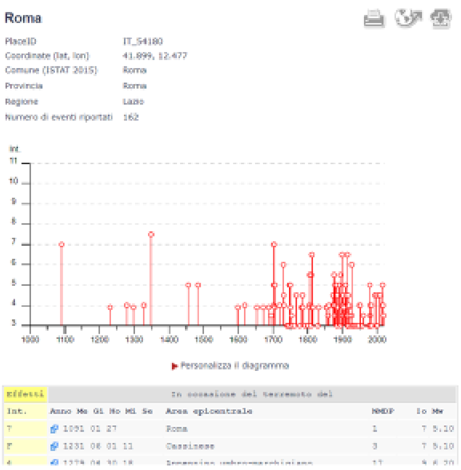
Il CPTI15 rappresenta un ulteriore aggiornamento e arriva fino al 2017 includendo i terremoti dell'Aquila, dell'Emilia e di Amatrice. Tuttavia include numerosissimi foreshocks e repliche e quindi non è adatto a uno studio di PSHA (eventi non indipendenti) a meno di procedere a un «declustering» (vedi in seguito)

Anno	Me	Gi	Or	Mi	Se	AE	Rt	Np	Imx	Io	Lat	Lon	Mw	Dw	Ms	Ds	Msp	Dsp	ZS9
1980	11	23	18	34	52	Irpinia-Basilicata	CFTI	1319	100	100	40.850	15.280	6.89	0.04	6.89	0.04	6.89	0.04	927

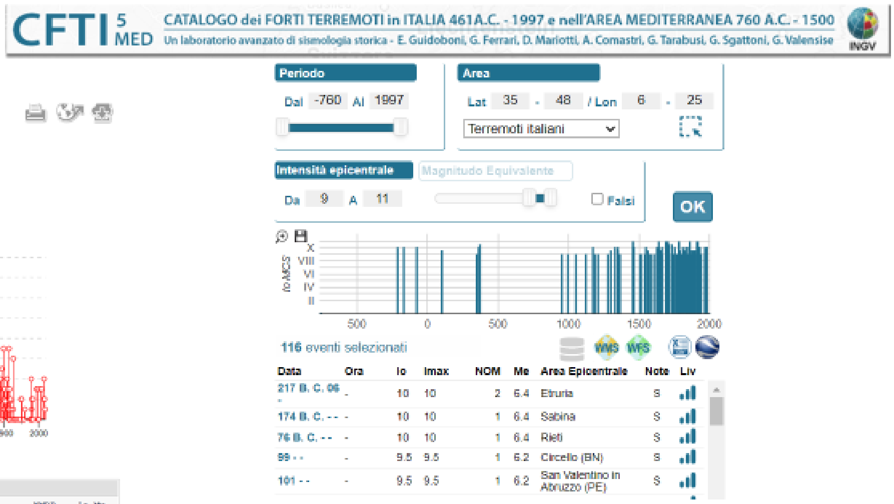
https://emidius.mi.ingv.it/CPTI15-DBMI15

DMBI15 Database Macrosismico Italiano – CFTI Catalogo dei forti terremoti in Italia

Database Macrosismico Italiano
Consente interrogazini per terremoto e per località



https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/



https://storing.ingv.it/cfti/cfti5/#

WEB-GIS
Fornisce informazioni delle fonti storiche su vittime e danni

F. Sabetta 8.26

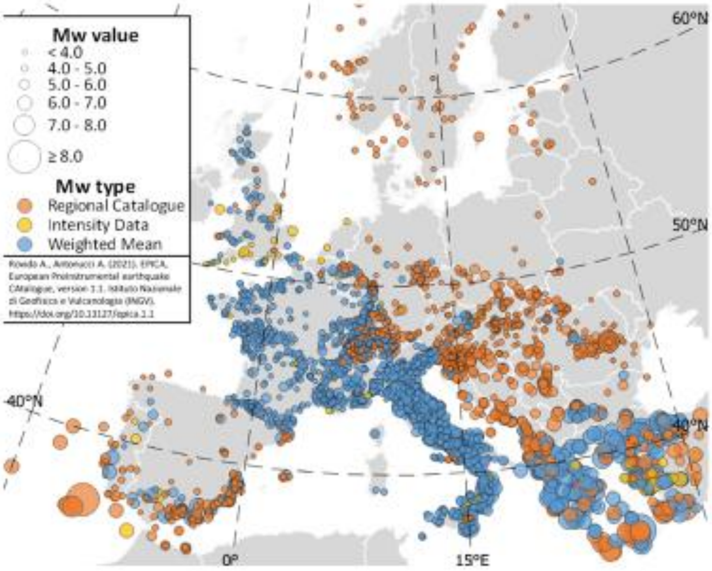
https://storing.ingv.it/cfti/cfti5/#

European catalogue ESHM20

http://efehrcms.ethz.ch/en/Documentation/specific-hazard-models//

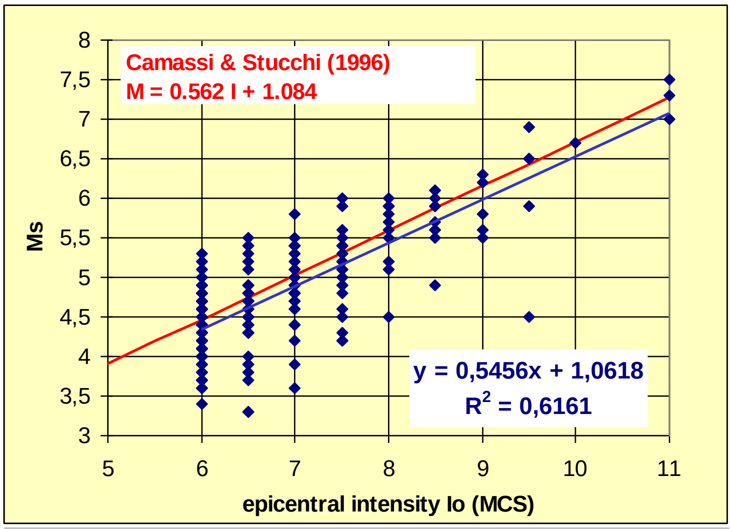
The ESHM20 unified earthquake catalogue consists of two parts:

- the so-called "**instrumental**" catalogue (**after 1900**) based on the updated European-Mediterranean Earthquake Catalogue (EMEC, Grünthal, G., Wahlström, et al.2012),
- the European **PreInstrumental** Earthquake Catalogue EPICA (Rovida and Antonucci, 2021;) earthquake catalogue (between the **years 1000 CE and 1899**).



EPICA version 1.1 contains 5703 earthquakes with either maximum observed intensity ≥5 or Mw ≥4.0.

Magnitude-Intensity correlation



Empirical regression Ms-Io derived from the NT4.1 catalogue. Data are relative to 274 events, with I ≥ VI and shallow focal depth (10-30 km), for which both intensity and Ms are available.

The majority of the ground motion predictive models used in seismic hazard assessment, require the **earthquake magnitude as input parameter**.

Empirical regressions between magnitude and epicentral intensity can be performed, giving rise to the so called **Macroseismic Magnitude (M_m)**

These correlations are strongly dependent on the scales adopted, on earthquake focal depth, and on the country where the data are taken from.

The uncertainty in in these correlations should be taken into account in the more sophisticated SHA.

De-clustering, stationarity and completeness

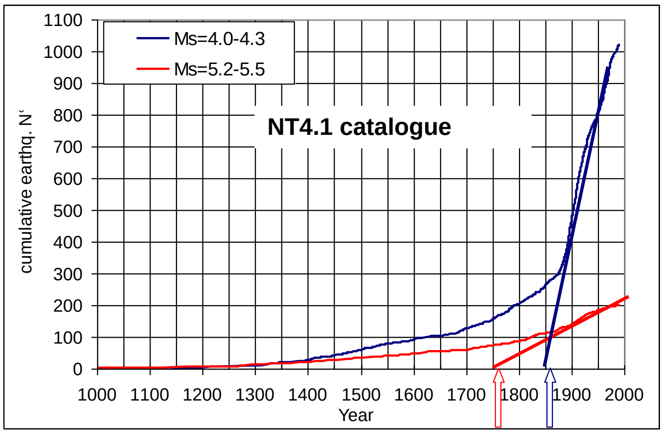
In order to satisfy the hypothesis of independence of events that is at the basis of the Cornell method (Poisson process) the ***foreshocks*** and ***aftershocks*** preceding and following the main large earthquake **should be removed from the catalogue (space and time de-clustering).**

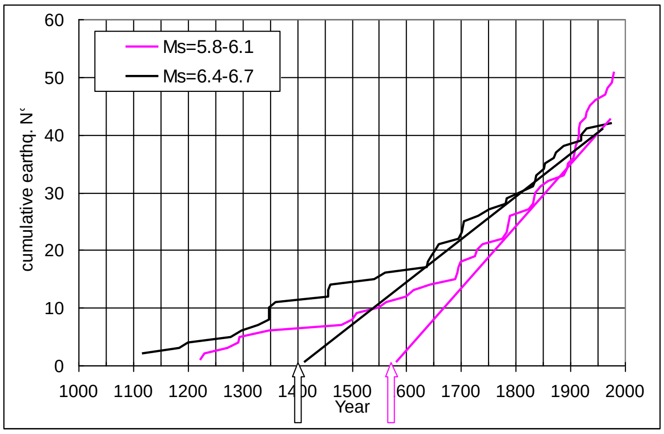
For example, in case of CPTI11 catalogue, de-clustering has been performed ***filtering* the catalogue**, around each main event, **with a space-time window of 30 km and ± 90 days.**

De-clustering, however, is often not a straightforward matter because it is common for earthquakes to occur in series, such as the 2016 Amatrice earthquakes in Italy, where none of the events is clearly identifiable as a main shock, although the events are evidently not independent.

In a study of the Electric Power Research Institute (EPRI 1986), earthquakes that clustered were defined by comparing them against the more random behaviour of background seismicity in the vicinity. As a result of the analysis **24% of the earthquakes** (M<4.5) **were eliminated** because they were found to be dependent. The inclusion of these events in the SHA of north-eastern U.S. resulted only in a **10% increase** in the probability of exceeding given ground motion values.

Catalogue completeness





Due to the lack of complete documentation, the probability of "lost" earthquakes increases as one goes back in time making the catalogue progressively less representative of actual seismicity.

An **earthquake catalogue** is defined **"complete"** if all the earthquakes happened during the time period covered are effectively reported in the catalogue.

For instrumental data **detection capability** is the determining factor. For historical data, **evolution in time of socio-cultural environment, population density, and record keeping** are the key factors.

The most common method for estimating **completeness period (Tc)** has been proposed by Stepp (1972) and consists of making plots of the cumulative number of events against time, from which, the period since present during which reporting has been complete, can be judgmentally estimated. **Estimation of Tc is often difficult and involves a high degree of subjective judgment.**

Stationarity and completeness

The effect of the completeness time interval Tc on the final results of SHA is strongly dependent on the particular time-distribution of earthquakes for the considered seism. zone**.**
The effect is often mitigated by the fact that varying Tc, generally changes also the number of events falling in that period. Consider, for example that your "1000 years" catalogue, for a

given source zone, reports **2 events** with intensity IX y in years **1350 and 1880**. If you assume, for that intensity, the **whole catalogue duration** as completeness period, the resulting occurrence rate will be of **0.002 earthquakes per year**. If you assume that I=IX completeness starts in **1600**, the resulting occurrence rate will be of **0.0025 earthquakes per year**.

Several authors have proposed different statistical methodologies for the evaluation of completeness time intervals (Stepp, 1972; Bath, 1983; Tinti & Mulargia, 1985; Mulargia et al., 1987).

The decrease in seismicity rate that is normally observed in the catalogues going back with time is due to incompleteness or to the effective non-stationarity of the earthquake generating process?

Any statistical approach based exclusively on catalogue data is in some way a “vicious circle” because **you are using an incomplete data base to evaluate its incompleteness**. The only way to get out of this, would be **to use independent historical information**, based on the knowledge of the variation during historical time of the availability of historical sources, **that is rarely accessible**.

Normally to overcome the problem an **“a priori” assumption on the stationary characteristics of the seismicity** (allowed by the de-clustering) is made, so that the incompleteness is attributed to the deviation of the seismicity reported in the catalogue from the “assumed” theoretical stationary model. In this way **the completeness test is transformed in a stationarity test**.

Gutenberg - Richter relationship

The events extracted from the catalogue, for each source zone, are arranged in ascending order of Magnitude/Intensity and summed to determine the **cumulative frequency N**, **which is the number of earthquakes of magnitude m or greater per year. N** is found by **summing the cumulative number of events** from the largest magnitude downwards, **and then dividing by completeness period** selected for each M/I range.

Gutenberg & Richter (1956) found that there is a logarithmic relationship between the cumulative frequency and the magnitude, known as ***recurrence relationship*** or ***Gutenberg -Richter (G-R) relationship :***

log (N) = a - b·m.

N is generally indicated as ***mean annual rate of exceedance*** λ_m.

$$\log\lambda_m = a - b \cdot m$$

The reciprocal of λ_m is commonly referred to as return period Tr, which is simply the mean time interval between occurrences of events ≥ m.

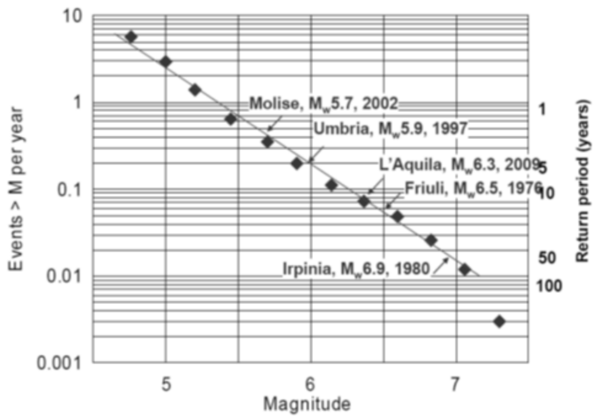
A basic assumption of PSHA is that the recurrence relation obtained from past seismicity is appropriate for the prediction of future seismicity.

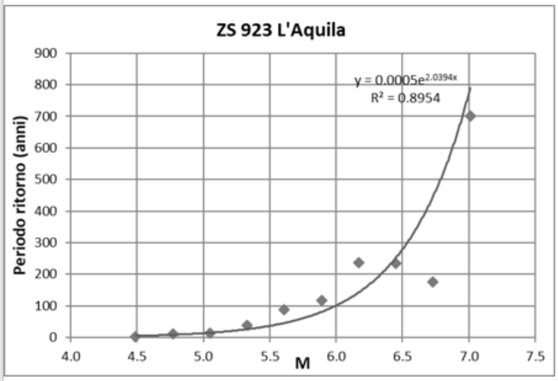
Recurrence relationship

The parameter ***a*** represents the seismic activity and is the log of the mean yearly number of events with m≥0. The **higher the seismicity of the region, the greater the value of *a***.

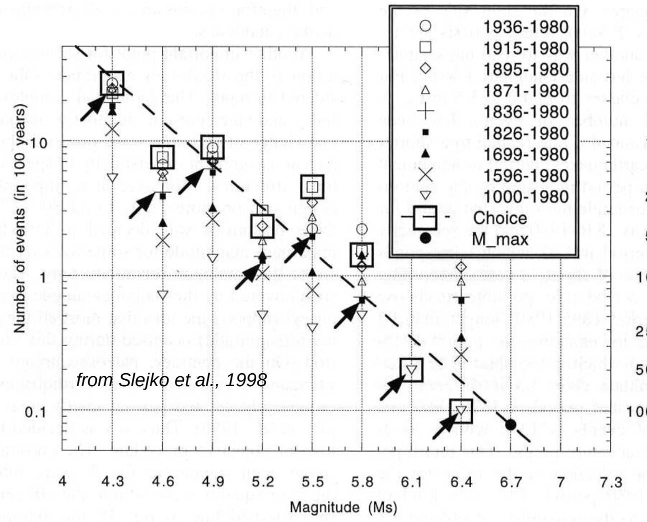
The ***b*-value describes the relative likelihood of small and large earthquakes**. A low *b*-value (shallow slope) would imply a relatively higher proportion of large earthquakes than a high *b*-value (steep slope).

The *b*-value varies with seismicity of the region and is usually close to 1.0





un terremoto distruttivo come quello dell'Irpinia **(Mw6.9)** ha un tasso medio di occorrenza di circa 0.02 eventi/anno, ovvero lo si attende in media sul territorio italiano **una volta ogni circa 50 anni**. Un terremoto come quello dell'Aquila (**Mw6.3**) avviene invece su scala nazionale con frequenza maggiore, approssimativamente **ogni 13 anni**. Su scala locale (zona 923 L'Aquila) circa ogni **200 anni**



Anno	Mese	Giorno	Località	Ms
1472	5	14	FRIULI	50
1514	7	12	GEMONA	50
1523	6	27	GEMONA	50
1692	5		M.VALCALDA	50
1853	2	19	MOGGIO UDINESE	50
1889	10	13	TOLMEZZO	50
1892	6	23	CLAUT	50
1908	7	10	CARNIA	50
1965	8	19	FAGAGNA	50
1455	2	3	SPILIMBERGO	52
1794	6	7	TRAMONTI	52
1812	10	25	SEQUALS	52
1931	12	25	TARCENTO	52
1920	5	5	CARNIA	53
1924	12	12	CARNIA	54
1977	9	16	TRASAGHIS	54
1389	8	20	MOGGIO UDINESE	55
1928	3	27	CARNIA	56
1690	12	4	KAERNTEN	59
1700	7	28	RAVEO	59
1776	7	10	TRAMONTI	59
1788	10	20	TOLMEZZO	59
1976	9	15	FRIULI	59
1511	3	26	GEMONA	62
1348	1	25	CARNIA	63
1976	5	6	FRIULI	65

Seismicity rates as a function of the completeness period for the Italian source zone N°4 (Friuli). Dashed line represents Gutenberg-Richter interpolation Log(N) = a - bM

The standard G-R recurrence relationship may also be expressed as:

$$\lambda_m = 10^{a-bm} = e^{\alpha-\beta m}$$

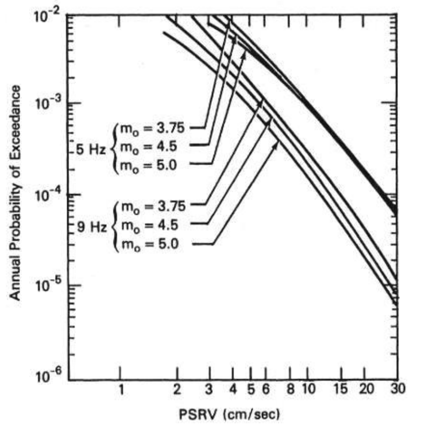
where **α=2.303·a** and **β=2.303·b.** It follows that **earthquake magnitudes are exponentially distributed** and the corresponding C.D.F. and P.D.F are

$$F_M(m) = P[M < m] = 1 - e^{-\beta m}$$

$$f_M(m) = \frac{d}{dm} F_M(m) = \beta e^{-\beta m}$$

Lower and upper bound magnitudes

The standard Gutenberg-Richter relation covers in theory an infinite range of magnitudes from 0 to ∞ but is generally used between a lower and upper bound. **The lower bound or minimum magnitude mo represents that level of earthquake size below which there is no engineering interest (earthquakes not capable of causing significant damage) or insufficient data.**



The upper bound magnitude m_{max} is the upper limit of earthquakes of all sizes that will enter into the analysis for each source; **its function is to truncate the recurrence relationship at the limit of the seismogenic potential of the seismic source**.

The recurrence relationship is effectively an extrapolation of observations of smaller earthquakes to predict the frequency of larger earthquakes; if it is not truncated at m_{max}, then it can predict physically impossible earthquakes.

PSHA allows for the consideration of events that are usually dismissed in DSHA as being highly unlikely.

For those faults for which paleoseismological studies have identified a characteristic earthquake, the value of m_{max} is known with some confidence. In other cases, the value of m_{max} is estimated by identifying the length of faults and then using empirical relationships to estimate the magnitude that would be associated with rupture along the entire length considered.

The largest historical earthquake is almost always the lower limit for m_{max}. In practice, m_{max} is usually defined by adding an increment Δm to the largest known magnitude in the source. The value of Δm should reflect the length and completeness of the earthquake catalogue, the more reliable the seismic record being, the smaller its value.

<u>**Increment of m_{max} has an influence only for return periods greater than 1000 years**</u>

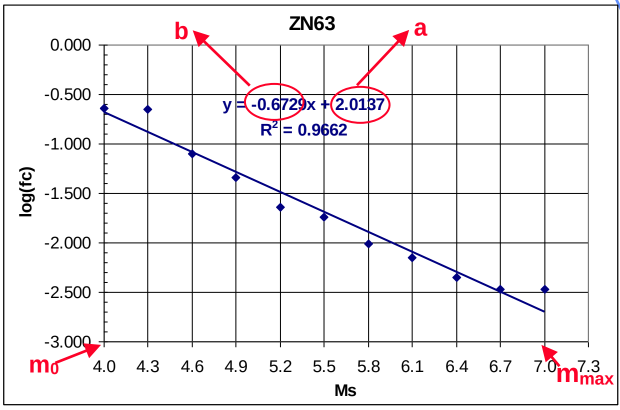
Truncated Gutenberg-Richter relation (TGR)

Ms	N ° earthqk	Compl. Period	Time interval	fs (N/year)	fc cumulated	log (fc)
4.0	1	1860	132	0.0076	**0.2308**	-0.637
4.3	19	1860	132	0.1439	0.2232	-0.651
4.6	7	1780	212	0.0330	0.0793	-1.101
4.9	5	1780	212	0.0236	0.0462	-1.335
5.2	1	1760	232	0.0043	0.0227	-1.645
5.5	2	1760	232	0.0086	0.0183	-1.737
5.8	1	1610	382	0.0026	0.0097	-2.012
6.1	1	1610	382	0.0026	0.0071	-2.149
6.4	1	1100	892	0.0011	0.0045	-2.348
6.7	0	1100	892	0.0000	0.0034	-2.473
7.0	3	1100	892	0.0034	0.0034	-2.473

The introduction of m_0 and m_{max} leads to the so called ***truncated Gutenberg -Richter relation*** (TGR)

$$\lambda(m) = \begin{cases} \lambda_0 \exp[-\beta(m - m_0)] & \text{if } m_0 \le m < m_{max} \\ 0 & \text{if } m \ge m_{max} \end{cases}$$

If plotted in semi-log scale this model is a straight line truncated at *m=m_{max}*. λ_0 is the magnitude exceedance rate for *m=m₀*



Seismicity rates and Gutenberg-Richter interpolation for the Italian source zone N° 63 (Irpinia).

Attenuation relationships

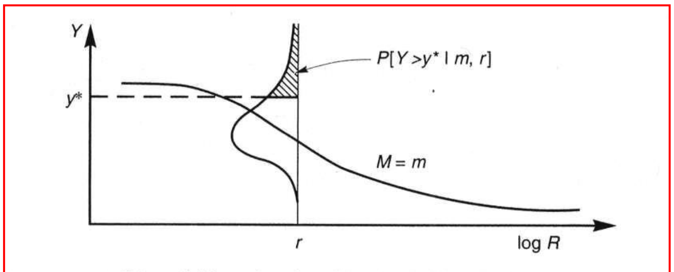
In carrying out a PSHA **most discussion centers about source zonation and mmax. More often than not they play a lesser role with respect to attenuation relationships**. Unfortunately the integrative nature of PSHA is such that only after one examines the results and carries out sensitivity studies, the effect of different ground motion models can be assessed.

As we have seen in a previous lesson, the attenuation relationships are characterized by a scatter in the data resulting from randomness in the mechanism of rupture and from variability and heterogeneity of the source, travel path, and site conditions.

This considerable random uncertainty must be accounted for in PSHA. **Scatter in the data is usually quantified by the standard deviation s of the attenuation relation**.

The probability that a particular ground motion parameter ***Y*** exceeds a certain value ***y**** for an earthquake of magnitude ***m*** and distance ***r*** is given by:

$$P[Y > y^* | m, r] = 1 - F_Y(y^*)$$



Schematic illustration of conditional probability of exceeding a particular value of a ground motion parameter for a given magnitude and distance.

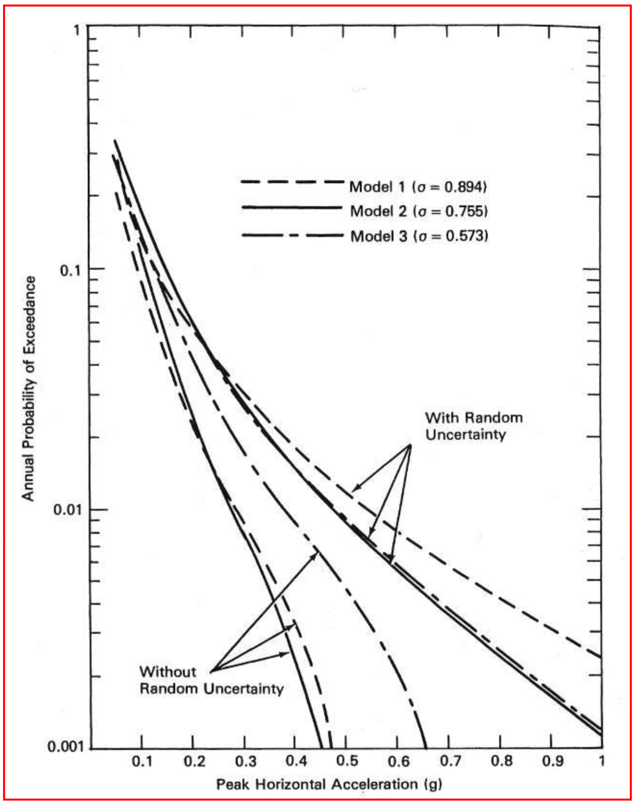
after Kramer, 1996 and Reiter, 1990

Where $F_Y(y)$ is the value of CDF of ***Y*** at ***m*** and ***r***. The value of $F_Y(y)$ depends on the probability distribution used to represent ***Y***.

In general **ground motion parameters are assumed to be log-normally distributed**.

It has to be pointed out that **the unbounded characteristics of that distribution can attribute a nonzero probability to unrealistic values of the ground motion parameter**.

Standard deviation



It is obvious from this figure that the effect of including the standard deviation, increases as the probability of exceedance decreases.

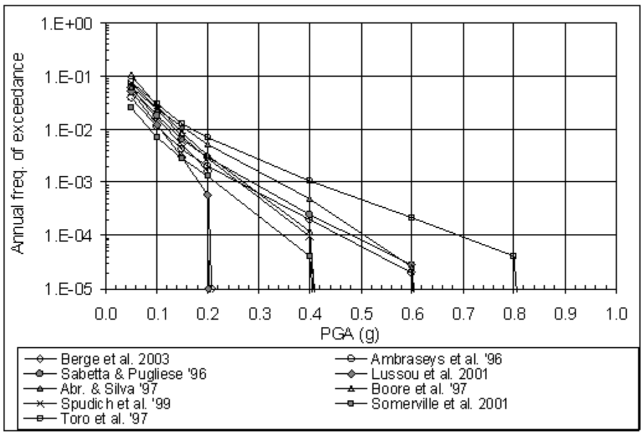
At high ground motion levels the hazard, without uncertainty, may be dominated by the likely, high ground motion from the occurrence of unlikely but large and/or nearby earthquakes.

When uncertainty is included the effect of low likelihood high ground motion from high likelihood smaller and/or more distant earthquakes may be also taken into account. The relative contribution of these events can become more important.

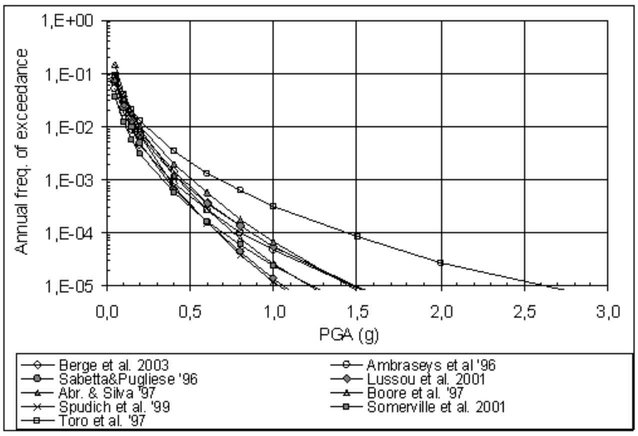
Apparently, the larger the random uncertainty, the lower the impact of m_{max}

Hazard estimates for San Francisco using three different ground-motion models with and without random uncertainty σ.

(after Reiter, 1990)



Hazard curves (PGA) for an Italian site calculated using only the median value of the selected ground motion relations (Sabetta et al. 2004)



Hazard curves calculated including the standard deviation of each model (Sabetta et al. 2004)

Time between events and Poisson process

The final ingredient required as input for a PSHA is the probabilistic distribution of the earthquake occurrence with respect to time. **The temporal occurrence of earthquakes is most commonly described by a Poisson process**. A Poisson process has the characteristics of being **stationary** in time (the probability of a favourable event is the same in all trials) and that the number of occurrence in one time interval are **independent** from the number in any other time interval.

These properties indicate that the events of a Poisson process occur randomly, with no *memory* of the time, size, or location of any preceding event (**memory-less process**). This is clearly not compatible with the processes of plate tectonics and elastic rebound that generate earthquakes.

Nonetheless, the assumption of a Poisson process is acceptable when the hazard is being evaluated for **any period of exposure**, regardless of the time of occurrence of the last earthquake, and in case of **multiple sources of earthquakes**.

The **time between events in a Poisson process is exponentially distributed**. In case of PSHA, a trial is a period of time, usually a year, for which the project is being exposed, and the number of trials will generally be its **design life, *t***. A favourable event in a given trial is an earthquake of magnitude ***m*** or greater and the frequency of occurrence is the **mean annual rate of exceedance *lm*** as defined previously. Therefore, the probability, ***P(N=n***), of ***n*** earthquakes of magnitude ***m*** or greater during a design life ***t*** is given by:

$$P[N=n]=\frac{(\lambda_m t)^n e^{-\lambda_m t}}{n!}$$

POISSON DISTRIBUTION

$$m_N=\lambda_m t=\sigma_N^2 \ldots\ldots V_N=\sigma/m=(\lambda t)^{-1/2}$$

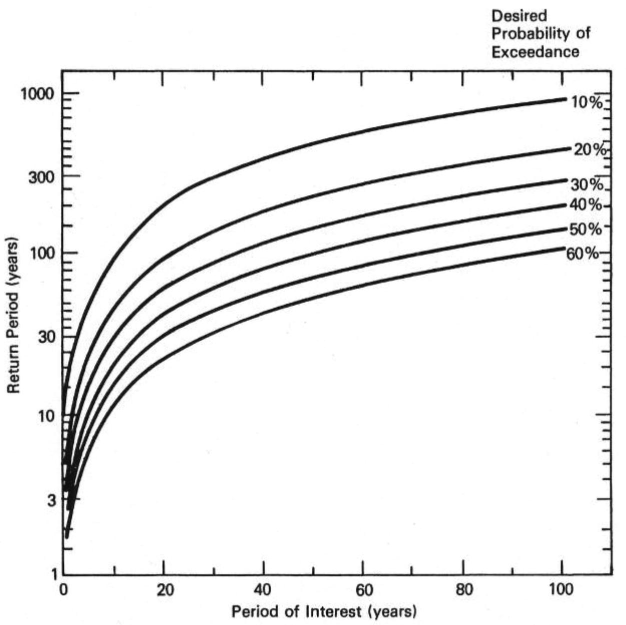
The concern in seismic hazard assessment is the probability of **at least one earthquake occurring during the exposure time t**. This is known as the **probability of exceedance P[N≥1]** and is equal to the difference between unity and the probability of no earthquakes occurring:

$$P[N\geq 1]=1-P[N=0]=1-e^{-\lambda_m t}$$

EXPONENTIAL DISTRIBUTION

$$m_N=1/\lambda_m=\sigma_N \ldots\ldots V_N=\sigma/m=1$$

Return period



Relationship between return period, period of interest and desired probability of exceedance during the period of interest for the Poisson model (after TERA Corporation 1980).

$0.1 = 1 - e^{-50/475}$

$0.63 = 1 - e^{-1}$

when $T_r >> t$ $P[N \geq 1] \approx t / T_r$

after Reiter, 1990

As a result of there being no preferred occurrence in any particular year, the **return period, T_r** is the reciprocal of the mean annual rate of exceedance λ_m and simply represents the mean interval between occurrences of events of ***m*** or greater and does not imply that earthquakes will occur every T_r years, nor that, during a period of time T_r, an earthquake will definitely occur.

$$T_r = 1/\lambda_m \rightarrow P[N \geq 1] = 1 - e^{-\lambda_m t} = 1 - e^{-t/T_r}$$

$$T_r = -t / \ln(1 - P[N \geq 1])$$

It is easy to deduce from where the rather **strange number of 475 years**, encountered in many hazard studies and many design codes, is obtained: it corresponds to a **probability of exceedance of 10% during an exposure time (period of interest) of 50 years**.