Performance-based earthquake engineering *before*, *during*, and *after* a mainshock

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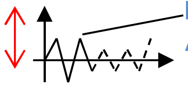
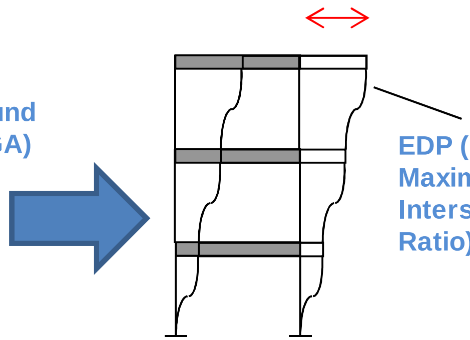
ECGS – Luxembourg , November 20 2015.

Seismic risk definition and performance-based earthquake engineering framework



IM (e.g., Peak Ground Acceleration or PGA)

Ground motion intensity (IM)



EDP (e.g., Maximum Interstory Drift Ratio)

Loss rate

$$\lambda_l = \int_{im}\int_{edp}\int_{dm} P\left[L > l \mid DM = dm\right] \cdot f_{DM|EDP}\left(dm\right) \cdot f_{EDP|IM}\left(edp\right) \cdot d\left(dm\right) \cdot d\left(edp\right) \cdot \left|d\lambda_{IM}\right|$$

Loss exceedance probability given damage

Structural damage probability depending on building seismic response

Seismic response probability depending on ground motion intensity

Probabilistic seismic hazard

Probabilistic seismic hazard (ground motion intensity rate)

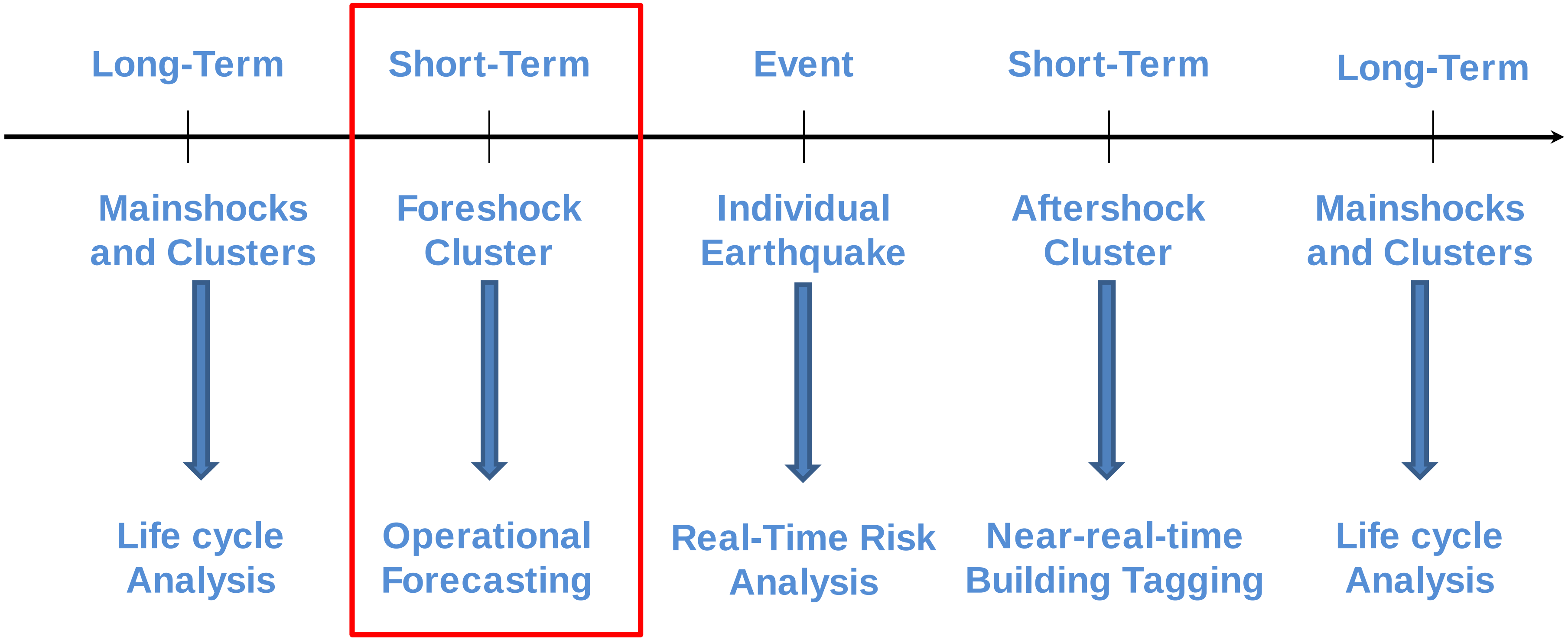
$$\lambda_{IM} = \lambda \cdot P\left[IM > im\right] = \lambda \cdot \int_r \int_m P\left[IM > im \middle| M = m, R = r\right] \cdot f_{M,R}\left(m, r\right) \cdot dm \cdot dr$$

Rate of earthquakes on the source

Attenuation law

Distribution of event fatures due to the source of interest

A possible scheme of seismic risk scales

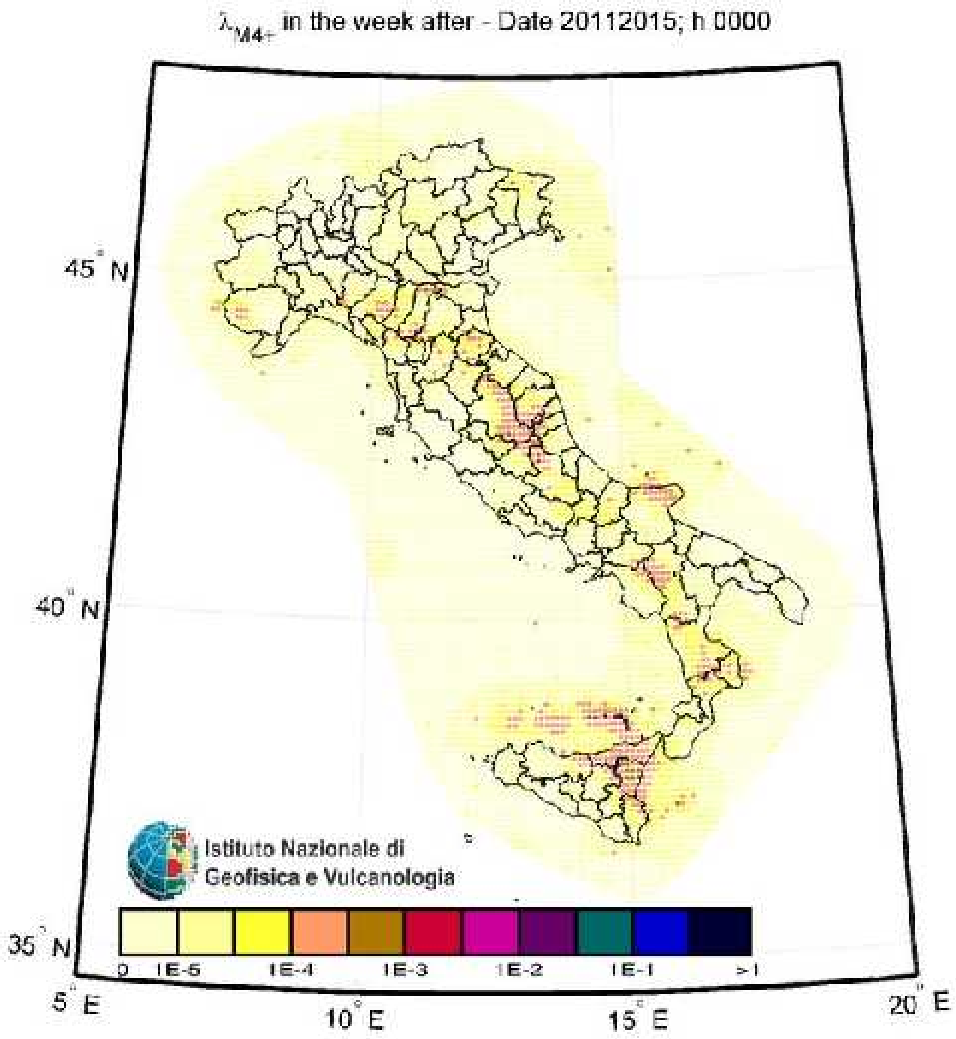


Background and motivation

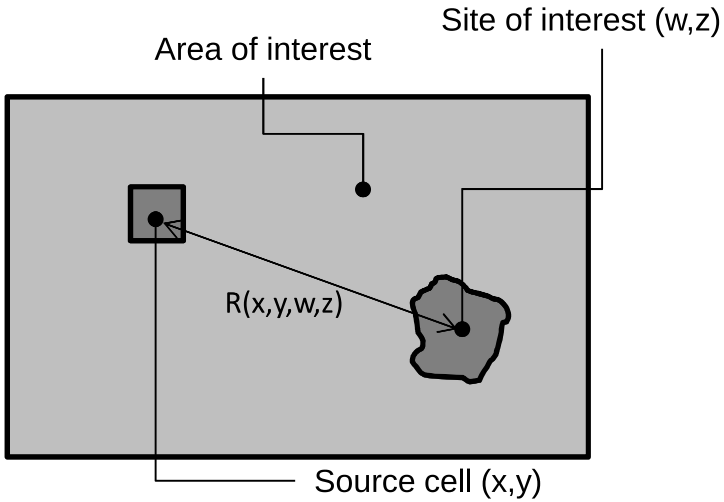
- The **OEF-Italy** system of **INGV** provides weekly rates of events with magnitude (M) 4+ for a 0.1° grid including the whole country. (Updated daily.)

- The **Italian Civil Protection** asked to investigate whether it is possible (and useful) to use the INGV data to produce consequence estimates.

- The framework is that of **performance-based earthquake engineering**, that is including probabilistic measures of hazard, vulnerability and exposure at a National scale.



1. Probabilistic seismic hazard analysis based on OEF



Rates of events causing some seismic intensity (MS) at a site of interest

Rates of events at (w,z) with MS=ms because of earthquakes occurring at (x,y)

OEF rates at (x,y)

MS prediction equation (attenuation law)

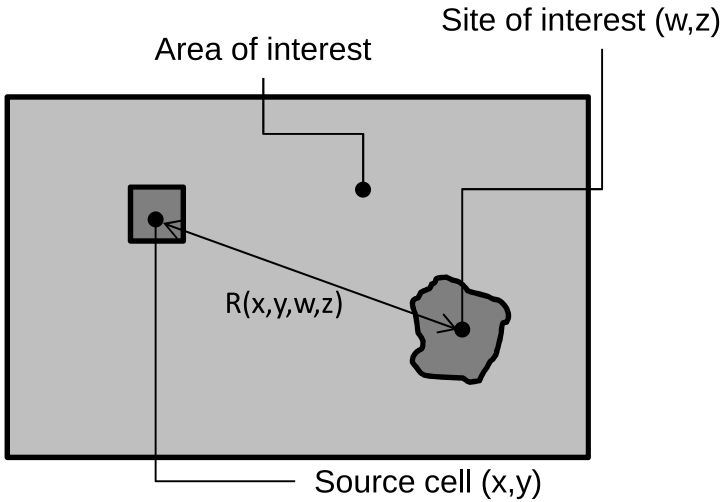
Distribution of M for earthquakes at (x,y)

$$\lambda_{MS=ms}\left(t,w,z\,\middle|\,H(t)\right)=\lambda\left(t,x,y\,\middle|\,H(t)\right)\cdot\int_m P\left[MS=ms\,\middle|\,m,R(x,y,w,z)\right]\cdot f_M(m)\cdot dm$$

Indicating that varies with time (OEF updates)

Indicating dependence on recorded history

2. Weekly rates of events causing building damage

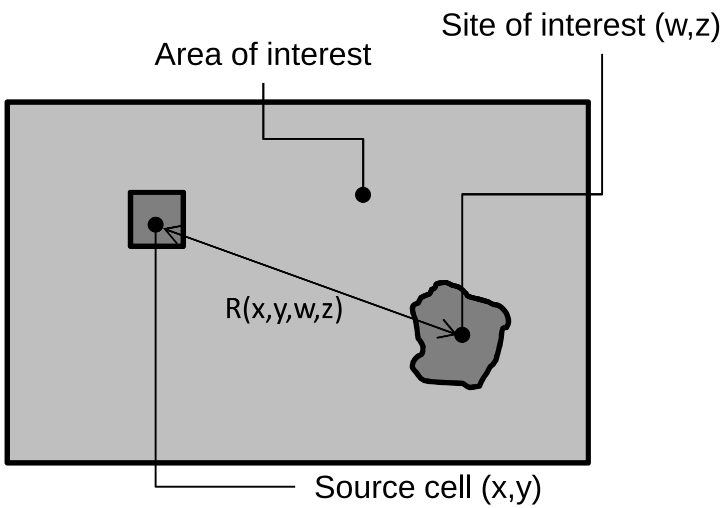


Rates of events causing some damage state (DS) in a building of certain structural typology (k) at site of interest

$$\underbrace{a_{DS^{(k)}=ds}\left(t,w,z\middle|H(t)\right)}_{\text{Rates of events at (w,z) causing DS=ds because of earthquakes occurring in the whole area}}=\iint_{x,y}\underbrace{a\left(t,x,y\middle|H(t)\right)}_{\text{OEF rates at (x,y)}}\cdot\underbrace{\sum_{ms}P\left[DS^{(k)}=ds\middle|ms\right]}_{\text{Probability of some damage state to a structure of typology K given ms intensity}}\cdot\underbrace{\int_{m}P\left[MS=ms\middle|m,R(x,y,w,z)\right]\cdot f_M(m)\cdot dm}_{\text{Same as per the previous slide}}\cdot dy\cdot dx$$

Summing up over all source cells gives the total damage rate at (w,z) site

3. Weekly rates of events causing individual loss



Rates of events causing some individual consequence to an occupant of a building of a given structural typology (k) at site of interest

Rates of events at (w,z) causing casualty in buildings of typology k

OEF rates at (x,y)

Summation is to account that casualty can be caused by any DS

Probability of casualty in a building of typology K given damage state DS=ds

$$\text{a}_{Cas^{(k)}}\left(t,w,z\,|\,H(t)\right)=\iint_{x,y}\text{a}\left(t,x,y\,|\,H(t)\right)\cdot\sum_{ds}P\left[Cas^{(k)}\,|\,ds\right]\times$$

$$\times\sum_{ms}P\left[DS^{(k)}=ds\,|\,ms\right]\cdot\int_{m}P\left[MS=ms\,|\,m,R(x,y,w,z)\right]\cdot f_M(m)\cdot dm\cdot dx\cdot dy$$

Same as per the previous slide

Expected losses in the week after the OEF rates release

Expected number of buildings of typology k at (w,z) in damage state DS=ds in the week after OEF rates release

Buildings

Rate of events causing damage

$$E\left[N_{ds,(t,t+\Delta t)}^{(k)} \middle| H(t)\right] \approx N_B^{(k)} \cdot \text{a}_{DS^{(k)}=ds}\left(t,w,z \middle| H(t)\right) \cdot \Delta t$$

One week

Expected number of displaced and shelter-seeking people

Expected number of casualties due to damage in the week after OEF rates release

Occupants in buildings

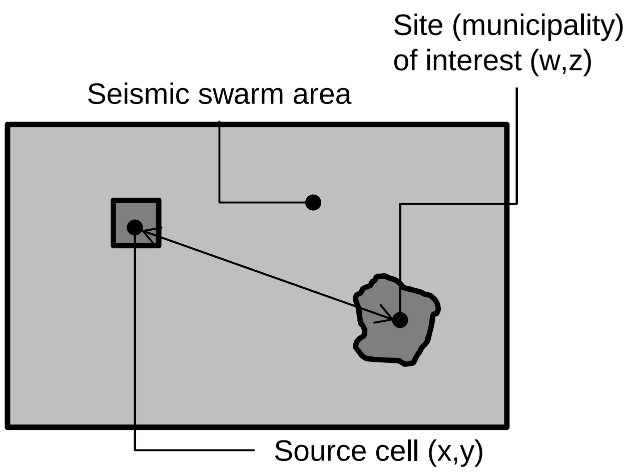
Rate of events casualties in buildings

$$E\left[N_{Cas,(t,t+\Delta t)}^{(k)} \middle| H(t)\right] \approx N_P^{(k)} \cdot \text{a}_{Cas^{(k)}}\left(t,w,z \middle| H(t)\right) \cdot \Delta t$$

One week

Expected number of fatalities and injuries

Operational earthquake loss forecasting (OELF) procedure summary



Rate of events in the source cell of interest from OEF

↓

Probability of any macroseismic intensity level given the event ← Intensity attenuation law

↓

Probability of any damage level for any vulnerability class given the event ← Vulnerability model

↓

Probability of casualties or injuries for any damage level in any vulnerability class given the event

↓

Sum-up over all source cells

↓

Inventory data for buildings at the site of interest → Expected number of damaged buildings → Expected number of injures, fatalities, displaced people ← Exposure data for residents at the site of interest

Vulnerability based on damage probability matrices

Class	MS	DS0	DS1	DS2	DS3	DS4	DS5
A	5	0.3487	0.4089	0.1919	0.0450	0.0053	0.0002
B	5	0.5277	0.3598	0.0981	0.0134	0.0009	0.0000
C	5	0.6591	0.2866	0.0498	0.0043	0.0002	0.0000
D	5	0.8587	0.1328	0.0082	0.0003	0.0000	0.0000
A	6	0.2887	0.4072	0.2297	0.0648	0.0091	0.0005
B	6	0.4437	0.3915	0.1382	0.0244	0.0022	0.0001
C	6	0.5905	0.3281	0.0729	0.0081	0.0005	0.0000
D	6	0.7738	0.2036	0.0214	0.0011	0.0000	0.0000

Probabilities of casualty given structural damage

Loss	Structural Typology	Vulnerability Class	DS0	DS1	DS2	DS3	DS4	DS5
Fatalities	Masonry	A or B or C	0	0	0	0	0.04	0.15
Fatalities	R.C.	C or D*	0	0	0	0	0.08	0.3
Injuries	Masonry	A or B or C	0	0	0	0	0.14	0.7
Injuries	R.C.	C or D*	0	0	0	0	0.12	0.5

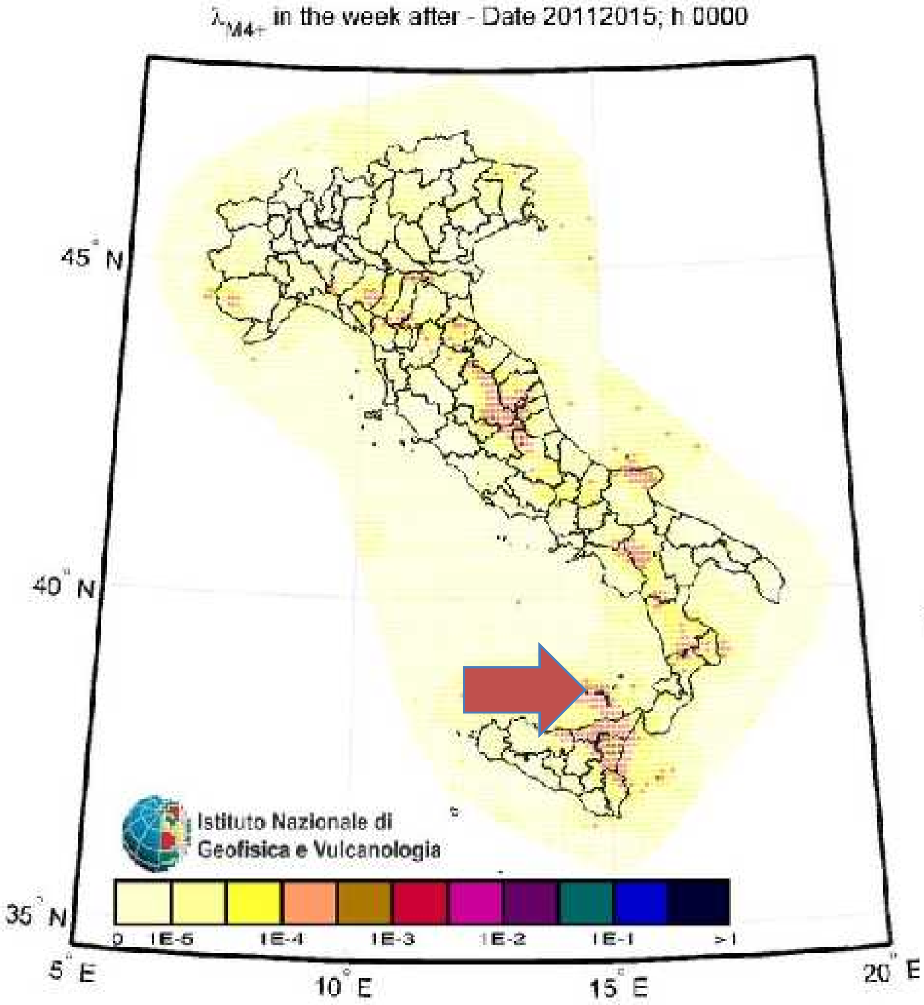
Exposure by municipality

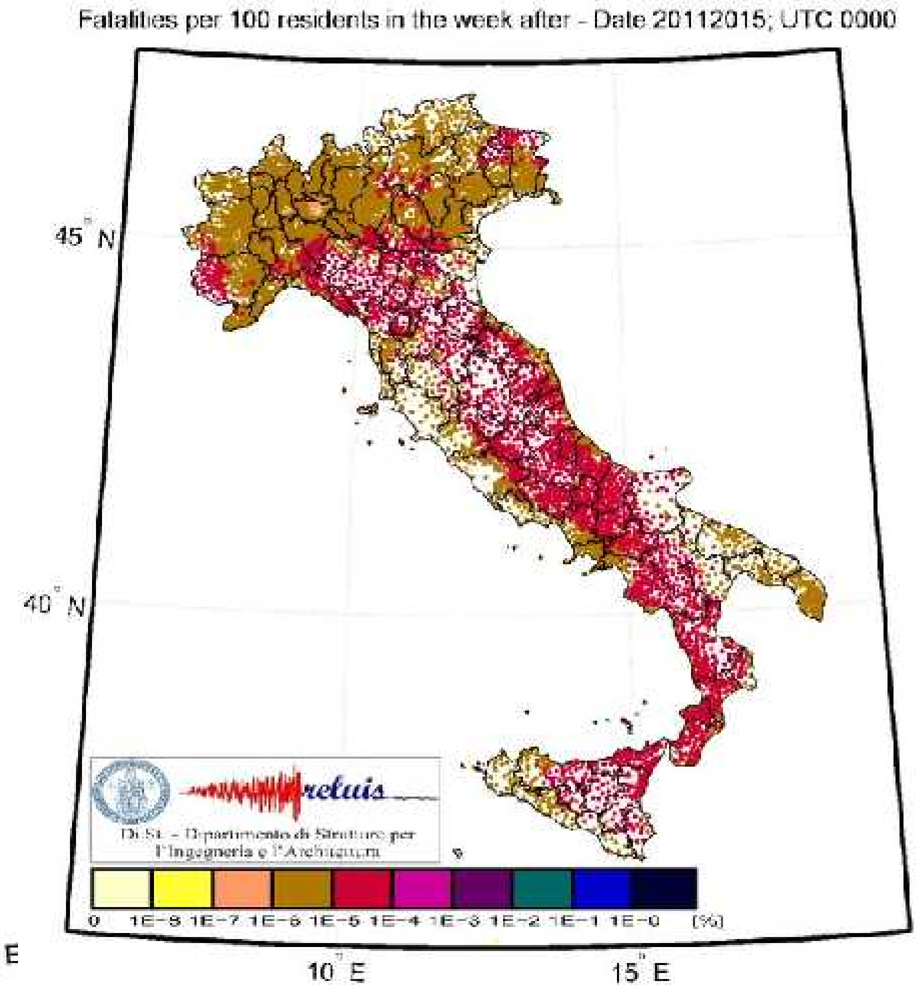
Code	Name	Prov.	A	B	C	D	ab_A	ab_B	ab_C	ab_D
1001	Agliè	001	222	163	286	186	697	535	350	990
1002	Airasca	001	75	60	152	138	497	351	357	2350
1003	Ala di Stura	001	186	209	220	47	218	100	64	95
1004	Albiano d'Ivrea	001	192	147	80	84	646	419	199	432
1005	Alice Superiore	001	136	121	85	76	177	116	51	270
1006	Almese	001	261	318	511	792	1006	741	547	3364
1007	Alpette	001	144	125	122	42	116	51	32	101
1008	Alpignano	001	222	288	620	832	1214	1400	1573	12461
1009	Andezeno	001	153	110	83	116	512	315	164	714
1010	Andrate	001	141	131	123	44	250	104	61	62

Buildings per vulnerability class (A–D)

Residents per vulnerability class (ab_A–ab_D)

MANTIS K. The system for continous OELF in Italy*

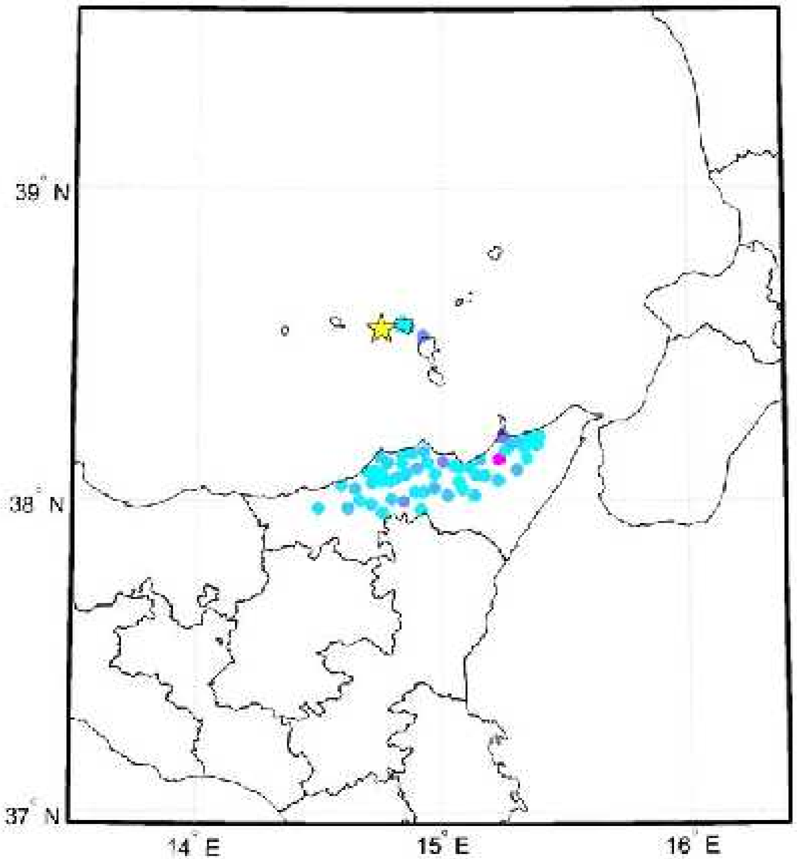




*Iervolino I., Chioccarelli E., Giorgio M., Marzocchi M., Zuccaro G., Dolce M., Manfredi G. (2015) Operational (short-term) earthquake loss forecasting in Italy. Bulletin of the Seismological Society of America 105: 2286–2298.

Local OELF at 00:00 of November 20 2015 (around the cell with maximum OEF rate)

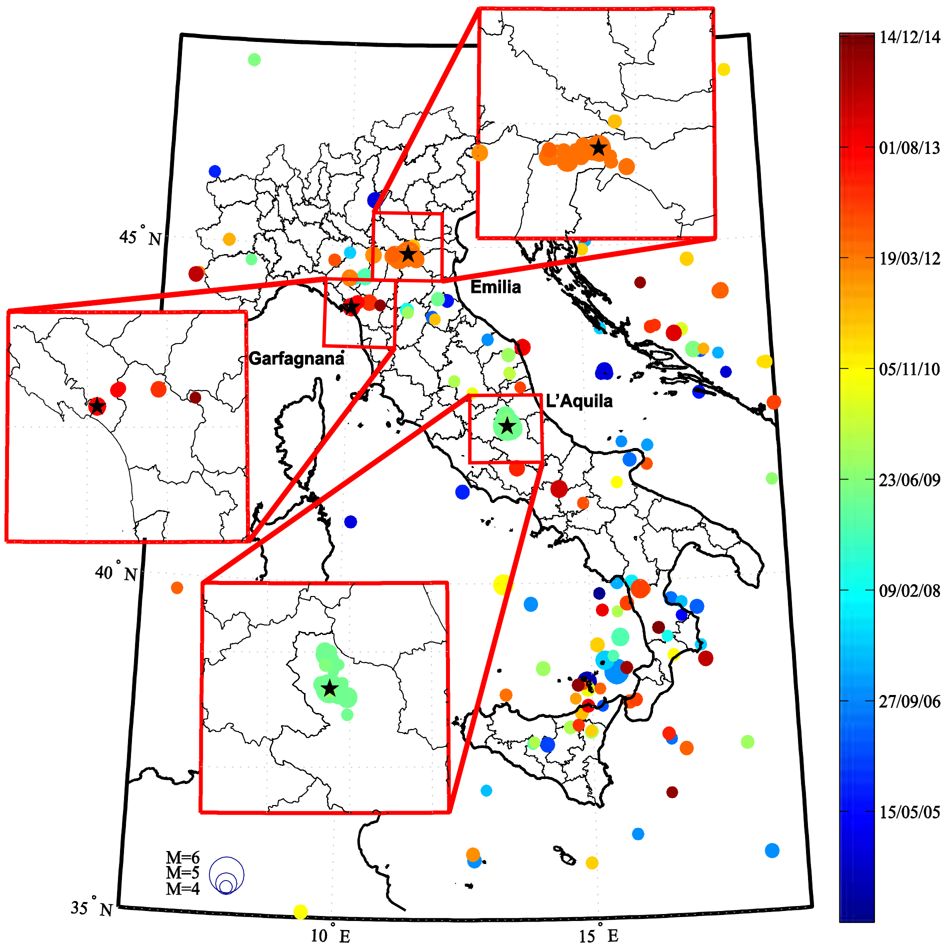
Area of interest

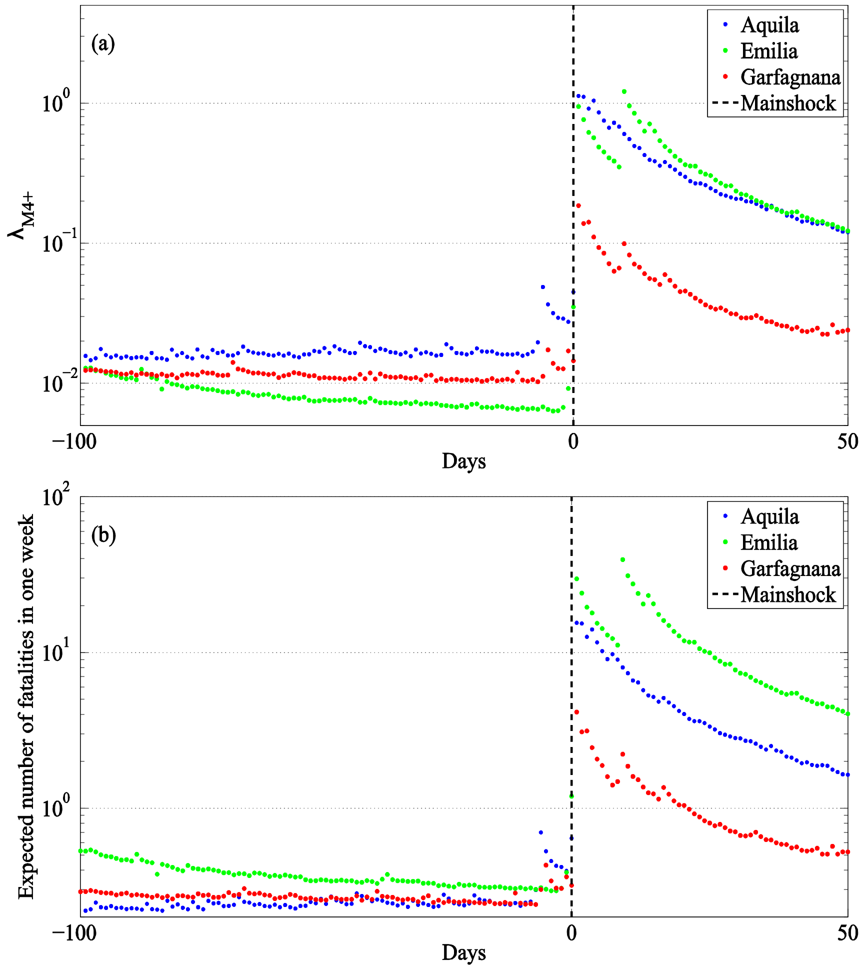


Expected weekly losses (Nov. 20-26)

Distance from the maximum rate	Total number of buildings	Total number of residents	Collapsed buildings	Displaced	Injuries	Fatalities
< 10km	1708	2299	0.04	0.14	0.006	0.002
< 30km	8180	12538	0.11	0.57	0.024	0.006
< 50km	20667	47986	0.22	1.36	0.053	0.014
< 70km	97417	277682	1.03	8.48	0.333	0.088

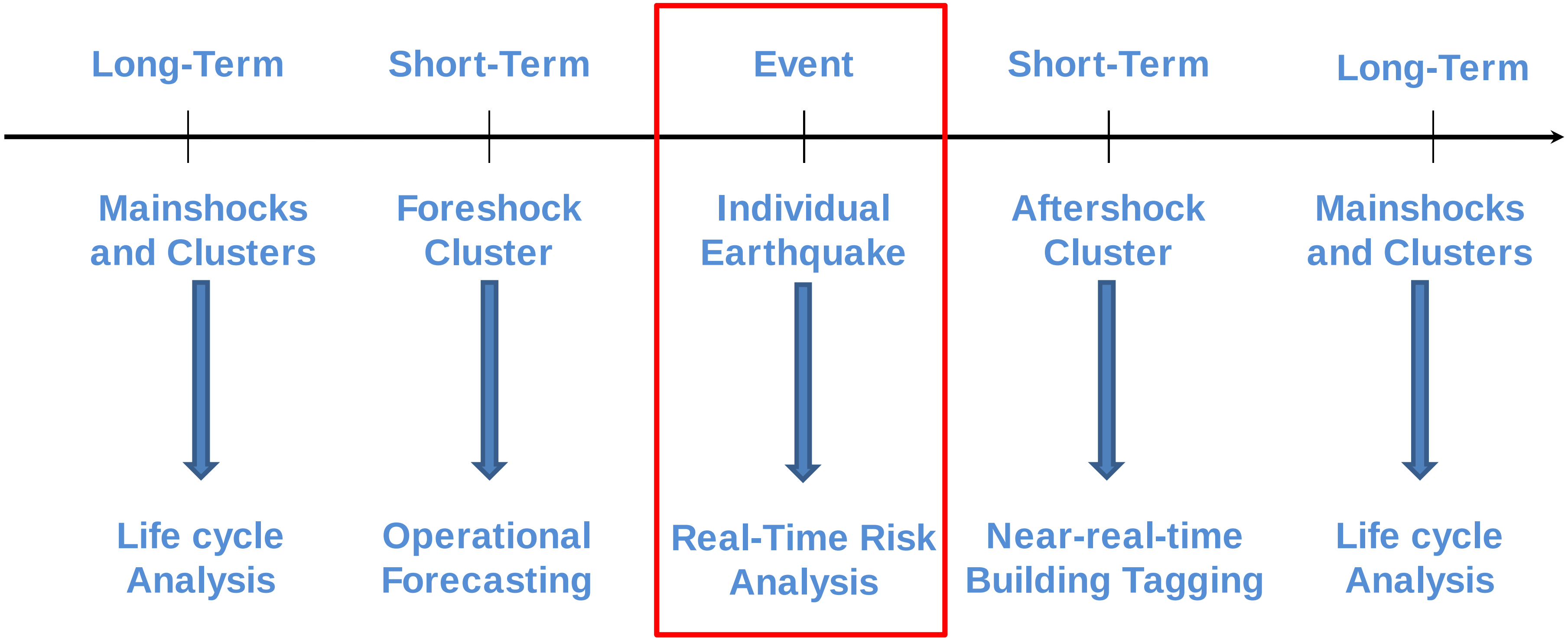
A critical retrospective analysis of OELF based on some recent Italian seismic sequences*





*Chioccarelli E., Iervolino I. (2015) Operational earthquake loss forecasting: a retrospective analysis of some recent Italian Seismic Sequences. *Bulletin of Earthquake Engineering.* DOI: 10.1007/s10518-015-9837-8

A possible scheme of seismic risk scales

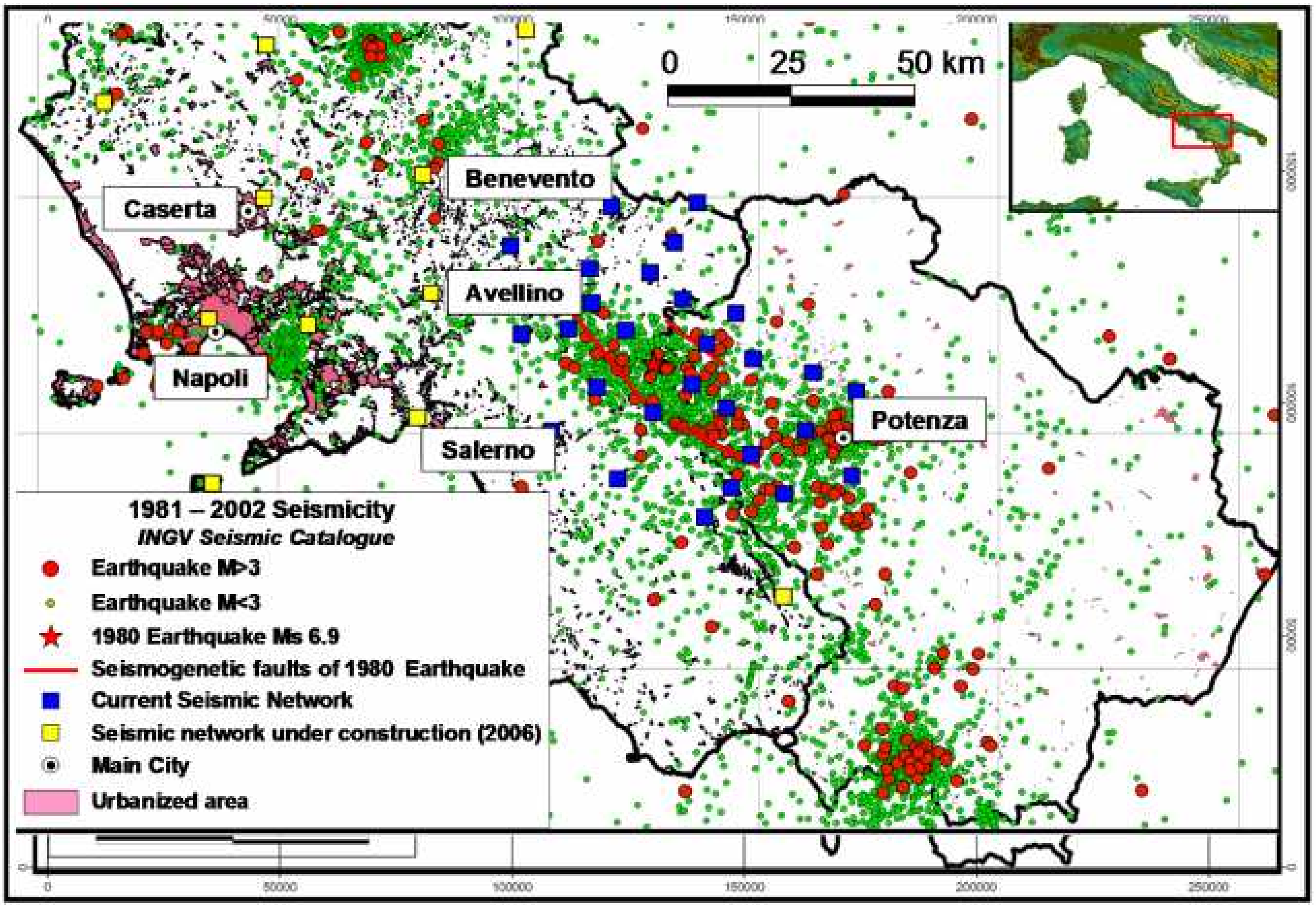


Basic elements of an EEW system*

1. A seismic sensor network with real-time capabilities;
2. An unit, local or central, to process the data of the sensor network and to eventually issue the alarm;
3. A transmission infrastructure to issue the warning to the structure, system, or community to alert;
4. An automated system aimed at risk reduction for structures.

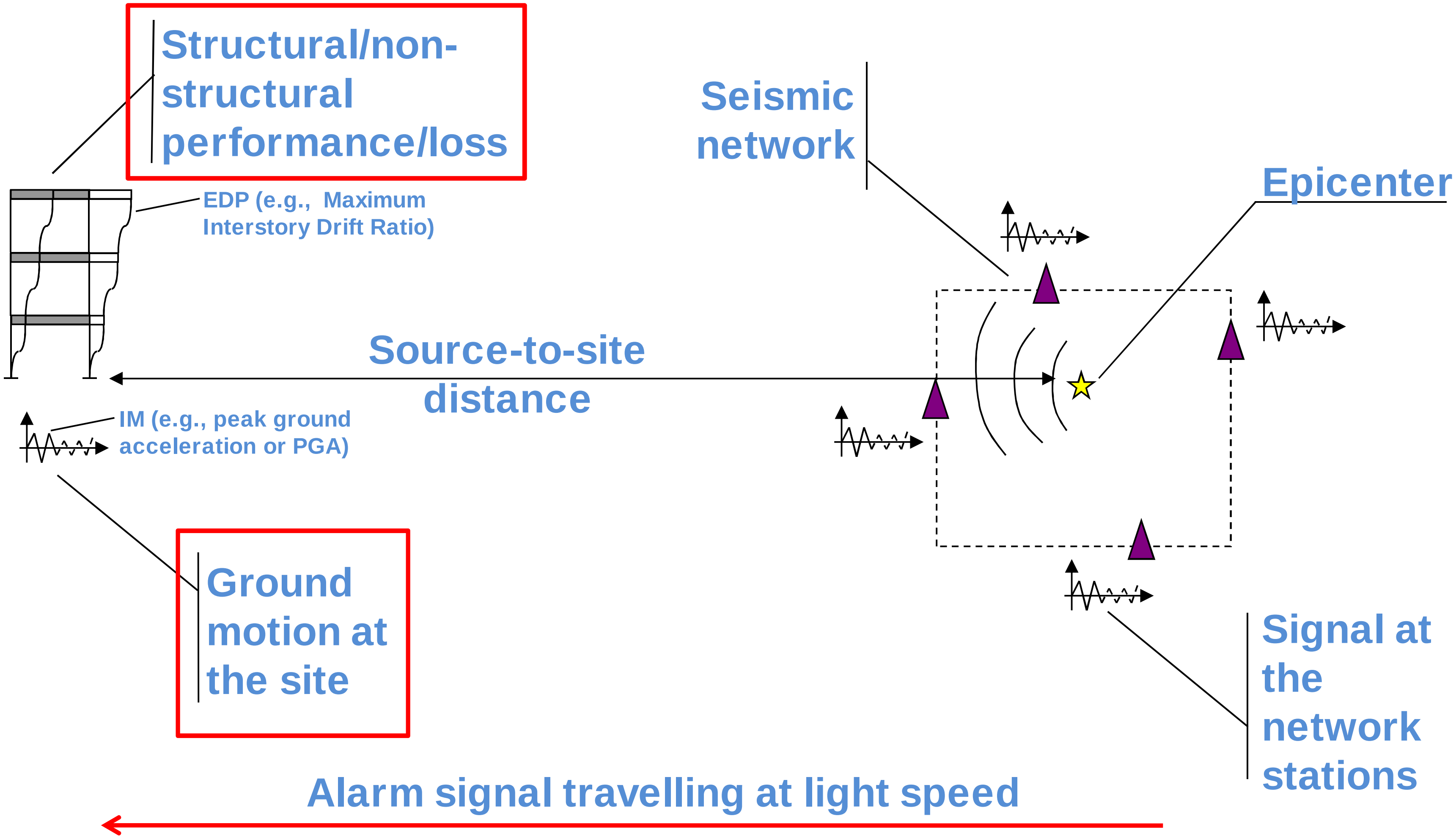
*Heaton, T. H. (1985). A model for a seismic computerized alert network. *Science*, *228*(4702), 987-990.

ISNet – Irpinia Seismic Network*



*Weber, E., et al. (2007) An advanced seismic network in the southern Apennines (Italy) for seismicity investigations and experimentation with earthquake early warning, *Seismol. Res. Lett.*, 78, 622–634.

Structure-specific early warning via regional seismic networks: problem statement



Lead Time = Seismic waves travel time after alarm issuance

This problem required a strong interdisciplinary approach of:

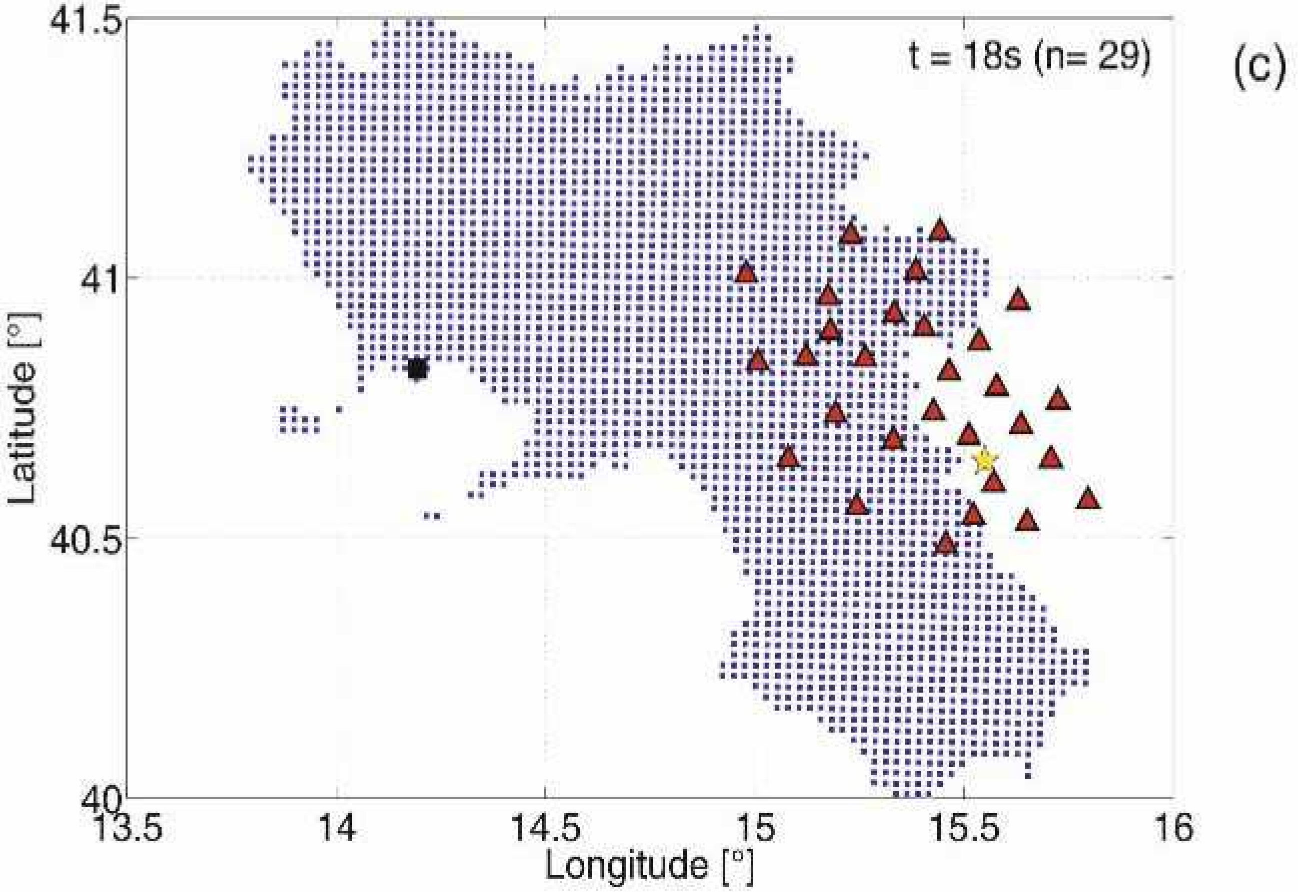
1) Seismologists for the real-time estimation of source features (***Real-Time Seismology***);

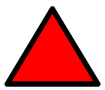
2) ICT specialists to enable real-time computation and transmission;

3) Earthquake engineers for the alarming decision and design of risk mitigation actions (***Performance-Based Earthquake Early Warning,* or PBEEW***).

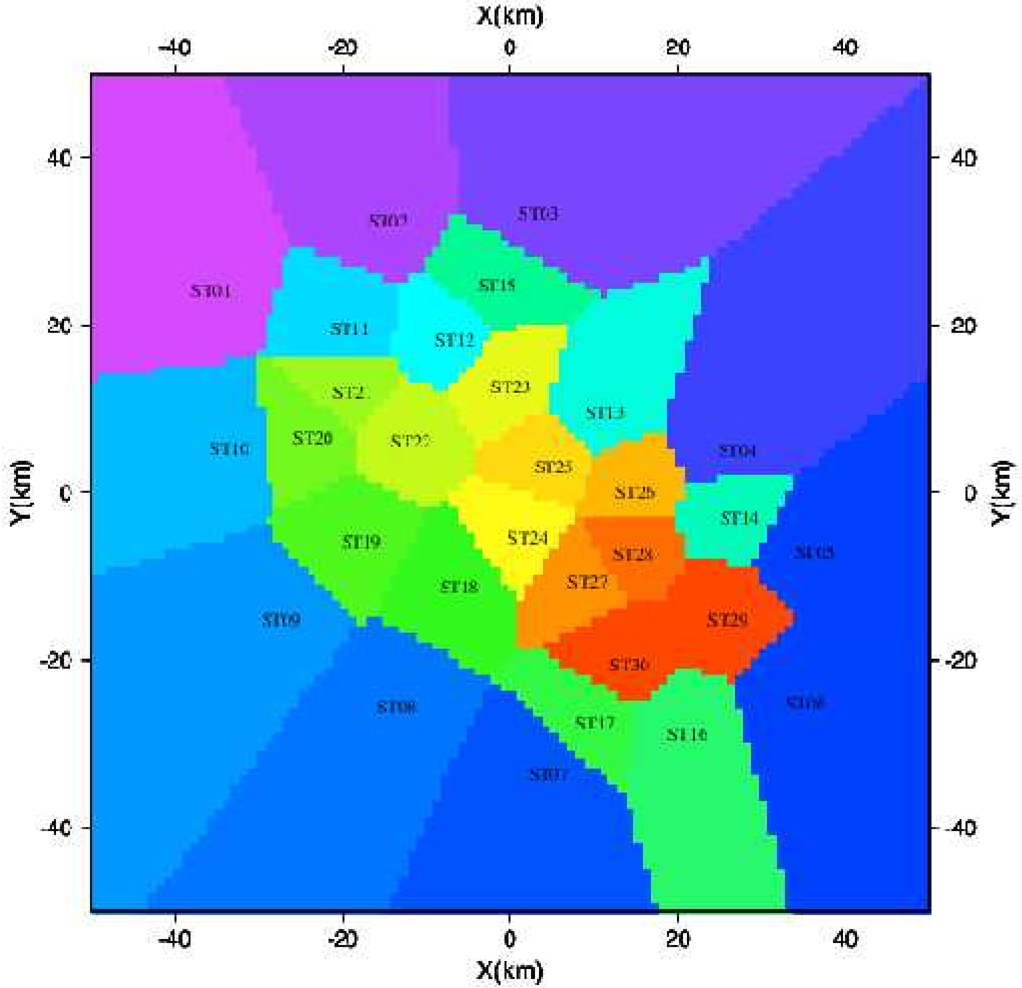
*Iervolino I. (2011) Performance-Based Earthquake Early Warning, *Soil Dynamics and Earthquake Engineering,* 31, 209-222.

Making use of real-time information to quantify uncertainty on earthquake magnitude: Bayesian updating



 = τ available

Real-time seismology: earthquake location (1)



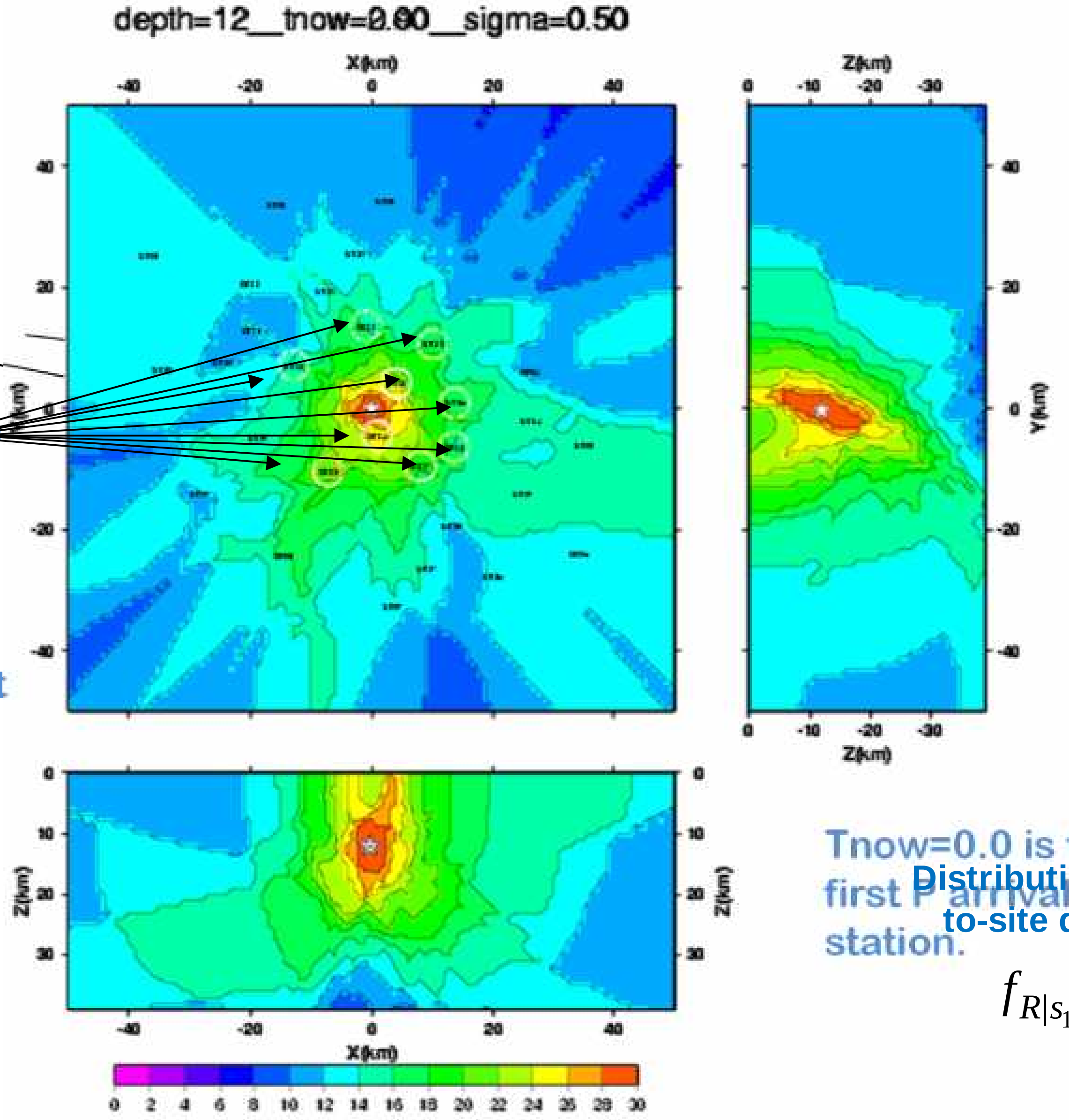
Voronoi cells approach provides the earthquake location given that the first P-wave arrival is recorded at the closest station.*

*Satriano, C., A. Lomax, and A. Zollo (2008), Real-time evolutionary earthquake location for seismic early warning, *Bull. Seismol. Soc. Am.*, 98, 1482–1494.

Real-time seismology: earthquake location (2)

Color is proportional to the probability of the hypocenter being coincident with the point

P wave arrival at the second station seconds from the arrival at the first station

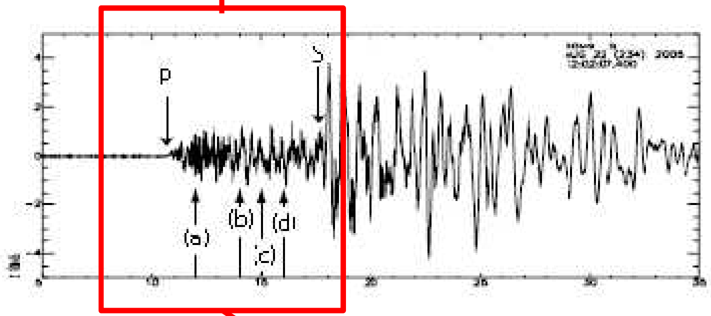


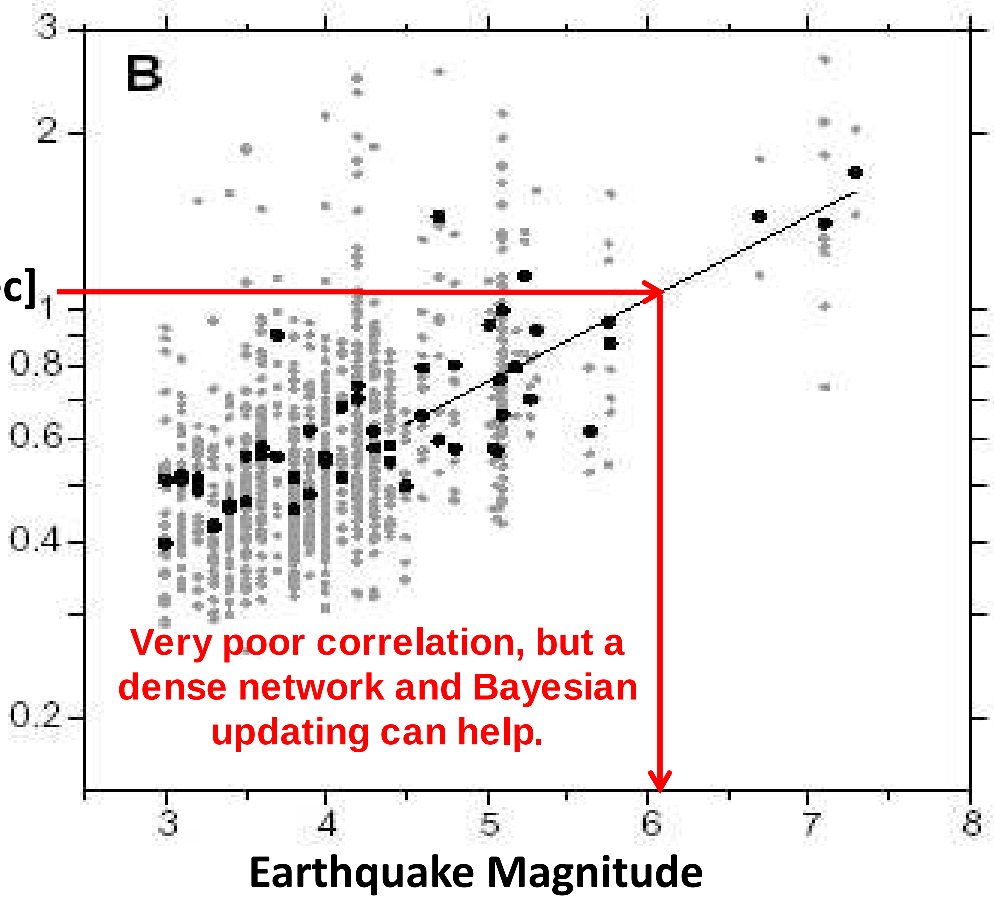
Tnow=0.0 is the time of the first P arrival at the closest station.

Distribution of source-to-site distance (R)

$$f_{R|s_1,s_2,\ldots,s_n}(r)$$

Real-time seismology: earthquake magnitude





Very poor correlation, but a dense network and Bayesian updating can help.

Seismologists* claim it is possible to estimate the magnitude from the first (4) seconds of the P-wave velocity recording

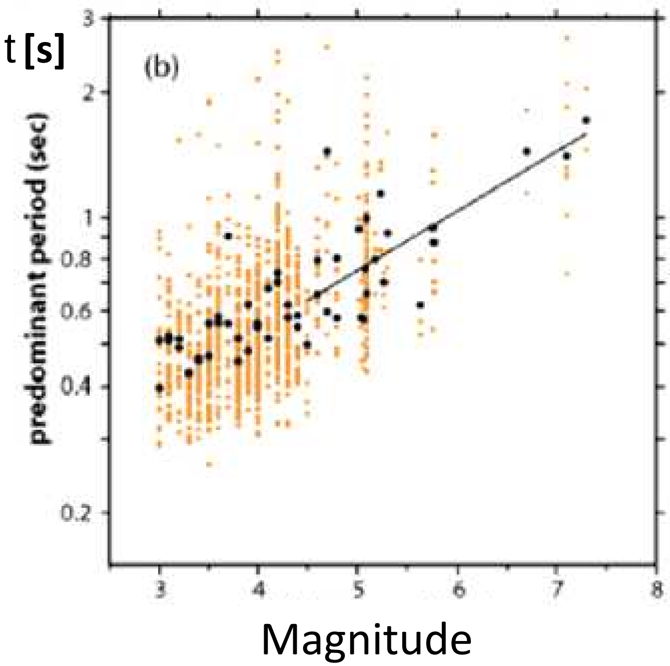
*Allen, R. M. and Kanamori, H. (2003) The potential for earthquake early warning in Southern California, *Science*, 300, 786–789.

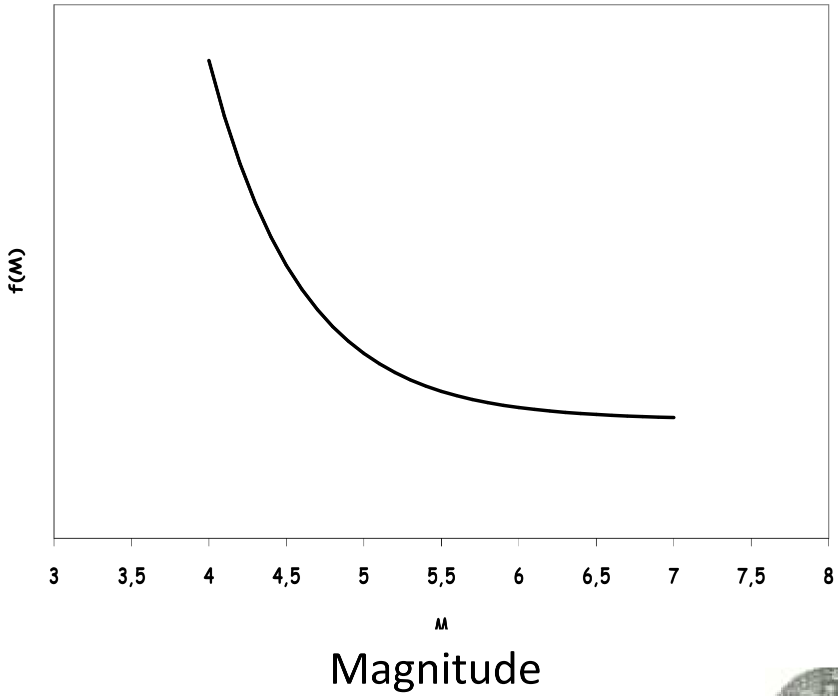
Making use of real-time information to quantify uncertainty on earthquake magnitude: Bayesian updating* (2)

$$f_{M|\underline{²}}(m) = c \cdot e^{\left(2\cdot«_{\log(²)}\cdot\left(\sum_{i=1}^{n}\ln(²_i)\right) - n\cdot«^2_{\log(²)}\right) \Big/ 2\cdot±^2_{\log(²)}} \qquad e^{-\;\;m} = f_{M|²}(m)$$

Real-Time measurements

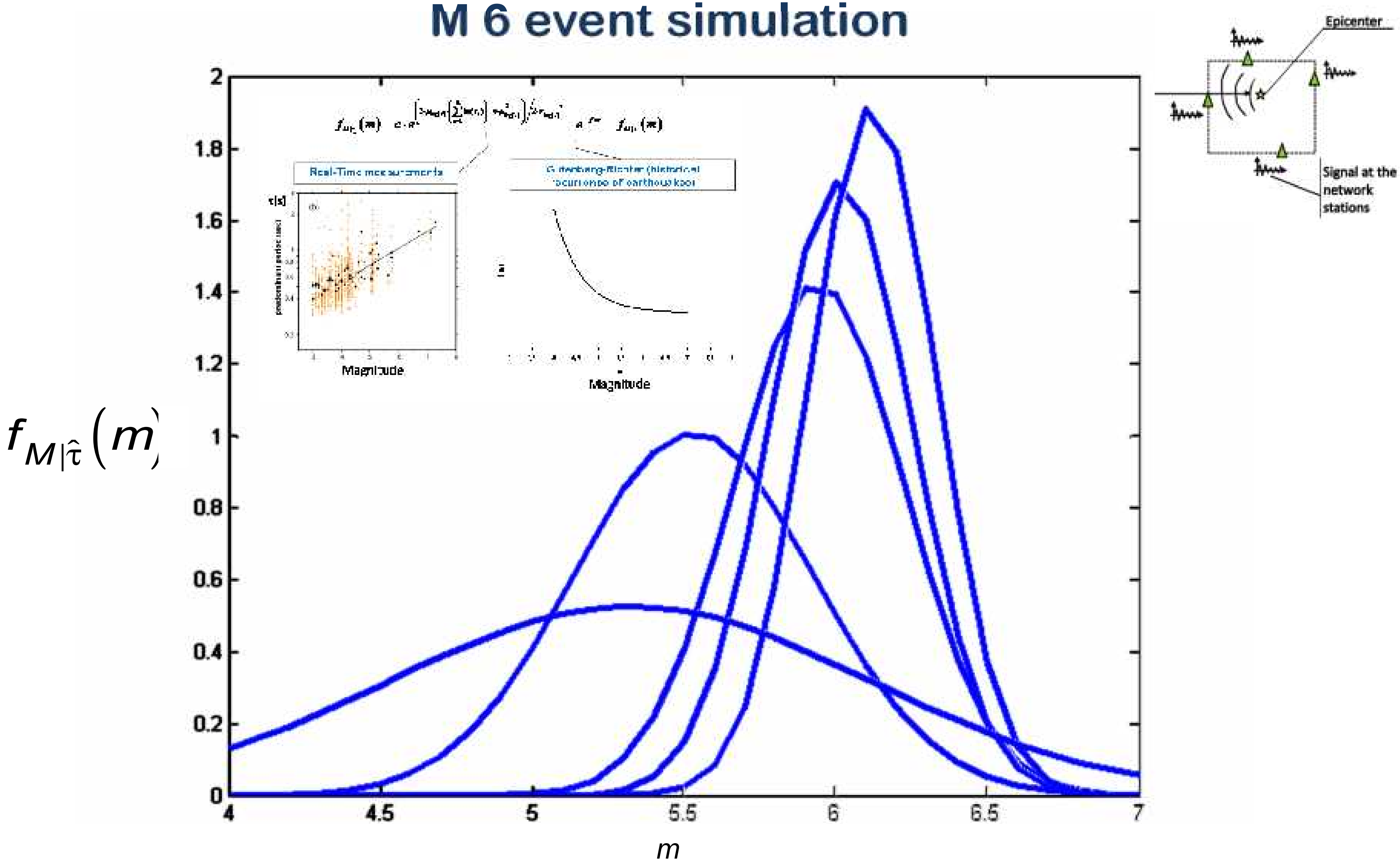
Gutenberg-Richter (historical recurrence of earthquakes)





*Iervolino, I., Giorgio, M., Manfredi, G. (2007). Expected loss-based alarm threshold set for earthquake early warning systems, *Earthquake Engineering and Structural Dynamics*, 36, 1151–1168.

M 6 event simulation



t = 12s

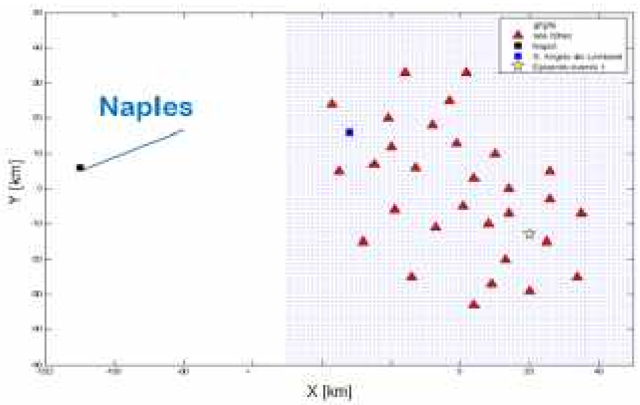
28 stations

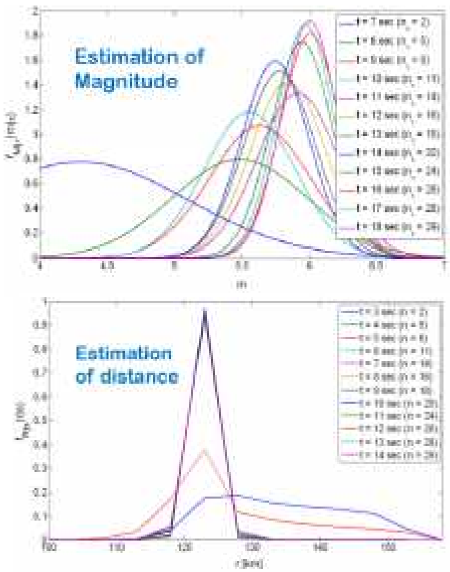
Real-Time Probabilistic Seismic Hazard Analysis (RT-PSHA)**

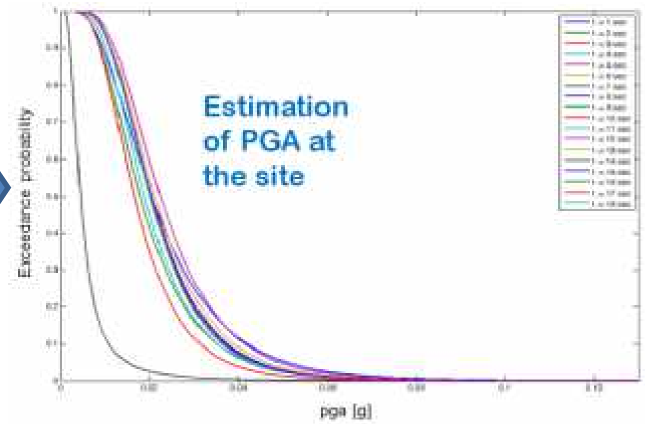
Real-Time probabilistic seismic hazard

$$P\left[PGA > pga \mid \underline{\tau}, \underline{s}\right] = \int_M \int_R P\left[PGA > pga \middle| M = m, R = r\right] \cdot f_{M|\tau_1,\tau_2,\ldots,\tau_n}(m) \cdot f_{R|s_1,s_2,\ldots,s_n}(r) \cdot dr \cdot dm$$

- **Distribution of PGA at the site conditional on the measures of the seismic instruments**
- **Ordinary Attenuation relationship**
- **Distribution of magnitude conditional on the real-time measures**
- **Distribution of source-to-site distance due to rapid localization method**

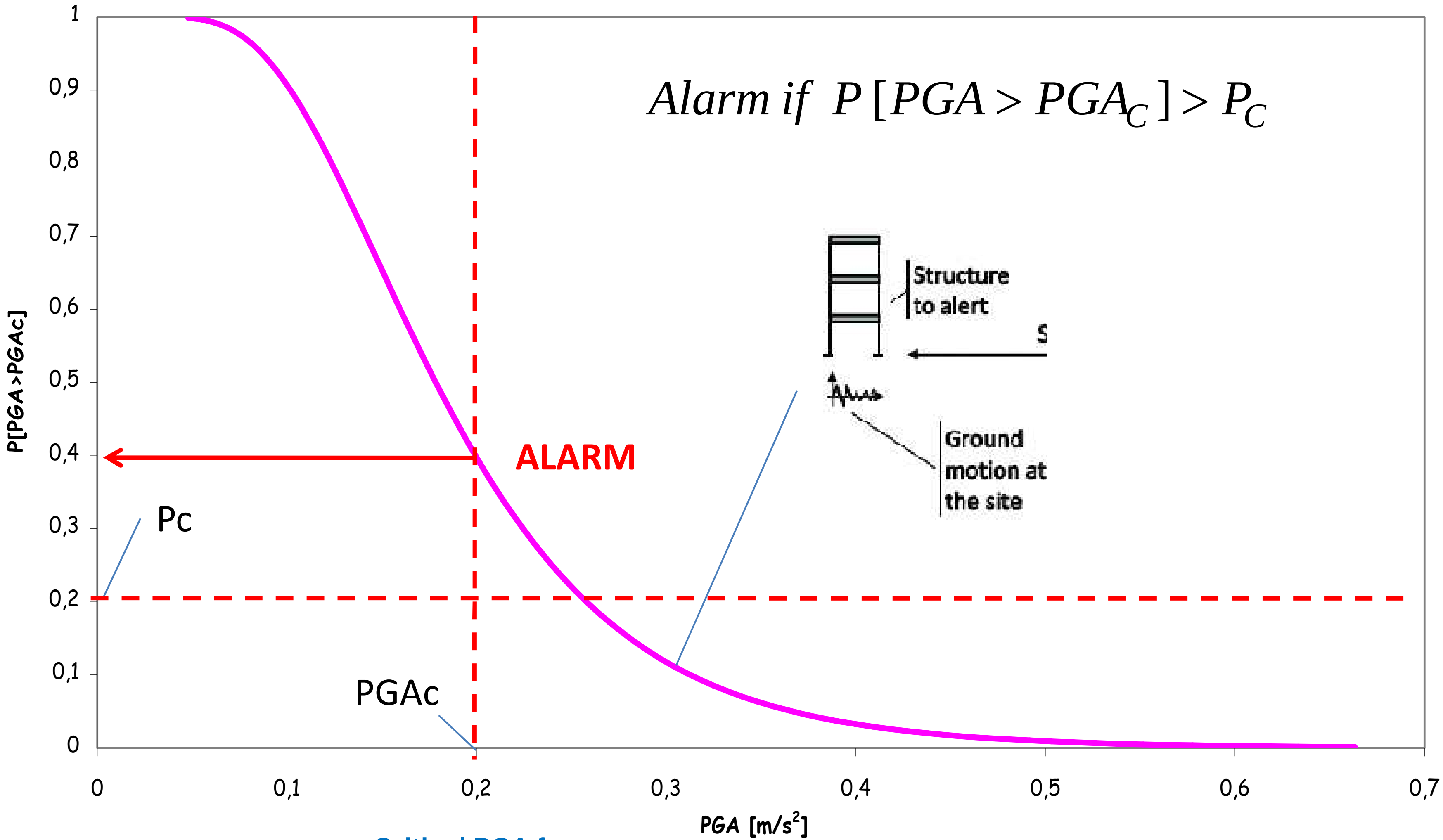






*Iervolino, I., Convertito, V., Giorgio, M., Manfredi, G., Zollo, A. (2006). Real-time risk analysis for hybrid earthquake early warning systems. *Journal of earthquake Engineering,* 10, 867–885.
**Convertito V., Iervolino I., Manfredi G., Zollo A. (2008) Prediction of response spectra via real-time earthquake measurements. *Soil Dynamics and Earthquake Engineering*, 28, 492–505.

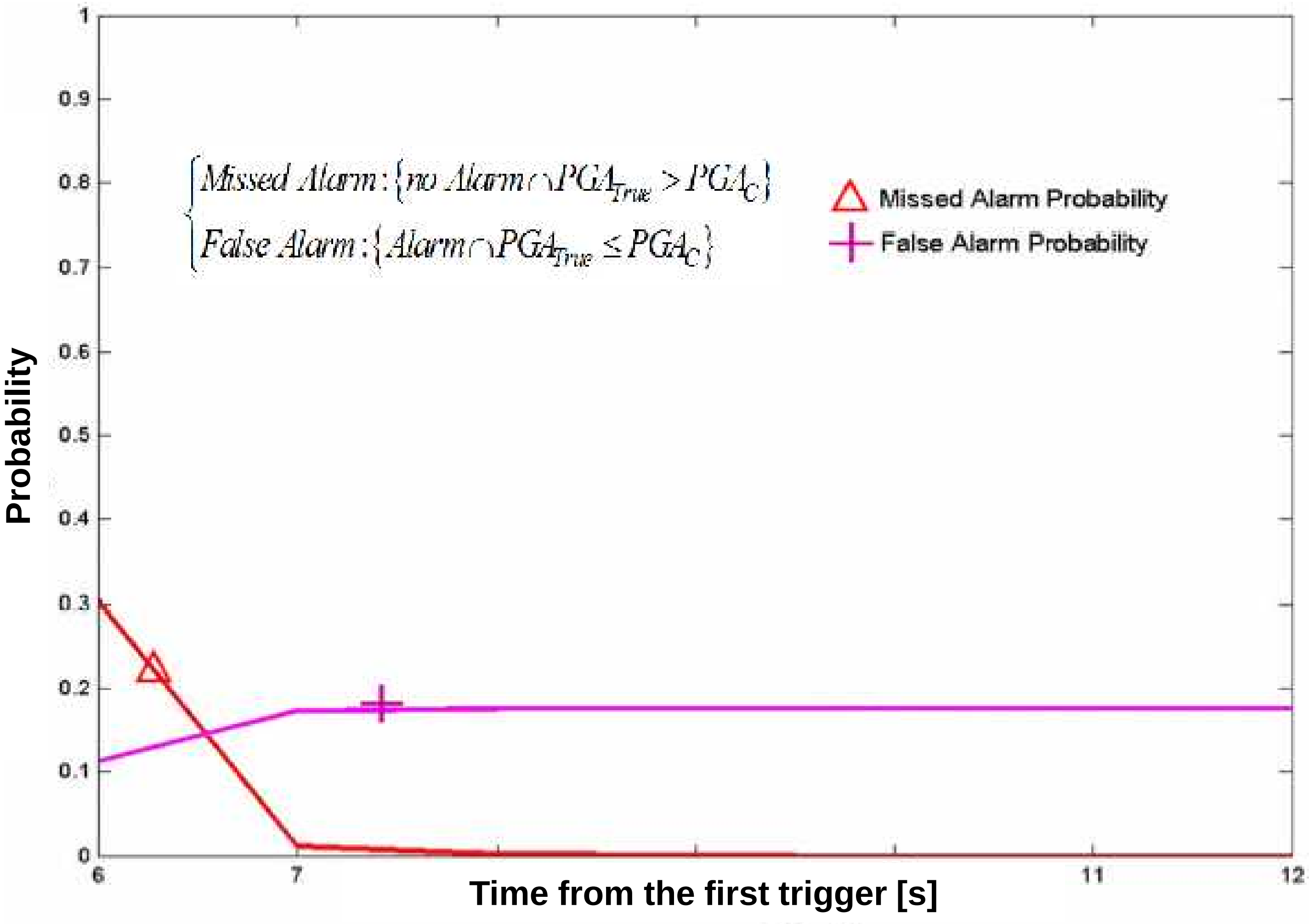
When to activate security measures?



Critical PGA for the Structure*

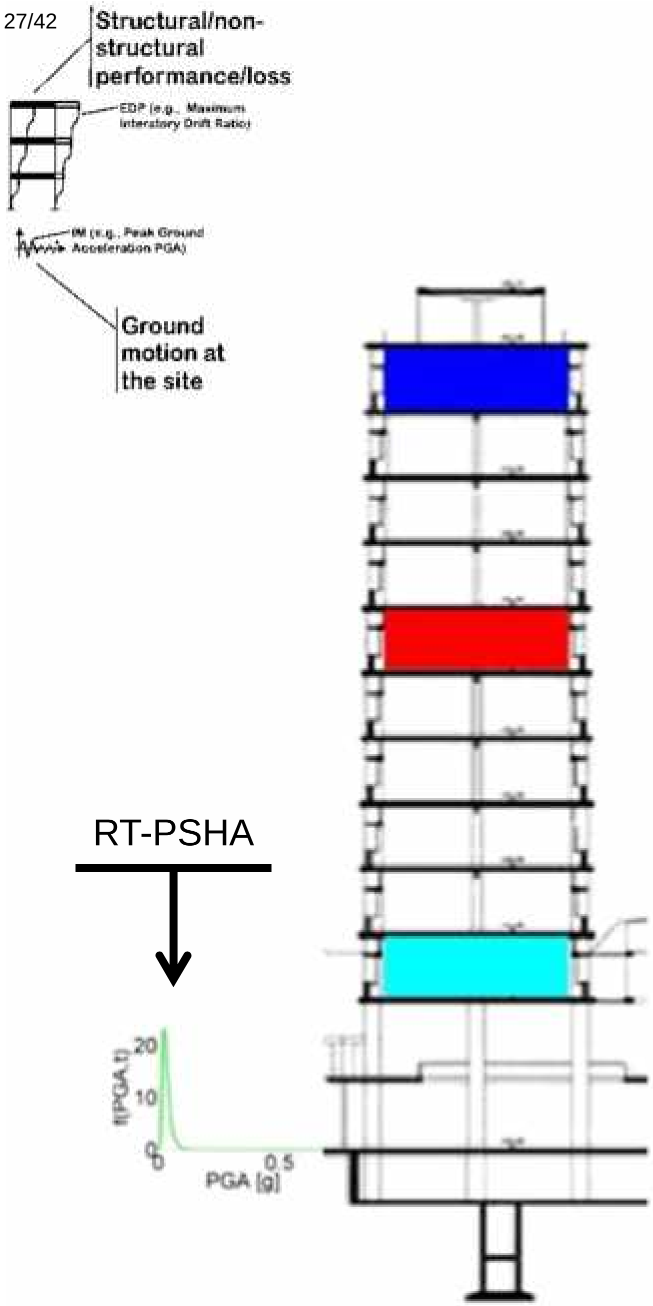
*Iervolino, I., Convertito, V., Giorgio, M., Manfredi, G., Zollo, A. (2006). Real-time risk analysis for hybrid earthquake early warning systems. *Journal of earthquake Engineering*, 10, 867–885.

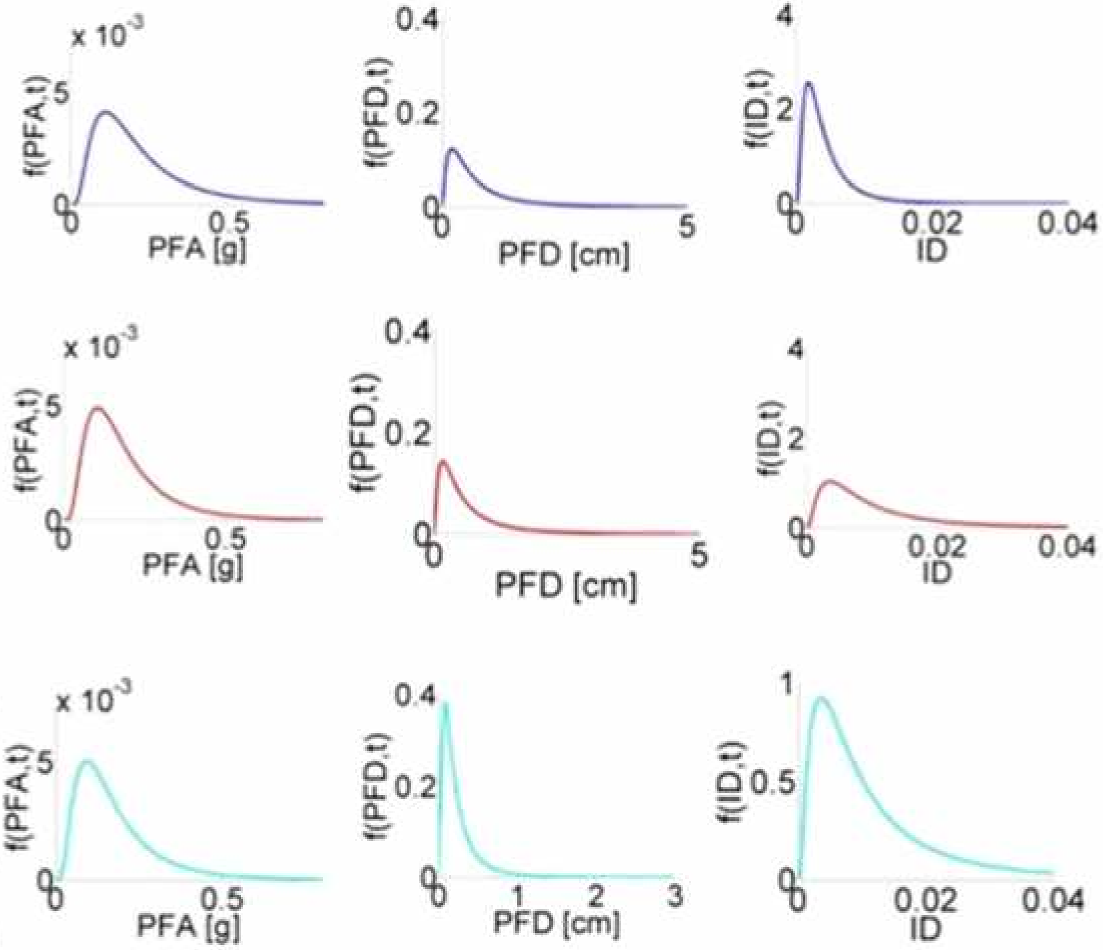
How missed and false alarms may be defined according to this approach?*



*Iervolino, I., Convertito, V., Giorgio, M., Manfredi, G., Zollo, A. (2006). Real-time risk analysis for hybrid earthquake early warning systems. *Journal of earthquake Engineering*, 10, 867–885.

$$f_{EDP|\hat{2}}\left(edp\right)=\int_{im} f_{EDP|IM}\left(edp\right)\cdot f_{IM|\hat{2}}\left(im\right)\cdot d\left(im\right)$$





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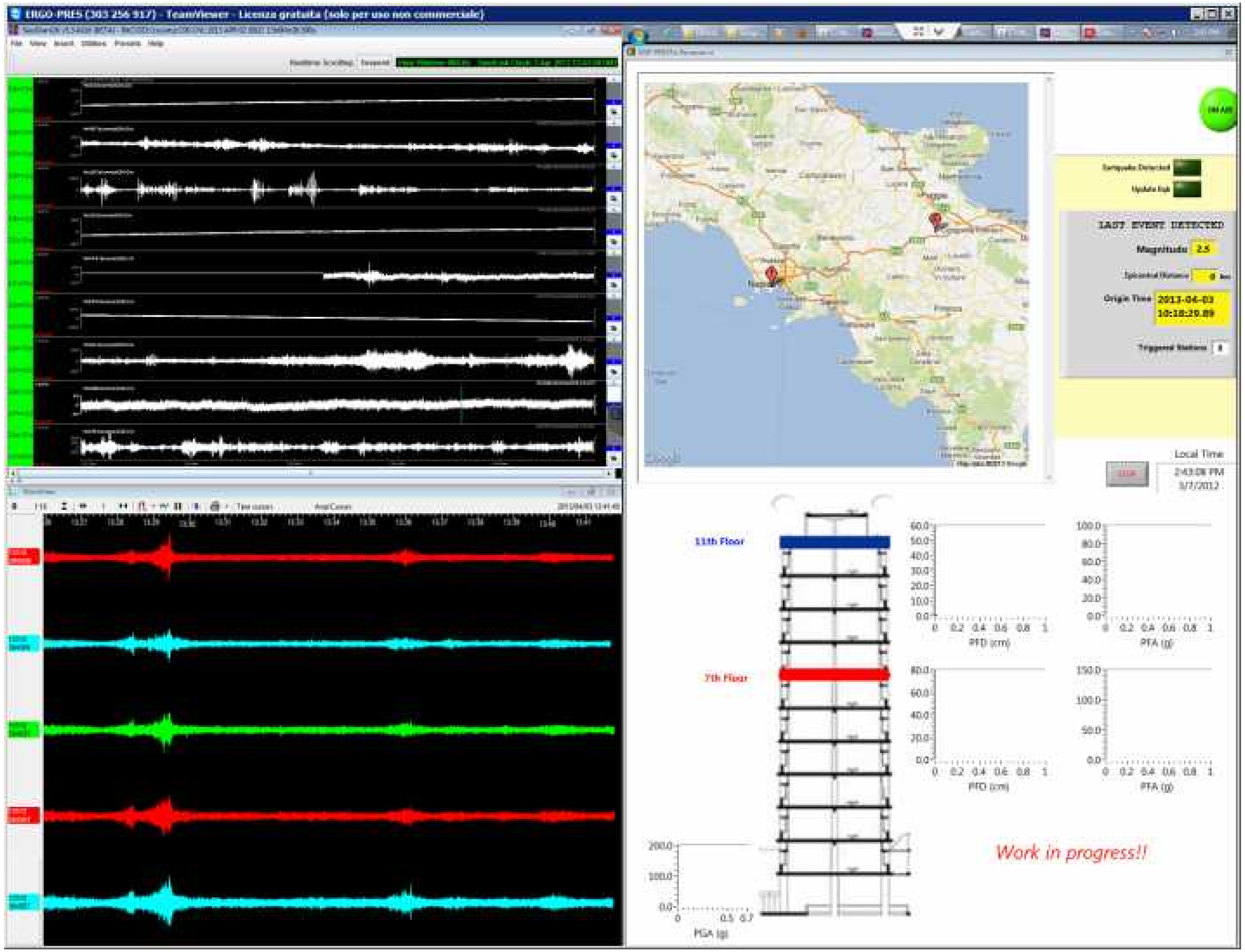
If you're looking at this slide it means the link with the actual system didn't work.

1. ISNet signals

2. Real-time seismology

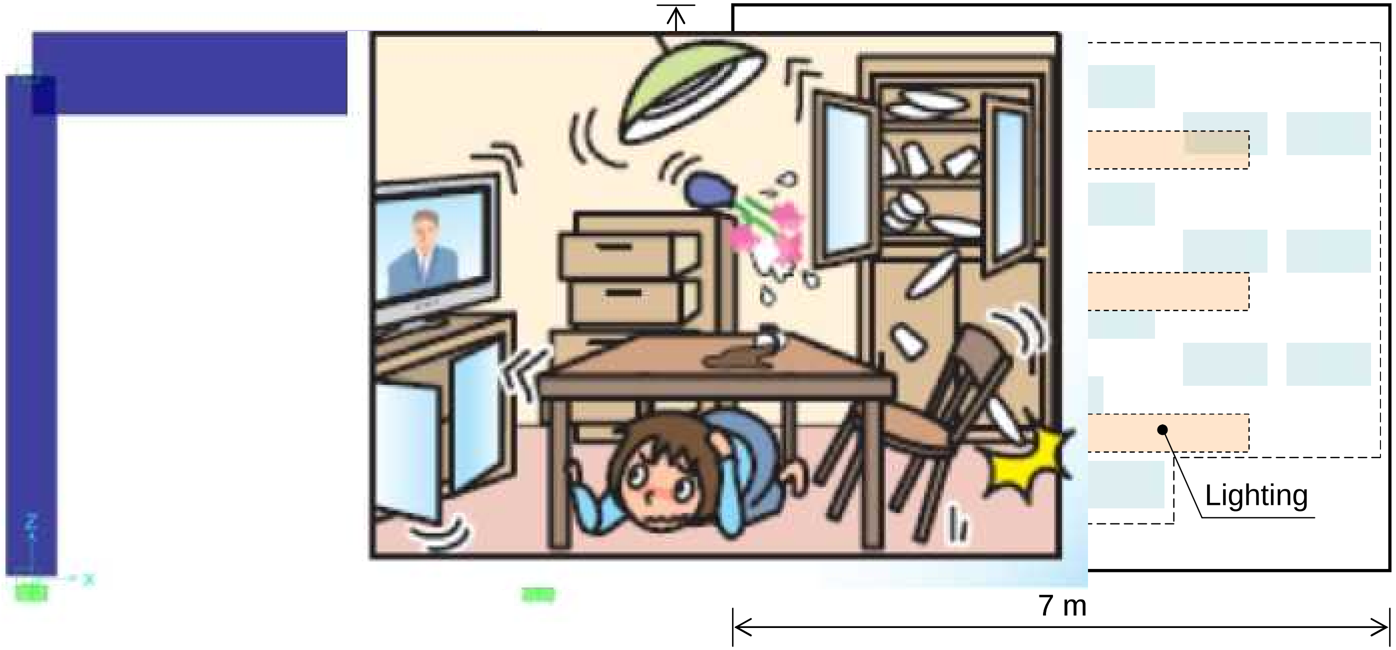


3. Real-time earthquake engineering (PBEEW)

4. On-site sensors (not part of the EEW system)

Iervolino I. (2011) Performance-Based Earthquake Early Warning, *Soil Dynamics and Earthquake Engineering.* 31(2): 209-222.

A classroom equipped with an EEW terminal



What causes loss? (assumptions)

a) Structural collapse (DS);

b) No structural damage, yet collapse of lighting (NDS);

c) No structural damage, no lighting damage, yet warning (loss due to false alarm);

d) No structural damage, no lighting damage, no warning, yet shaking felt (loss due to panic).

How the expected loss specializes for EEWS? *

Expected loss in the case of warning

$$E^{W}\left[L|\hat{\tau}\right]=E^{W}_{DS}\left[L|\hat{\tau}\right]+E^{W}_{DNS,\overline{DS}}\left[L|\hat{\tau}\right]+E^{W}_{\overline{DNS},\overline{DS}}\left[L|\hat{\tau}\right]$$

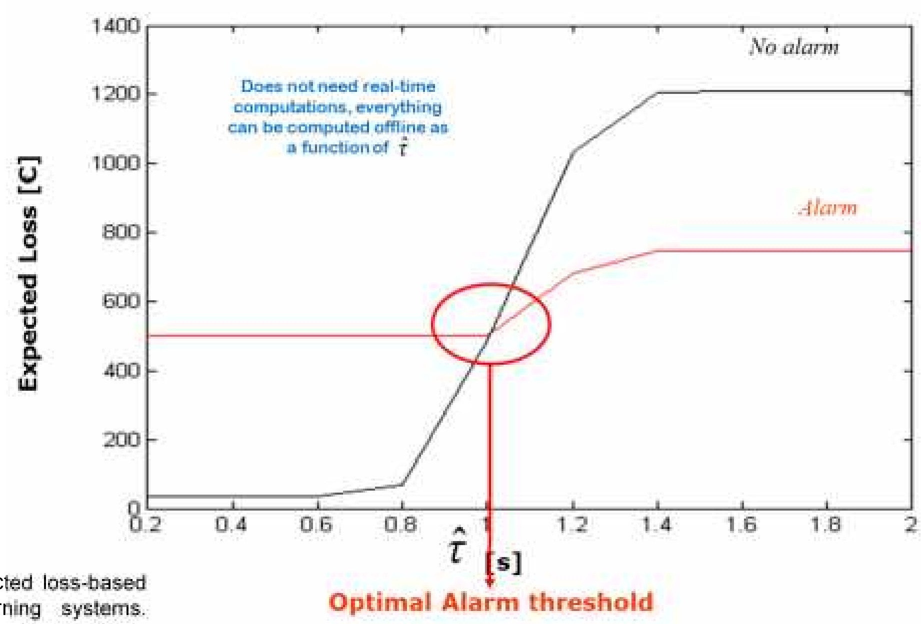
Loss due to structural collapse (independent of the alarming decision)

Loss due to collapse of non structural elements (reduced in the case of warning and security action initiated)

Loss in the case of no damage (cost of false alarm in the case of warning or cost of panic in the case of non-warning if ground motion is felt)

Expected loss in the case of non-warning

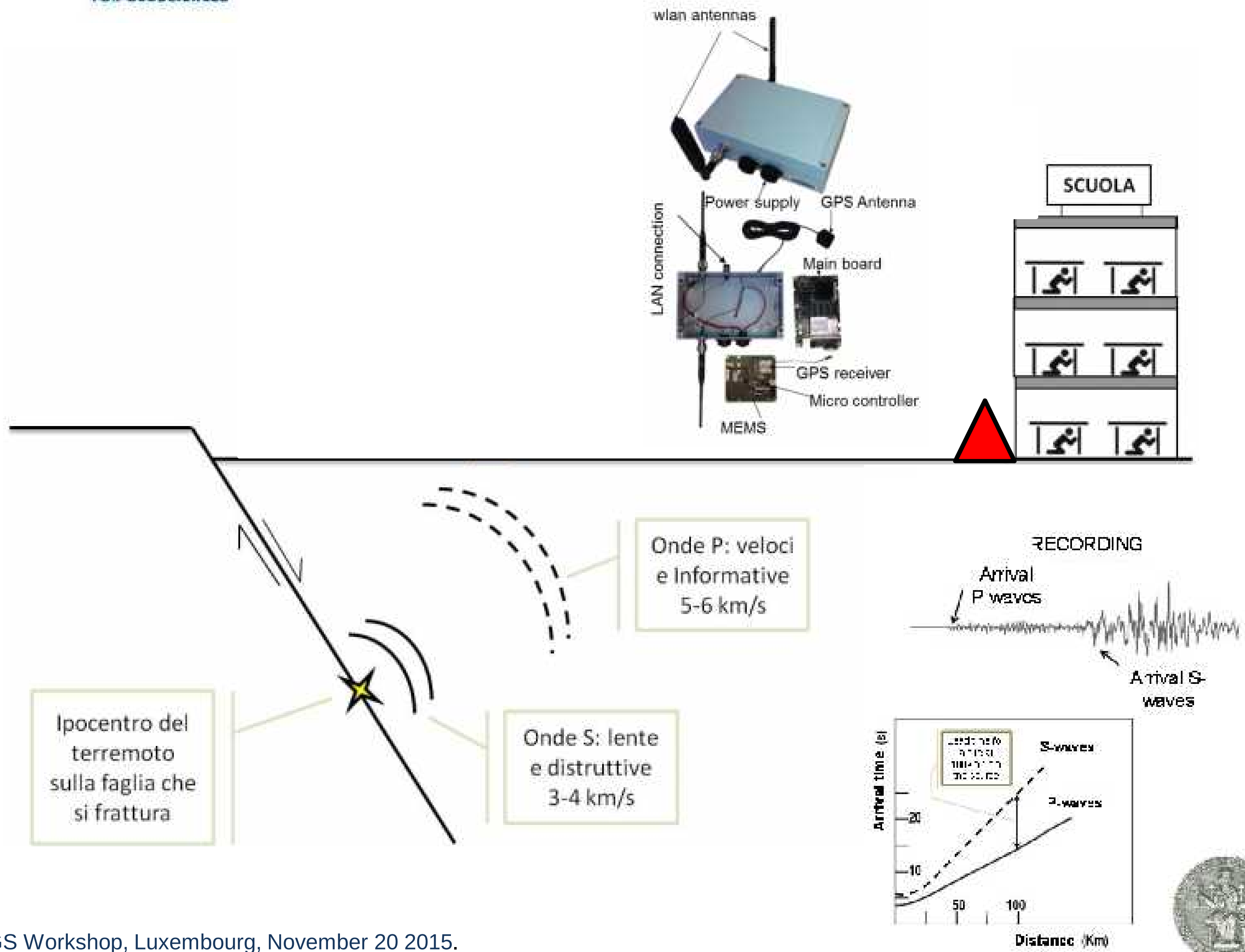
$$E^{\overline{W}}\left[L|\hat{\tau}\right]=E^{\overline{W}}_{DS}\left[L|\hat{\tau}\right]+E^{\overline{W}}_{DNS,\overline{DS}}\left[L|\hat{\tau}\right]+E^{\overline{W}}_{\overline{DNS},\overline{DS}}\left[L|\hat{\tau}\right]$$



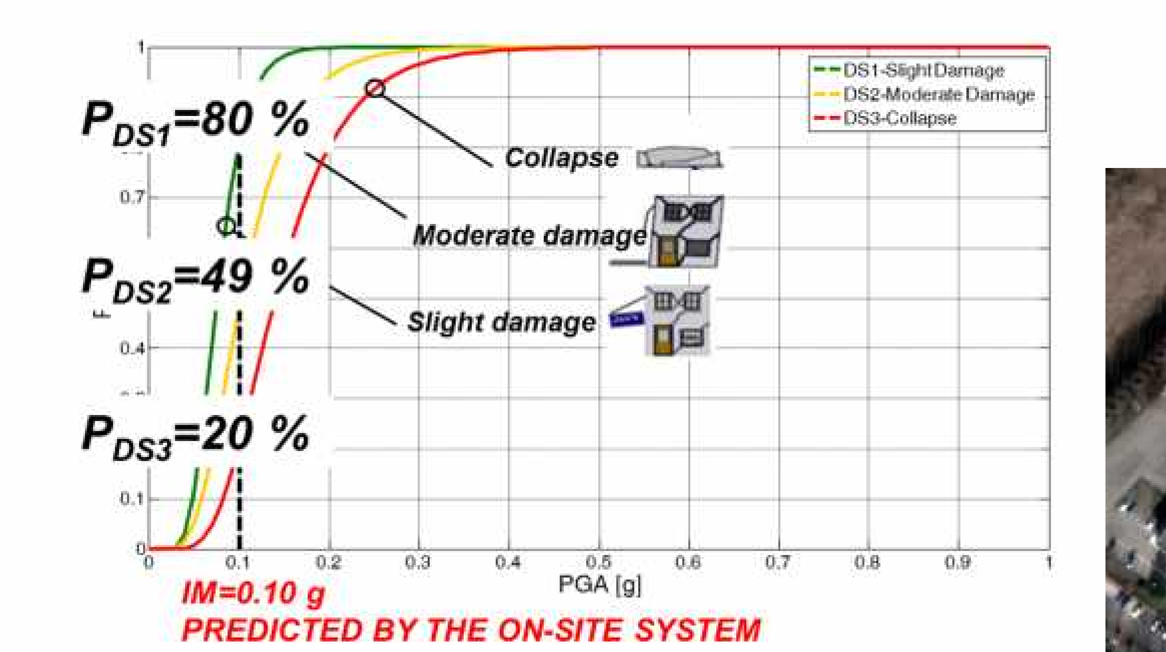
*Iervolino I., Giorgio M., Manfredi G. (2007). Expected loss-based alarm threshold set for earthquake early warning systems. *Earthquake Engineering and Structural Dynamics, 36, 1151–1168.*

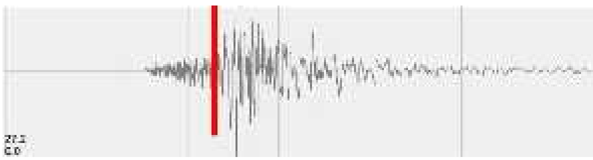
ISLAR (Industrial Seismic Loss Assessment and Reduction) project.

GFZ Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences



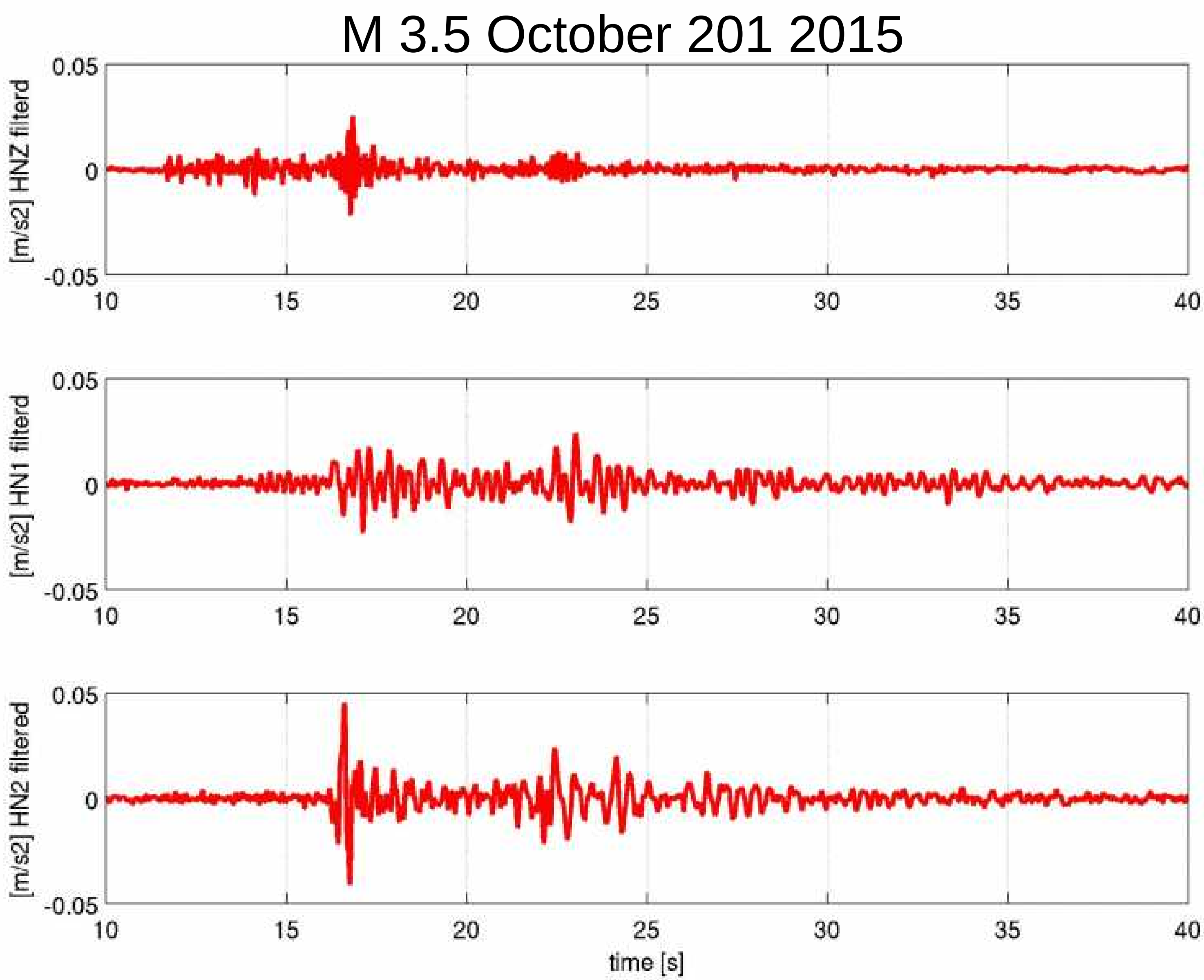
The Magneti Marelli (FCA Group) facility in Crevalcore



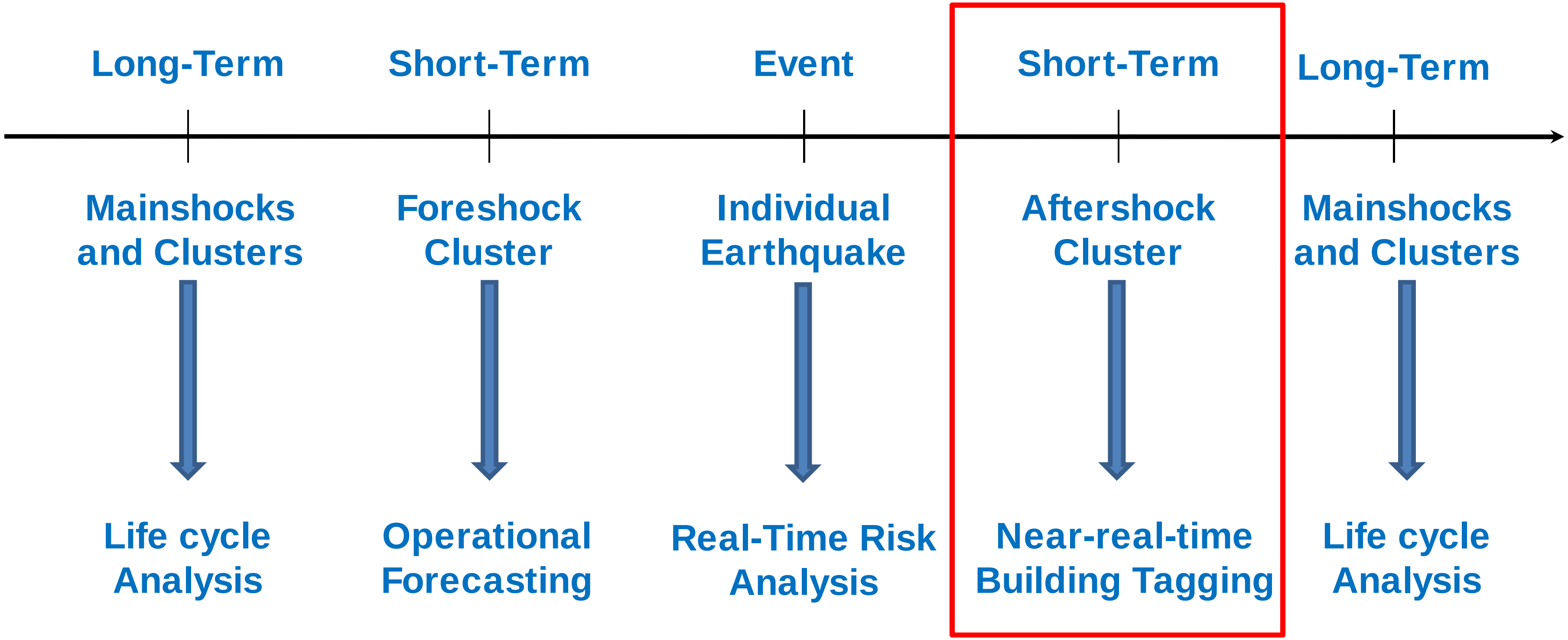


$$\begin{cases} \log(PGV) = 0.73\log(P_d) + 1.3 \\ \pm = 0.36 \end{cases}$$

*Bindi D., Boxberger T., Orunbaev S., Pilz M., Stankiewicz J., Pittore M., Iervolino I., Ellguth E., Parolai S. (2015) On-site early-warning system for Bishkek (Kyrgyzstan). *Annals of Geophysics*, 58(1): S0112; doi:10.4401/ag-6664.

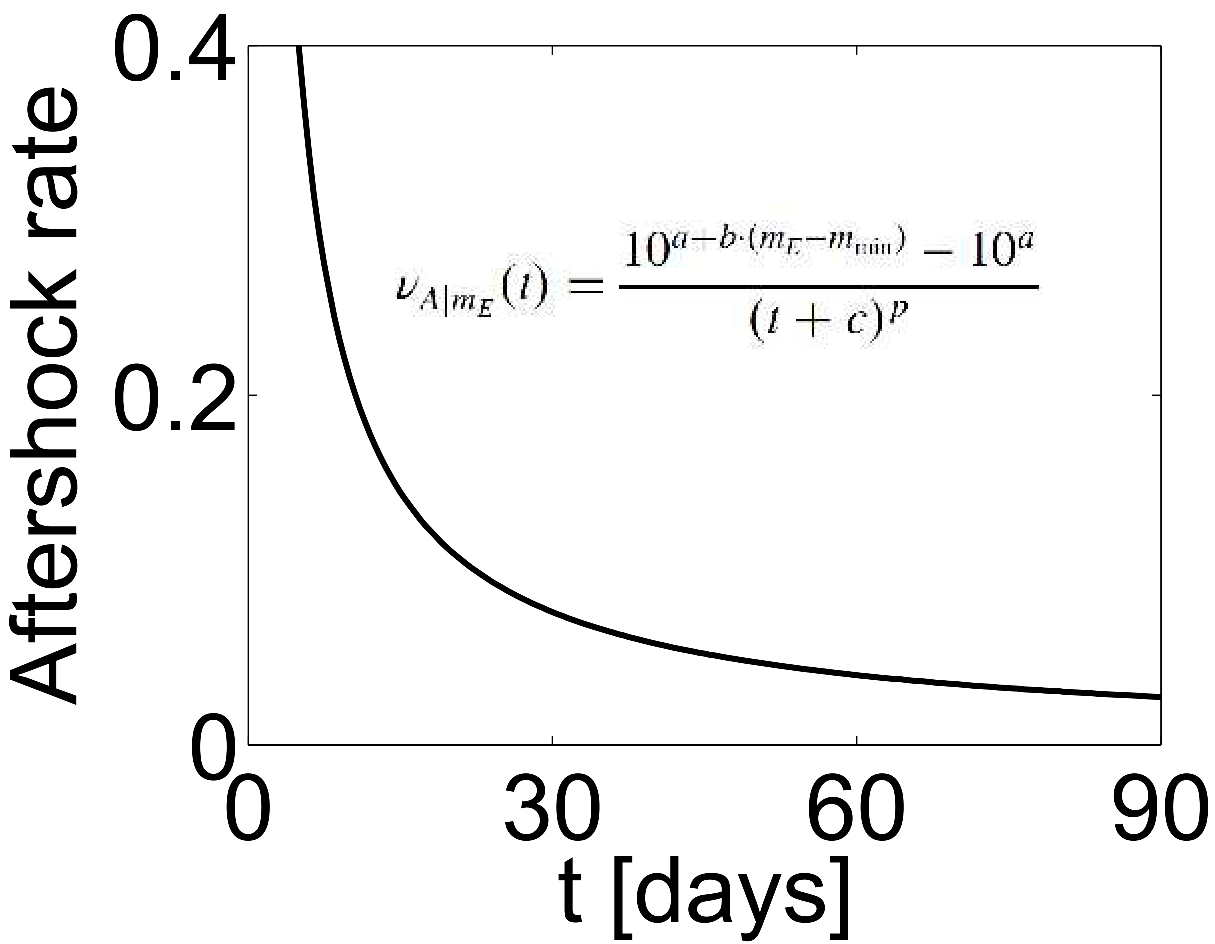

M 3.5 October 201 2015
[m/s2] HNZ filterd
[m/s2] HN1 filterd
[m/s2] HN2 filtered
0.05
0
-0.05
10 15 20 25 30 35 40
time [s]

A possible scheme of seismic risk scales

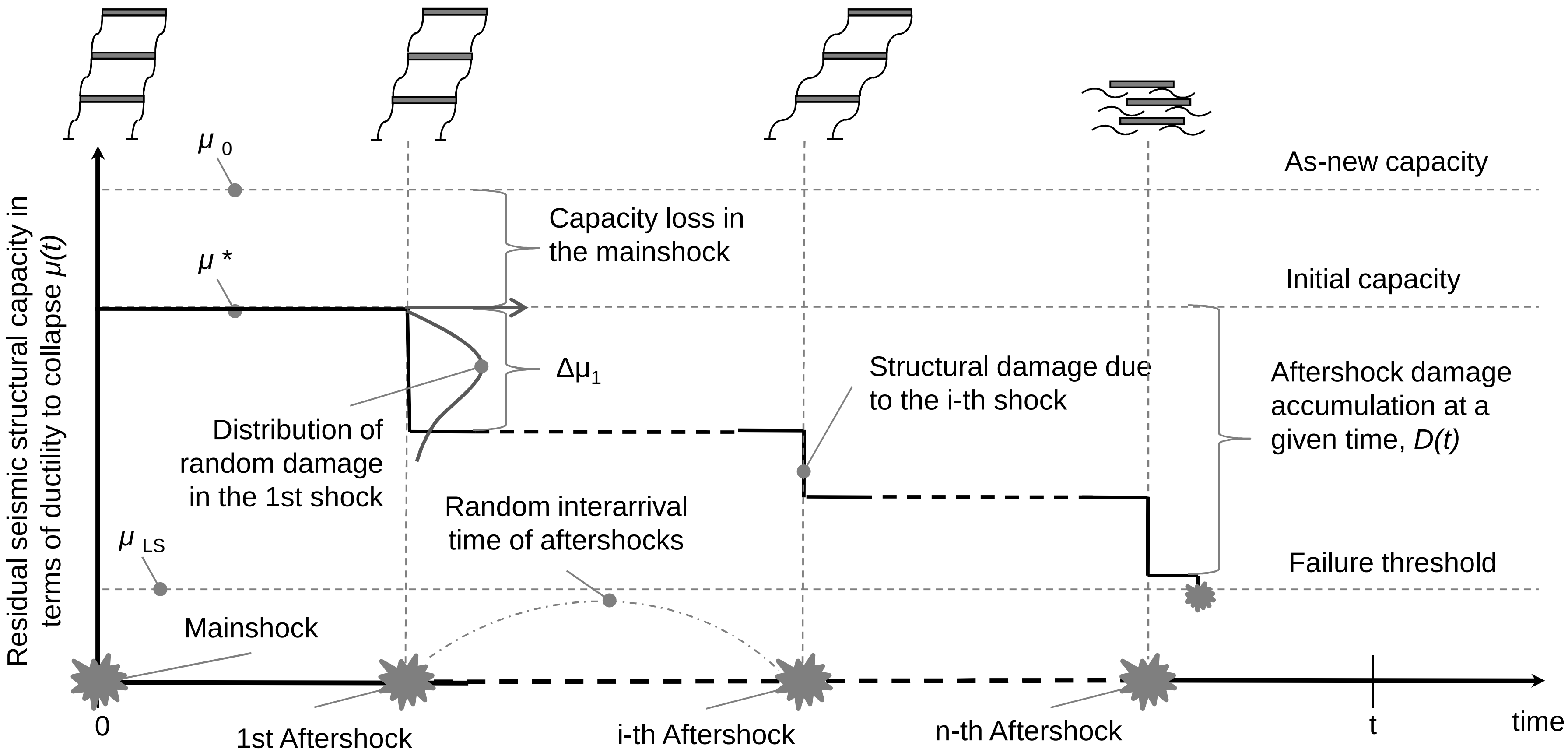


Background and motivation

- **Major earthquakes (i.e., mainshocks) typically trigger a sequence of lower magnitude events clustered both in time and space (aftershocks).**
- **Seismic hazard results (conditionally) increased for some weeks (or months).**
- **The structural systems of interest might have suffered some damage in the mainshock and, as a consequence, vulnerability may be increased.**

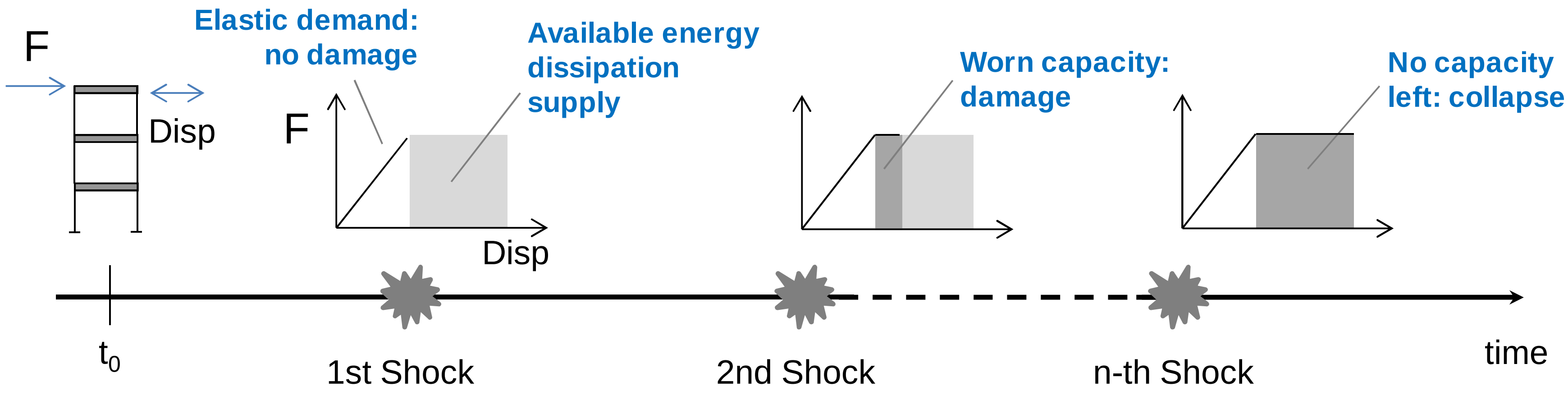


Short-term vulnerability* (1)



*Iervolino I., Giorgio M., Chioccarelli E. (2014) Closed-form aftershock reliability of damage-cumulating elastic-perfectly-plastic systems. *Earthquake Engineering and Structural Dynamics*, 43:613–625.

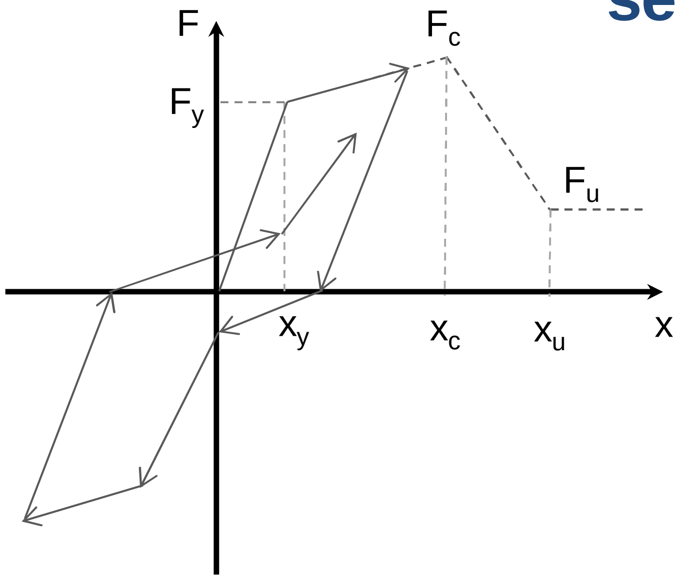
Short-term vulnerability* (2)

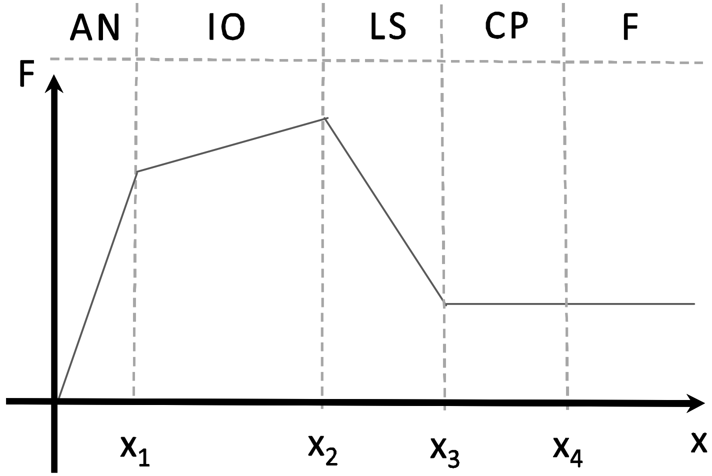


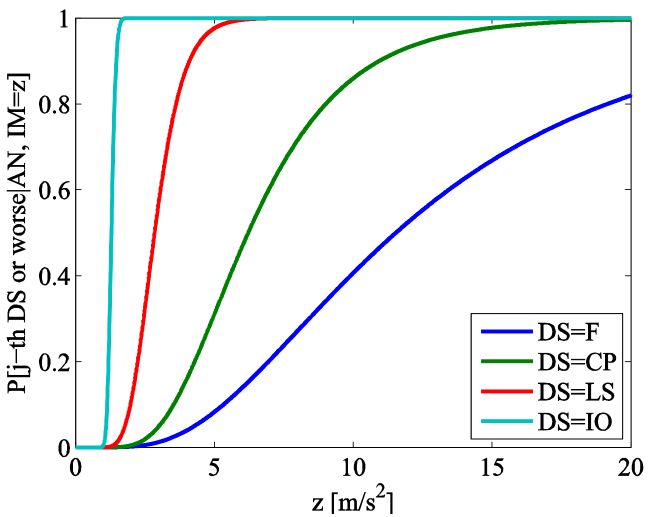
Because the structure has an available capacity, just like a battery. The mainshock and the aftershocks drain some of this capacity ‘until it is out of power’.

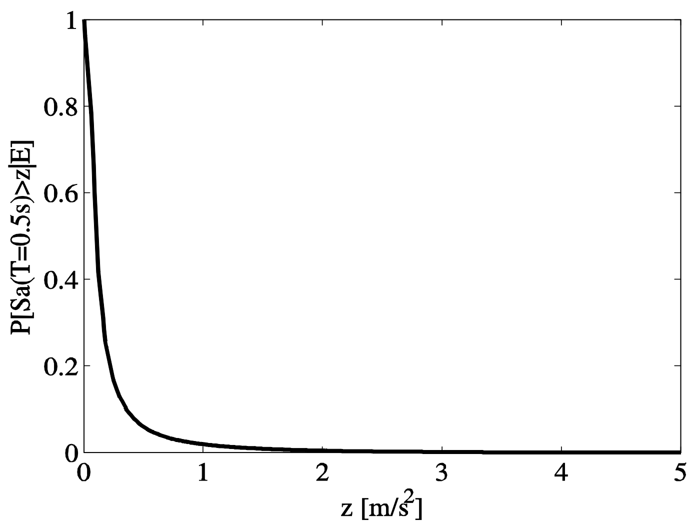
*Iervolino I., Giorgio M., Chioccarelli E. (2014) Closed-form aftershock reliability of damage-cumulating elastic-perfectly-plastic systems. *Earthquake Engineering and Structural Dynamics*, 43:613–625.

Modeling collapse risk during afterhock sequences* (1)



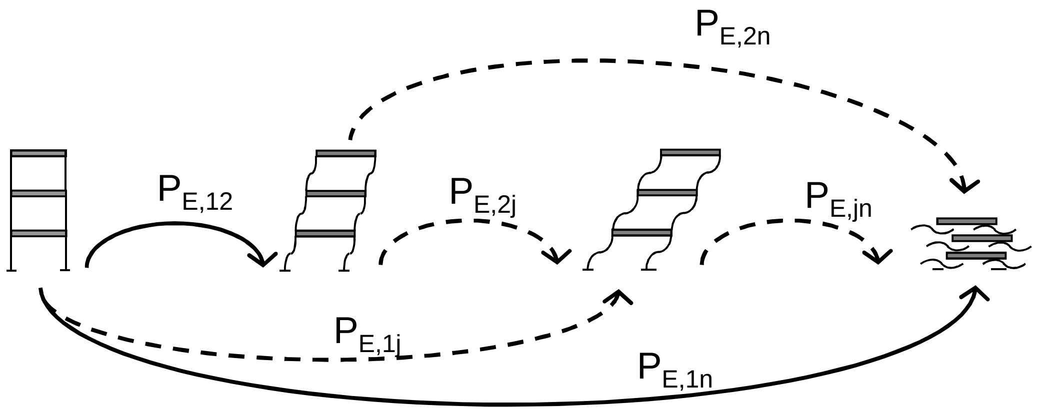






*Iervolino I., Giorgio M., Chioccarelli E. (2015) Markovian modeling of seismic damage accumulation. *Earthquake Engineering and Structural Dynamics.* DOI:10.1002/eqe.2668

Modeling collapse risk during afterhock sequences* (2)



$$[P_E(k,k+1)] = \begin{bmatrix} 1-\sum_{j=2}^{n} \nu_{A|m_E}(k)\cdot P_{1,j} & \nu_{A|m_E}(k)\cdot P_{1,2} & \cdots & \cdots & \nu_{A|m_E}(k)\cdot P_{1,n} \\ 0 & 1-\sum_{j=3}^{n} \nu_{A|m_E}(k)\cdot P_{2,j} & \cdots & \cdots & \nu_{A|m_E}(k)\cdot P_{2,n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \cdots & 0 & 1-\nu_{A|m_E}(k)\cdot P_{(n-1),n} & \nu_{A|m_E}(k)\cdot P_{(n-1),n} \\ 0 & \cdots & \cdots & 0 & 1 \end{bmatrix}$$

Rows: IO, LS, CP, F — Columns: IO, LS, CP, F

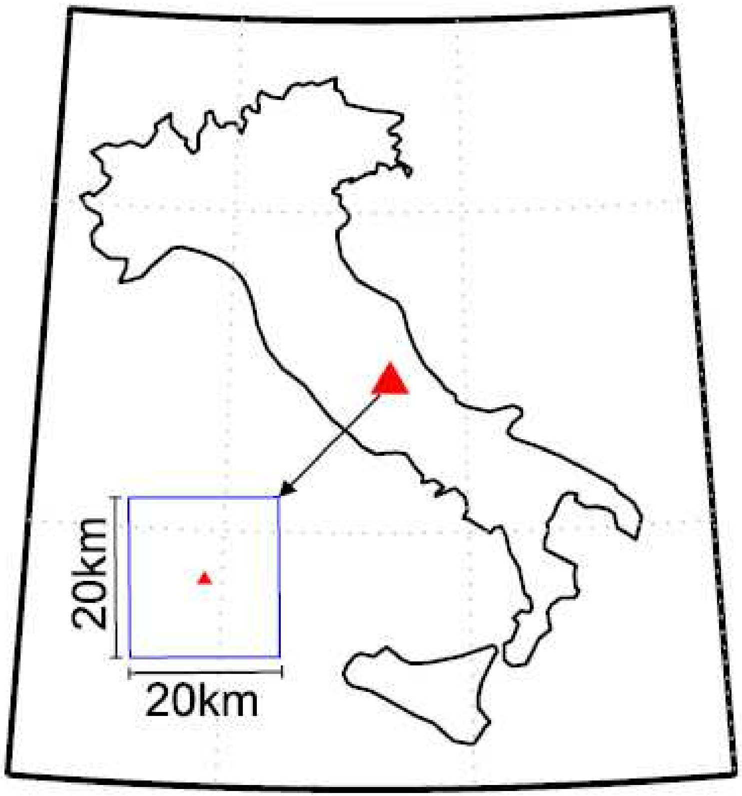
$$P_{i,j} = \int_{im} P[j-th\ \ state\ \ |i-th\ \ state \cap IM = z]\cdot f_{IM|E}(z)\cdot dz$$

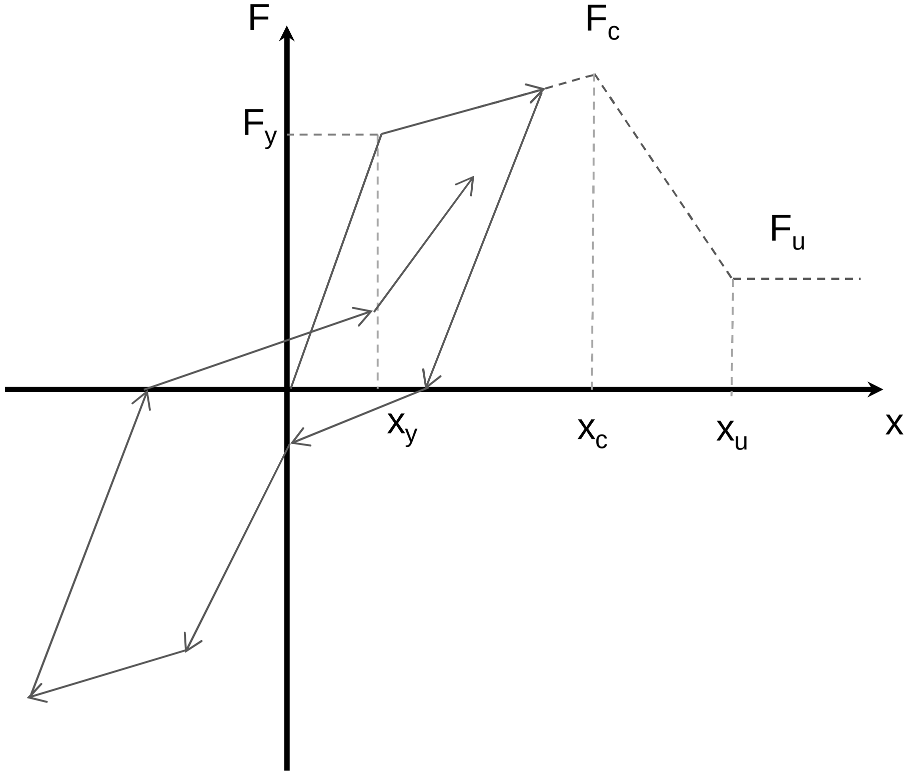
Unit-time transition matrix given by:

1. **Aftershock occurrence rate (Omori);**
2. **Distribution of ground motion intensity (IM) in one generic aftershock (from APSHA);**
3. **State-dependent fragility curves.**

*Iervolino I., Giorgio M., Chioccarelli E. (2015) Markovian modeling of seismic damage accumulation. *Earthquake Engineering and Structural Dynamics.* DOI:10.1002/eqe.2668

Distribution of ground motion intensity (spectral acceleration) of a generic aftershock of a M 6.3 mainshock in a generic location





Right before (foreshock management) | During (Real-Time) | Right after (aftershock management)

Summary

1. We have discussed **reconcilable** performance-based earthquake engineering models at three time-scales **(shortly before, during, and shortly-after)**;

2. **Operational earthquake loss forecasting** is feasible in Italy based on large-scale vulnerability and exposure data, and using as an input seismicity rates from OEF;

3. **Earthquake early warning** is a feasible and economically viable solution to reduce in real time the seismic risk **reducing the exposure** of the system of interest;

4. **Aftershock risk management** of damage cumulating structures is gaining attention because its potential of **reducing the business interruption** in those system (factories) where indirect earthquake loss are more important than direct structural damage costs;

5. All the discussed models are part of current European attempt to improve competencies to deal with seismic risk in a long-term effort to improve **resilience of European communities to earthquakes.**

Performance-based earthquake engineering *before*, *during*, and *after* a mainshock

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ECGS – Luxembourg , November 20 2015.