CRS Seminar 2019

Bridging the gap between engineering seismology and earthquake engineering

"Tutto quello che avreste voluto sapere sulla sismologia applicata all'ingegneria, ma non avete mai osato chiedere…"

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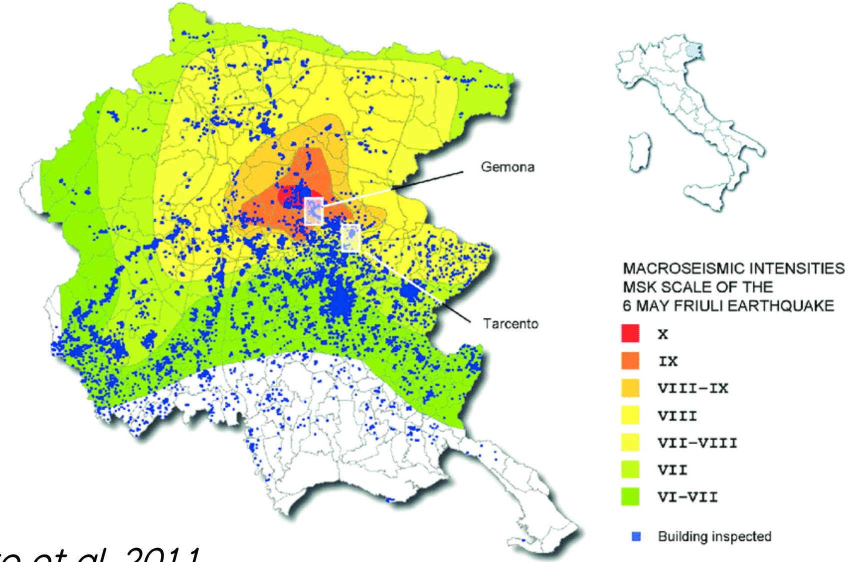
Seismological Research Center (CRS)
National Institute of Oceanography and Applied Geophysics (OGS)

The Seismological Research Center

The 1976 Ml 6.5 Friuli earthquake is known as one of the major devastating events in Italy in the last century, causing 989 victims, about 100.000 destroyed or severely damaged houses and more than 200.000 homeless people.



Slejko et al. 2011

Gemona del Friuli

Messaggero Veneto

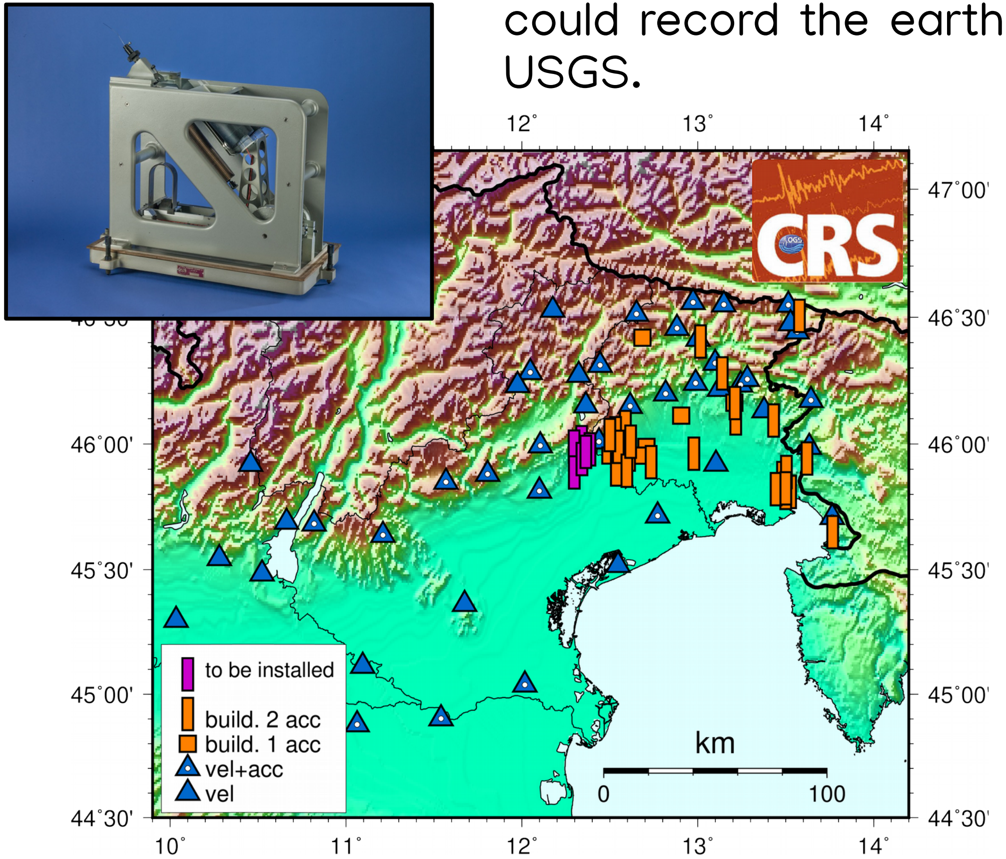
Catastrofico terremoto in Friuli

ALLE 21 UNA SCOSSA SISMICA DELL'OTTAVO GRADO DELLA SCALA MERCALLI HA DEVASTATO MAIANO, BUIA, GEMONA, OSOPPO, MAGNANO, ARTEGNA, COLLOREDO, TARCENTO, FORGARIA, VITO D'ASIO E MOLTI ALTRI PAESI DELLA PEDEMONTANA - GENEROSA OPERA DI SOCCORSO PER ESTRARRE LE VITTIME DALLE MACERIE - A UDINE E IN TUTTI I CENTRI DELLA REGIONE UNA NOTTE DI PAURA E DI VEGLIA ALL'APERTO - L'ALBA CI MOSTRA I SEGNI DELL'IMMANE DISASTRO

The CRS Network

Ewing-Press seismometer (20 seconds)

At the time, there was only one instrument in the region that could record the earthquake, installed in 1906 in Trieste by USGS.



As a followup, in 1977, the regional seismometric network was initiated, while the Seismological Research Centre (CRS) was instituted in 1982 in Udine, subsequently integrated as department of OGS (1991).

During the decades, a dense network of strong motion sensors has been created, that now allows to locate earthquakes and issue alerts in an automatic manner.

Interaction with Civil Protection

The Civil Protection was born after the experience of the special commissioning of the Friuli region, when it played a central role in managing the reconstruction.

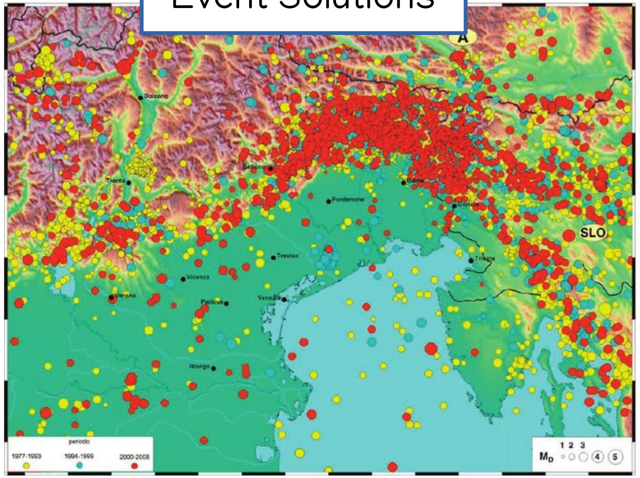
Historically, the CRS has supported the Civil protection, in particular in the regional seismic surveillance activities, by issuing alerts, event solutions (magnitude, location, focal mechanism) and preliminary ground shaking estimates

REGIONE AUTONOMA FRIULI · VENEZIA GIULIA
PROTEZIONE CIVILE
zivilschutz
protection civile
civil defence

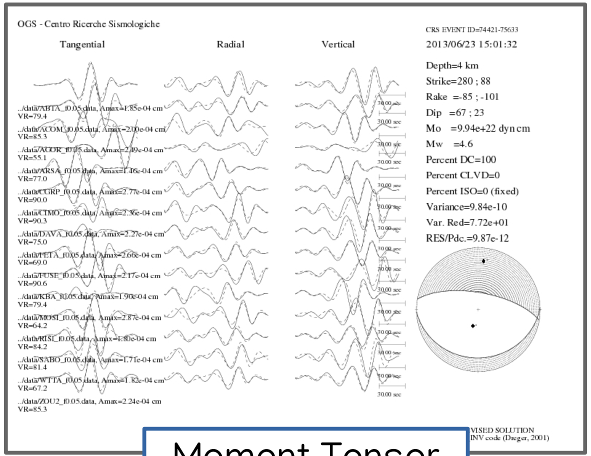
Protezione Civile
Regione Autonoma Friuli Venezia Giulia

CRS Seismological Products

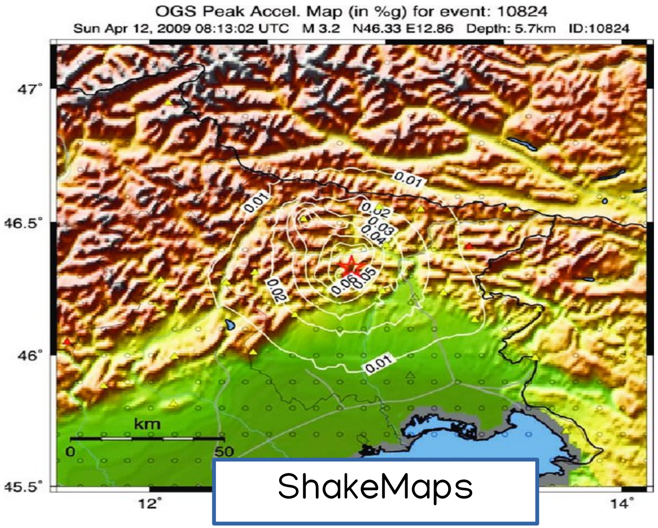
During the last decades, research activities at CRS have been focused (mainly, but not only) on seismological aspects, producing a wide amount of <u>valuable scientific knowledge for the region</u>.



Event Solutions



Moment Tensor Solutions



ShakeMaps

… and much, much more….

However....

Such information might be insufficient to guide emergency intervention after catastrophic events and, more in general, for the mitigation of damage through preventive land and urban planning

For that, a realistic prediction of the impact of the earthquake on population is needed.

Bare in mind that:

"Earthquakes don't kill people, collapsed buildings do so"

Nigel Priestley (1943–2014)

From Seismology to Earthquake Engineering

Based on all the data and the expertise developed at CRS, we aim at developing methodologies to assess the **impact of the earthquake on structures** (e.g. the expected damage, economic losses) **and population** (e.g. casualties, social vulnerability).

The purpose of the research is two-fold:

1) **scientific**: develop novel methodologies that combine the seismological and engineering know-how, to assess expected damage on the built environment.

2) **operational**: developing tools and products that have a direct impact on everyday life, e.g. to be used by civil protection for emergency planning and quick post-event intervention

Seismic Risk and Damage Assessment

The seismic risk (R) is expressed as the product between earthquake hazard (H), exposure (E) and vulnerability (V):

$$\boxed{R = H * E * V}$$

In the specific case of damage assessment, the equation reduces to:

$$\boxed{D = H * E * F}$$

While H is an immutable property of the target region and can only be better quantified, exposure and vulnerability (thus fragility) could be minimized by:

1) allowing a rationale urban planning, e.g. avoiding hazardous areas
2) increasing the seismic performance of buildings and structures.

What is Seismic Hazard in Practice?

Reduction of losses should be properly done by preemptive design and reinforcement of new and existing building and infrastructures.

This requires, however, a proper estimation of the ground shaking level likely expected at a site (within a given interval of time)

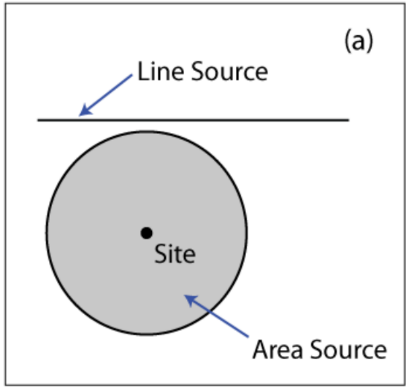
This is the task of Seismic Hazard Analysis (SHA)....

Question is: how and how precisely this level can be defined, given the little knowledge we have of the earthquake process?

Hazard Definition Requirements

For the calculation of hazard associated to a region is essential to know:
- Where the earthquakes occur and the geometry of the seismic sources
- How often earthquakes occur on each seismic source
- The size of the earthquakes generated by each source
- Mechanical properties of geological materials through which seismic waves will propagate (including surface geology)

Where
Seismogenic Models



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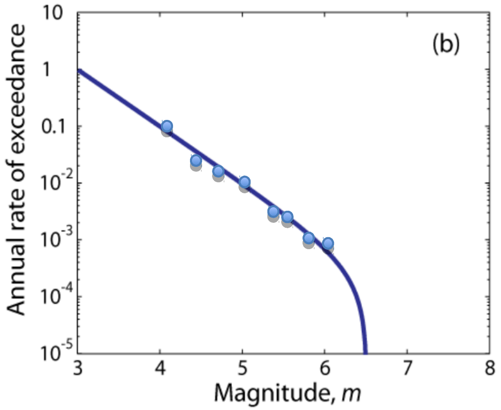
When (how often)
Recurrence Models



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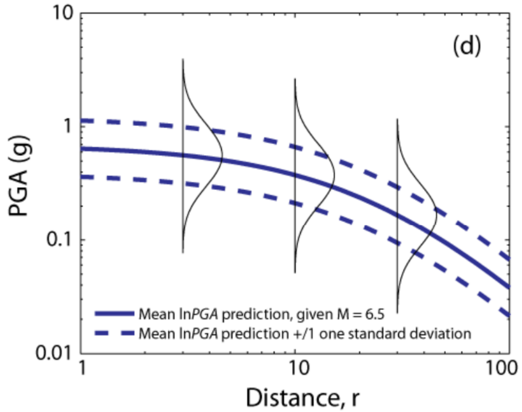
How (strong)
Ground Motion Models



Deterministic vs Probabilistic

Two are the main methodologies currently adopted for seismic hazard analysis:

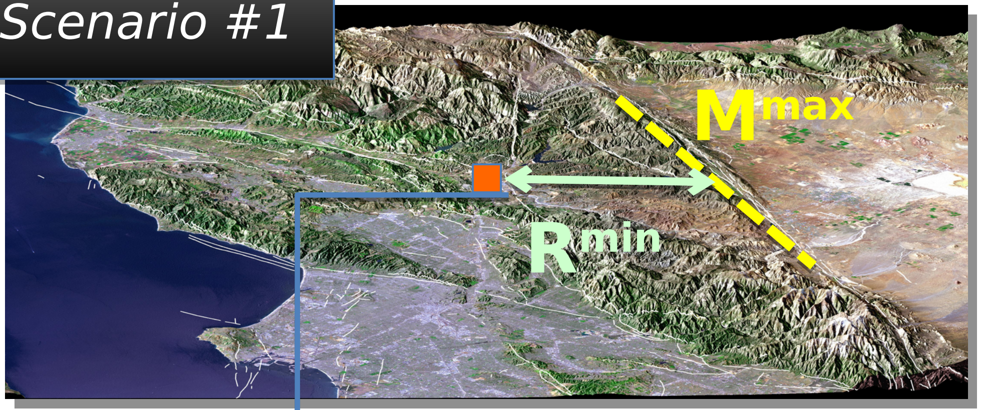
Deterministic. Also called the "*Worst Case Scenario*"
One or a few earthquake scenarios are selected and the corresponding ground motion computed assuming a level of uncertainty on ground motion (i.e. a number of standard deviations above the median value predicted by a Ground Motion Prediction Equation – GMPE).

Probabilistic: All possible scenarios of engineering relevance for the investigated site are considered in the analysis taking into account their probability of occurrence i.e. all ruptures (magnitude+distance) and levels of uncertainty on ground motion.

Scenario Based Approach

Scenario #1

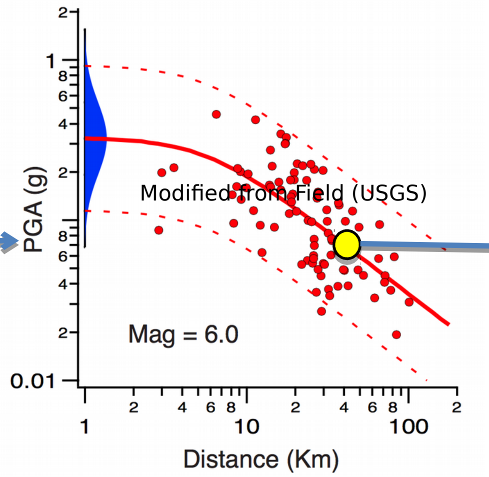
http://eoimages.gsfc.nasa.gov



1) Select one (or more) source through specific magnitude and distance combinations

2) Compute expected ground motion (accounting for variability)

3) Retain some significant level of shaking for engineering design



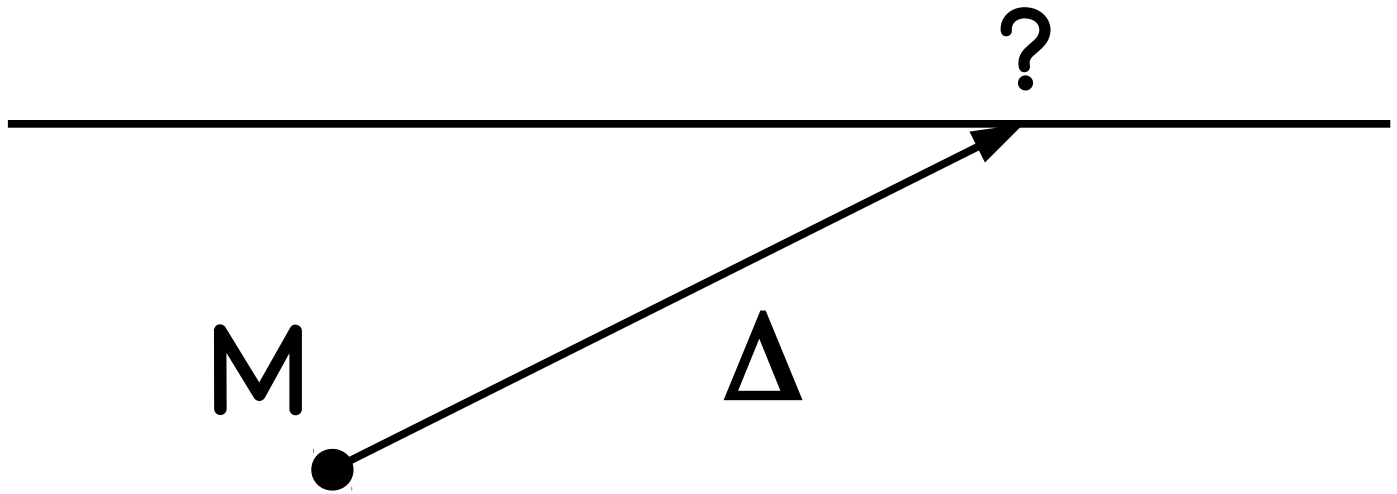
PGA @ 20Km + σ

GMPE or Simulation

Ground Motion Prediction

Ground Motion Prediction Equations (GMPEs) are the simplest **empirical** (but in few cases semi-analytical) answer to the following question:

"If we know where a major earthquake is likely to occur, how large will the ground motion be at a particular site?"

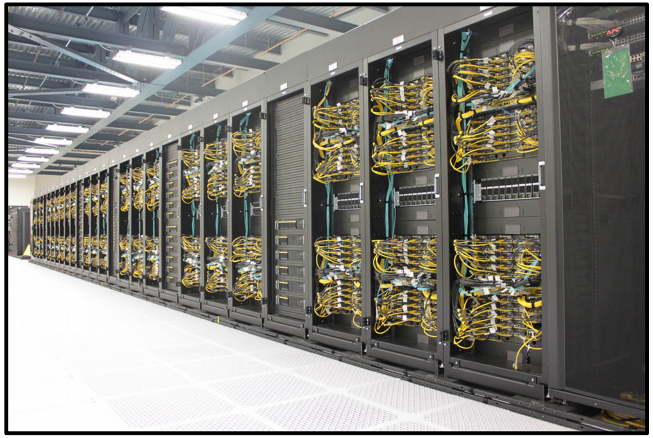


$$\log(Y) = f(M, \Delta, \ldots) + E$$

Prediction vs Simulation

Why an empirical prediction? Ground motion could also be estimated by numerical simulation. However....

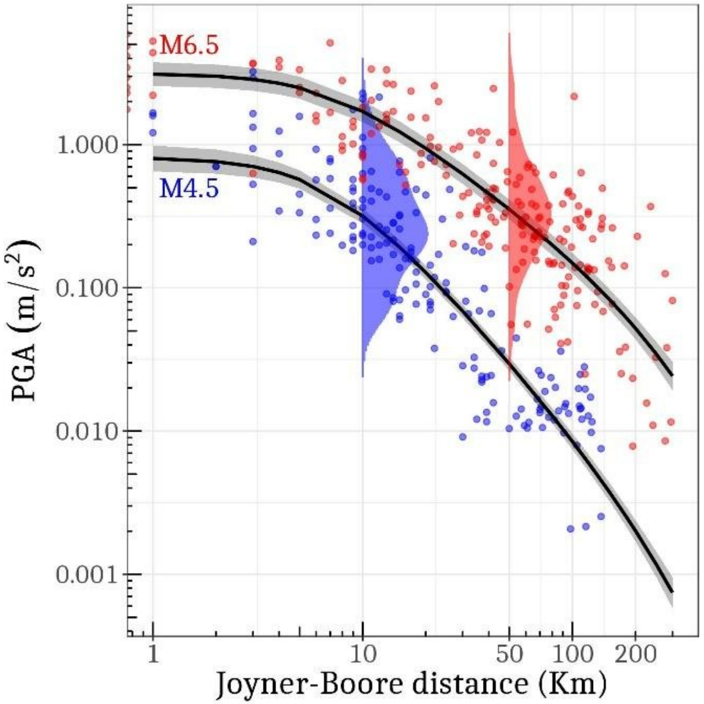
Numerical simulation is computationally expensive and does not (directly) provide estimates of the uncertainty. It also requires many parameters of difficult calibration.



...nonetheless, simulated ground motion at the end still needs to be compared with actual data!

Engineering Perspective

Engineers need a fast, simple and cost effective approach to be used massively, as in Probabilistic Seismic Hazard Analysis.



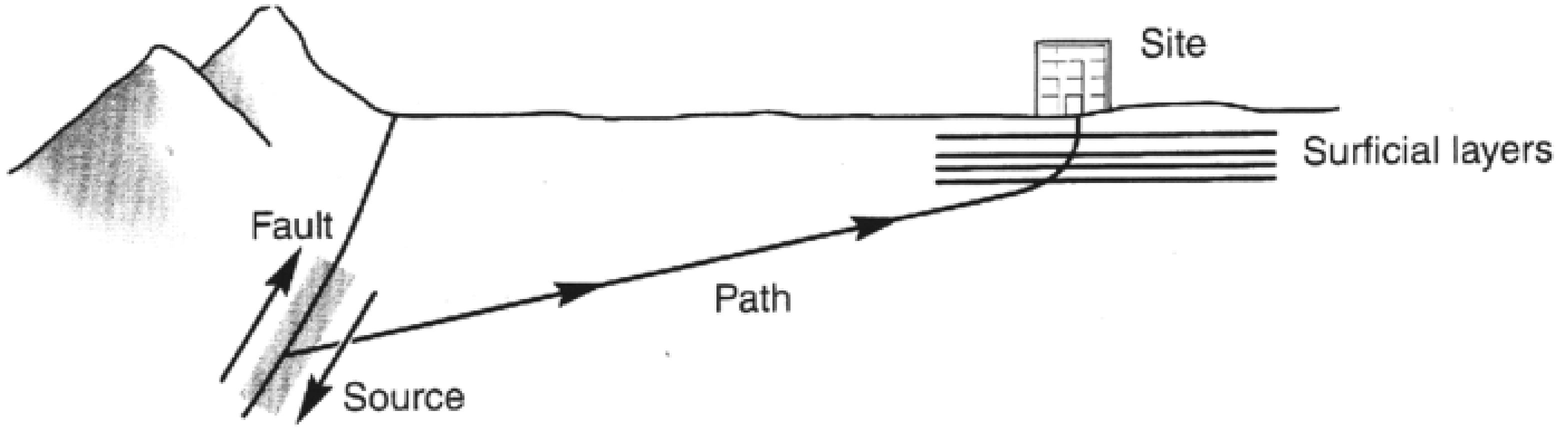
$$\log(Y) = f(M, \Delta, \ldots) + \boxed{E}$$

They also need a reliable assessment of the prediction uncertainty, which is often more important than accuracy of the mean estimate.

Source-Path-Site

Ground motion at any site can be seen as the combination of three contributions:

Source characteristics (fault size, magnitude, seismic moment, etc)
Wave propagation (geometrical and anelastic attenuation, scattering and dispersion),
Site amplification due to both the site response and the other effects



GM Amplitude = Source term * Path term * Site term

GMPE Functional Form

The functional form of empirical ground motion model is created following physical principles i.e. trying to reproduce the basic physics of the process.

Here is an "simple" example:

$$\log(Y) = c_0 + c_1 M + c_2 M^2 + c_3 \log\left(\sqrt{(R^2 + h^2)}\right) + \sigma$$

Different set of coefficients are defined for each ground motion measure type.

Table 2
Coefficients of Equation (1)

PSA at Frequency	c_0	c_1	c_2	c_3	σ-intra	σ-inter	σ-total
0.2	−4.374	1.134	0.0038	−1.426	0.26	0.17	0.31
0.33	−3.869	1.110	0.0039	−1.447	0.25	0.21	0.33
0.5	−4.503	1.532	−0.0430	−1.404	0.25	0.22	0.33
1	−2.009	1.890	−0.1248	−1.828	0.27	0.21	0.34
2	−4.128	1.792	−0.0791	−1.526	0.30	0.19	0.35
3.33	−2.076	1.889	−0.1257	−1.886	0.31	0.18	0.36
5	−3.918	2.112	−0.1266	−1.591	0.31	0.20	0.37
10	−2.839	1.905	−0.1134	−1.658	0.30	0.25	0.39
20	−2.337	1.902	−0.1252	−1.838	0.29	0.29	0.41
33	−2.313	1.840	−0.1119	−1.708	0.29	0.26	0.39
PGA	−2.427	1.877	−0.1214	−1.806	0.29	0.24	0.37
PGV	−4.198	1.818	−0.1009	−1.721	0.28	0.18	0.33

Equation (1) predicts 5% damped horizontal-component pseudospectral acceleration (PSA, in cm/s^2) for B/C site conditions, peak ground acceleration (PGA, in cm/s^2), and peak ground velocity (PGV, in cm/s). The standard deviation of residuals (σ-total) and its intraevent and interevent components are also given.

GMPE Functional Form

More recent GMPEs are far more complex and can have tens of coefficients!

$$
\begin{aligned}
\ln y_{ref} &= c_1 + \left\{c_{1a} + \frac{c_{1c}}{\cosh[2\max(M-4.5,0)]}\right\} F_{RV} + \left\{c_{1b} + \frac{c_{1d}}{\cosh[2\max(M-4.5,0)]}\right\} F_{NM} \\
&+ \left\{c_7 + \frac{c_{7b}}{\cosh[2\max(M-4.5,0)]}\right\} \Delta Z_{TOR} + \left\{c_{11} + \frac{c_{11b}}{\cosh[2\max(M-4.5,0)]}\right\} (\cos\delta)^2 \\
&+ c_2(M-6) + \frac{c_2-c_3}{c_n} \ln\left[1 + e^{c_n(c_M-M)}\right] + c_4 \ln\{r_{rup} + c_5 \cosh[c_6 \max(M-c_{HM},0)]\} \\
&+ (c_{4a}-c_4) \ln\sqrt{r_{rup}^2 + c_{RB}^2} + \left\{c_{\gamma 1} + \frac{c_{\gamma 2}}{\cosh[\max(M-c_{\gamma 3},0)]}\right\} r_{rup} \\
&+ c_8 \max\left[1 - \frac{\max(r_{rup}-40,0)}{30}, 0\right] \min\left[\frac{\max(M-5.5,0)}{0.8}, 1\right] e^{-c_{8a}(M-c_{8b})^2} \Delta DPP \\
&+ c_9 F_{HW} \cos\delta \left[c_{9a} + (1-c_{9a}) \tanh\left(\frac{R_x}{c_{9b}}\right)\right] \left[1 - \frac{\sqrt{r_{jb}^2 + Z_{TOR}^2}}{r_{rup}+1}\right] \\
\ln y &= \ln y_{ref} + \phi_1 \min\left[\ln\left(\frac{V_{s,30}}{1130}\right), 0\right] \\
&\phi_2 \left\{e^{\phi_3[\min(V_{s,30},1130)-360]} - e^{\phi_3(1130-360)}\right\} \ln\left(\frac{y_{ref}+\phi_4}{\phi_4}\right) \\
&\phi_5 \left(1 - e^{-\Delta Z_{1.0}/\phi_6}\right) \\
\Delta Z_{TOR} &= Z_{TOR} - E[Z_{TOR}] \\
E[Z_{TOR}] &= \max[2.704 - 1.226\max(M-5.849,0),0]^2 \quad \text{for reverse} \\
E[Z_{TOR}] &= \max[2.673 - 1.136\max(M-4.970,0),0]^2 \quad \text{For strike-slip/normal}
\end{aligned}
$$

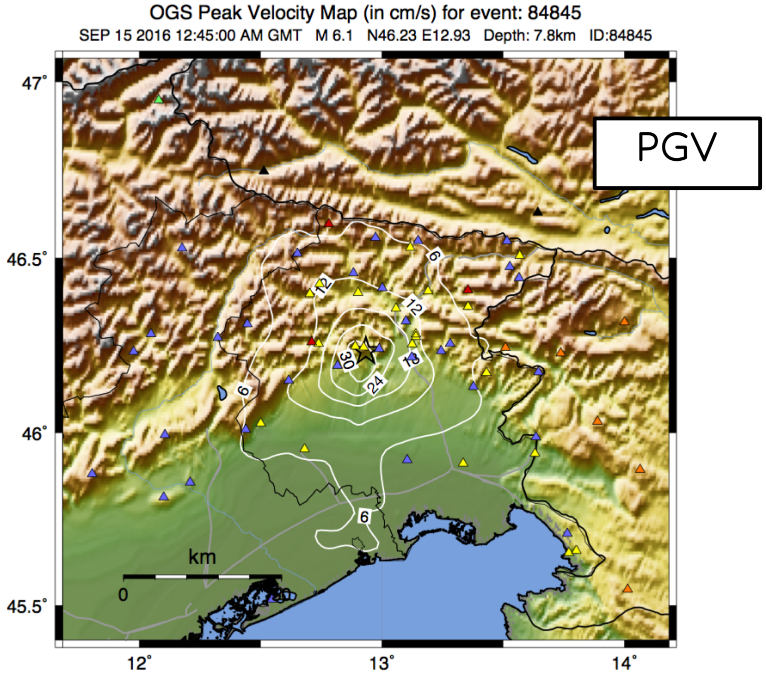
Chiou and Youngs 2014

$$
\begin{aligned}
\ln \mathrm{Sa}(g) &= f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) \\
&+ F_{HW} f_4(R_{jb}, R_{rup}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M) \\
&+ f_{10}(Z_{1.0}, V_{S30}) \\
f_1(M, R_{rup}) &= \begin{cases} a_1 + a_4(M-c_1) + a_8(8.5-M)^2 + [a_2 + a_3(M-c_1)]\ln(R) & \text{for} \quad M \le c_1 \\ a_1 + a_5(M-c_1) + a_8(8.5-M)^2 + [a_2 + a_3(M-c_1)]\ln(R) & \text{for} \quad M > c_1 \end{cases} \\
R &= \sqrt{R_{rup}^2 + c_4^2} \\
f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) &= \begin{cases} a_{10}\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) - b\ln(\widehat{\mathrm{PGA}_{1100}} + c) & \\ +b\ln\left(\widehat{\mathrm{PGA}_{1100}} + c\left(\frac{V_{S30}^*}{V_{LIN}}\right)^n\right) & \text{for} \quad V_{S30} < V_{LIN} \\ (a_{10} + bn)\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) & \text{for} \quad V_{S30} \ge V_{LIN} \end{cases} \\
\text{where} \quad V_{S30}^* &= \begin{cases} V_{S30} & \text{for} \quad V_{S30} < V_1 \\ V_1 & \text{for} \quad V_{S30} \ge V_1 \end{cases} \\
\text{and} \quad V_1 &= \begin{cases} 1500 & \text{for} \quad T \le 0.50\,\mathrm{s} \\ \exp[8.0 - 0.795\ln(T/0.21)] & \text{for} \quad 0.50 < T \le 1\,\mathrm{s} \\ \exp[6.76 - 0.297\ln(T)] & \text{for} \quad 1 < T < 2\,\mathrm{s} \\ 700 & \text{for} \quad T \ge 2\,\mathrm{s} \end{cases} \\
f_4(R_{jb}, R_{rup}, \delta, Z_{TOR}, M, W) &= a_{14}T_1(R_{jb})T_2(R_x, W, \delta)T_3(R_x, Z_{TOR})T_4(M)T_5(\delta) \\
\text{where} \quad T_1(R_{jb}) &= \begin{cases} 1 - \frac{R_{jb}}{30} & \text{for} \quad R_{jb} < 30\,\mathrm{km} \\ 0 & \text{for} \quad R_{jb} \ge 30\,\mathrm{km} \end{cases} \\
T_2(R_x, W, \delta) &= \begin{cases} 0.5 + \frac{R_x}{2W\cos(\delta)} & \text{for} \quad R_x \le W\cos(\delta) \\ 1 & \text{for} \quad R_x > W\cos(\delta) \quad \text{or} \quad \delta = 90^\circ \end{cases} \\
T_3(R_x, Z_{TOR}) &= \begin{cases} 1 & \text{for} \quad R_x \ge Z_{TOR} \\ \frac{R_x}{Z_{TOR}} & \text{for} \quad R_x < Z_{TOR} \end{cases} \\
T_4(M) &= \begin{cases} 0 & \text{for} \quad M \le 6 \\ M - 6 & \text{for} \quad 6 < M < 7 \\ 1 & \text{for} \quad M \ge 7 \end{cases} \\
T_5(\delta) &= \begin{cases} 1 - \frac{\delta - 30}{60} & \text{for} \quad \delta \ge 30 \\ 1 & \text{for} \quad \delta < 30 \end{cases} \\
f_6(Z_{TOR}) &= \begin{cases} \frac{a_{16}Z_{TOR}}{10} & \text{for} \quad Z_{TOR} < 10\,\mathrm{km} \\ a_{16} & \text{for} \quad Z_{TOR} \ge 10\,\mathrm{km} \end{cases} \\
f_8(R_{rup}, M) &= \begin{cases} 0 & \text{for} \quad R_{rup} < 100\,\mathrm{km} \\ a_{18}(R_{rup} - 100)T_6(M) & \text{for} \quad R_{rup} \ge 100\,\mathrm{km} \end{cases} \\
\text{where} \quad T_6(M) &= \begin{cases} 1 & \text{for} \quad M < 5.5 \\ 0.5(6.5 - M) + 0.5 & \text{for} \quad 5.5 \le M \le 6.5 \\ 0.5 & \text{for} \quad M > 6.5 \end{cases} \\
f_{10}(Z_{1.0}, V_{S30}) &= a_{21}\ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0}(V_{S30}) + c_2}\right) + \begin{cases} a_{22}\ln\left(\frac{Z_{1.0}}{200}\right) & \text{for} \quad Z_{1.0} \ge 200 \\ 0 & \text{for} \quad Z_{1.0} < 200 \end{cases} \\
\text{where} \quad \ln[\hat{Z}_{1.0}(V_{S30})] &= \begin{cases} 6.745 & \text{for} \quad V_{S30} < 180\,\mathrm{m/s} \\ 6.745 - 1.35\ln\left(\frac{V_{S30}}{180}\right) & \text{for} \quad 180 \le V_{S30} \le 500\,\mathrm{m/s} \\ 5.394 - 4.48\ln\left(\frac{V_{S30}}{500}\right) & \text{for} \quad V_{S30} > 500\,\mathrm{m/s} \end{cases} \\
a_{21} &= \begin{cases} 0 & \text{for} \quad V_{S30} \ge 1000 \\ \frac{-(a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right)}{\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right)} & \text{for} \quad (a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right) + e_2\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right) < 0 \\ e_2 & \text{otherwise} \end{cases} \\
e_2 &= \begin{cases} 0 & \text{for} \quad T < 0.35\,\mathrm{s} \quad \text{or} \quad V_{S30} > 1000 \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{T}{0.35}\right) & \text{for} \quad 0.35 \le T \le 2\,\mathrm{s} \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{2}{0.35}\right) & \text{for} \quad T > 2\,\mathrm{s} \end{cases} \\
a_{22} &= \begin{cases} 0 & \text{for} \quad T < 2\,\mathrm{s} \\ 0.0625(T-2) & \text{for} \quad T \ge 2\,\mathrm{s} \end{cases}
\end{aligned}
$$

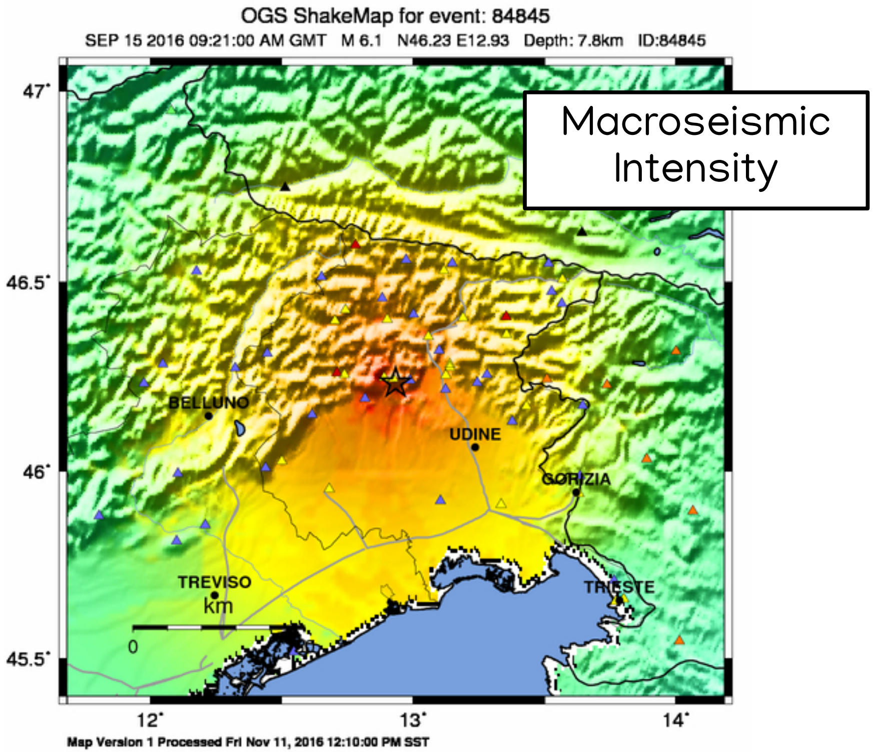
Abrahamson and Silva 2009

Application Example: ShakeMaps

ShakeMaps (©USGS) are the simplest example of using a GMPE to visualize (mean) ground motion distribution of an event.



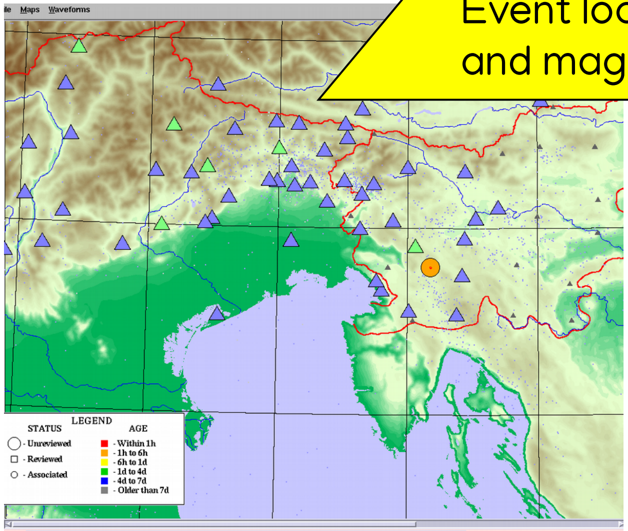
Scenario earthquake (MW=6.1; 15/9/2016)



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.06	0.2	0.8	2.0	4.8	12	29	70	>171
PEAK VEL.(cm/s)	*<0.02*	*0.08*	*0.3*	*0.9*	*2.4*	*6.4*	*17*	*45*	*>120*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

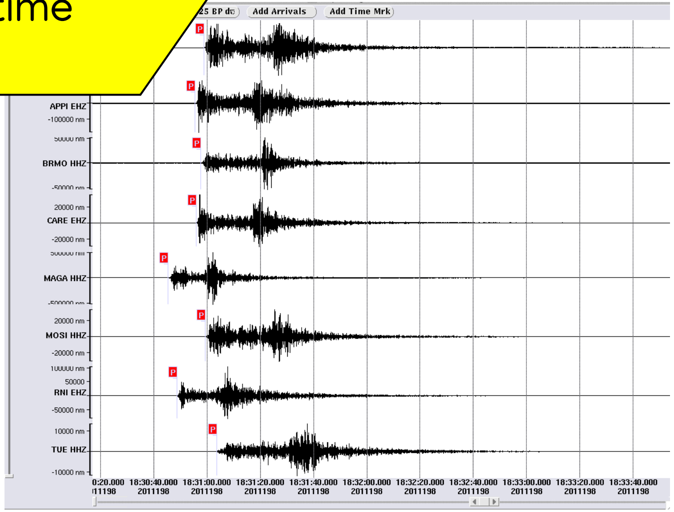
Scale based upon Faenza and Michelini, 2010

…More than Just a Prediction



Event location and magnitude

Real–time data



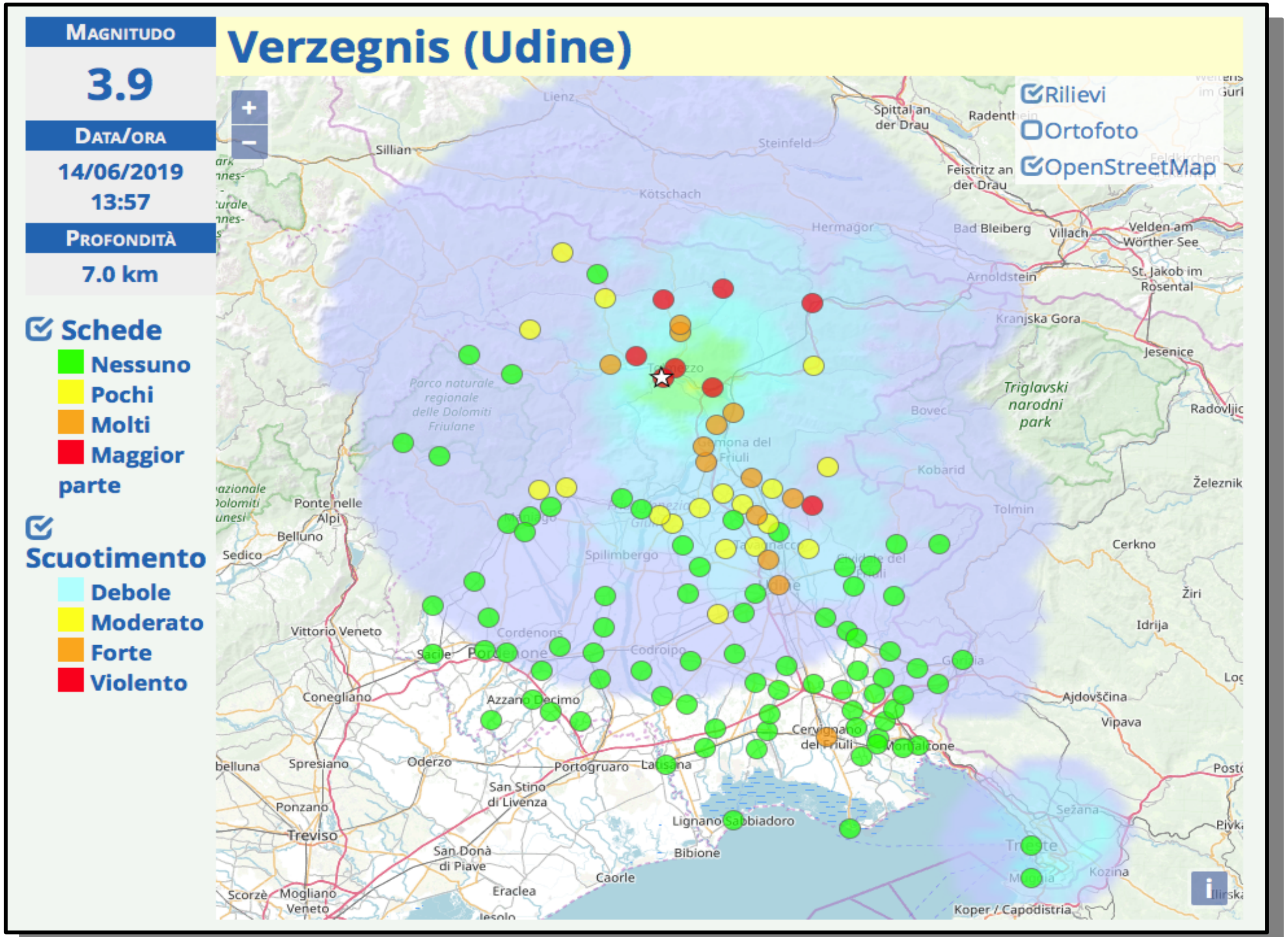
Ground motion estimation (PGA, PGV, SA)

Sites geology: Amplification factors

SHAKEMAPS (PGA, PGV, I)

Ground motion relations (GMPE, GMICE)

ShakeMaps for Emergency Control Room

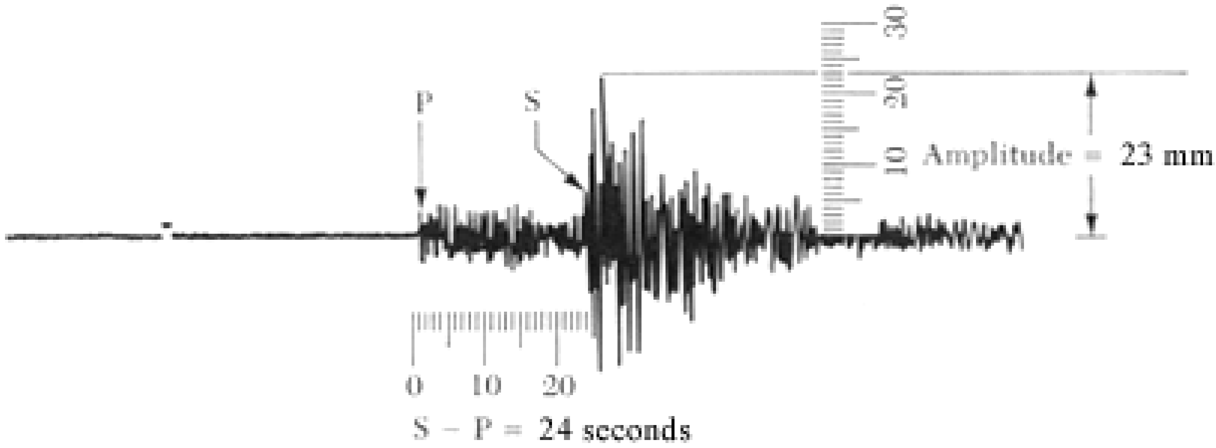


Measuring Ground Motion

For engineering purposes, seismograms and Fourier spectra are difficult to handle directly.

It is usually more convenient to use simplified ground motion parameters such as: peak values (instantaneous), frequency content, duration and various integral parameters.

Each of these emphasize a specific aspect of the earthquake phenomenon, and are thus used in different contexts.



Engineering Ground Motion Parameters

Instantaneous (peak) values:

PGA → peak ground acceleration (a_{max})

PGV → peak ground velocity (v_{max})

PGD → peak ground displacement (d_{max})

Duration: defines the length of ground motion. There are different definitions of duration. It depends on magnitude and epicentral distance of the earthquake.

Integral parameters: they express (indirectly) the energy content of a signal and they are defined by the integration of a(t), v(t), d(t), times series, SA(T), SV(T).

Response spectra: represents the way an input signal interacts with a structure of arbitrary period T.

Peak and Integral Parameters

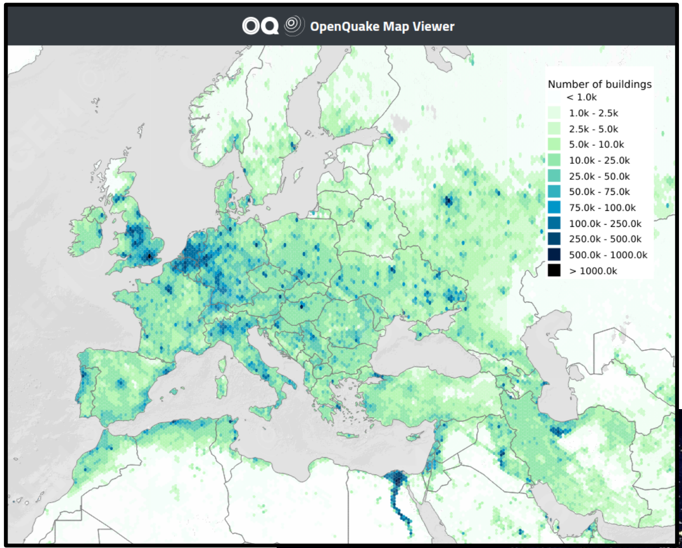
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
$I_a = \frac{\pi}{2g}\int [a(t)]^2 dt$	Arias Intensity
Sa (5%, 1.0Ts)	Spectral acceleration T = 1.0Ts (sliding mass)
Sa (5%, 1.5Ts)	Spectral acceleration T = 1.5Ts (sliding mass)
Sa (5%, 2.0Ts)	Spectral acceleration T = 2.0Ts (sliding mass)
$CAV = \int [a(t)] dt$	Cumulative Absolute Velocity
$I_c = a_{RMS}^{3/2}\sqrt{T_D}$	Characteristic Intensity
$VSI = \int_{0.1}^{2.5} S_v(5\%, T)dT$	Velocity Spectrum Intensity

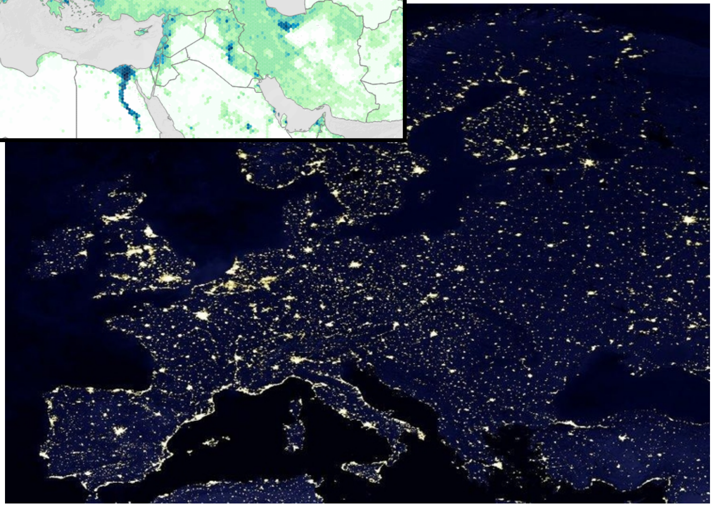
Sv (5%, 1.0Ts)	Spectral velocity T = 1.0Ts (sliding mass)
Sv (5%, 1.5Ts)	Spectral velocity T = 1.5Ts (sliding mass)
Sv (5%, 2.0Ts)	Spectral velocity T = 2.0Ts (sliding mass)
$a_{RMS} = \sqrt{\frac{\int [a(t)]^2 dt}{T_D}}$	Root-Mean Square of acceleration
$v_{RMS} = \sqrt{\frac{\int [v(t)]^2 dt}{T_D}}$	Root-Mean Square of velocity
$ASI = \int_{0.1}^{0.5} S_a(5\%, T)dT$	Acceleration Spectrum Intensity
$D_{5\text{-}95}$	Significant duration
T_P	Pulse period
$T_m = \frac{\sum \left(\frac{C_i^2}{f_i}\right)}{\sum C_i^2}$	Mean period

Different sensitivity / correlation to damage!

Moving to Structures: Exposure

Exposure defines the spatial distribution of elements, such as critical facilities, infrastructures, residential buildings, which are susceptible to a specific hazard.



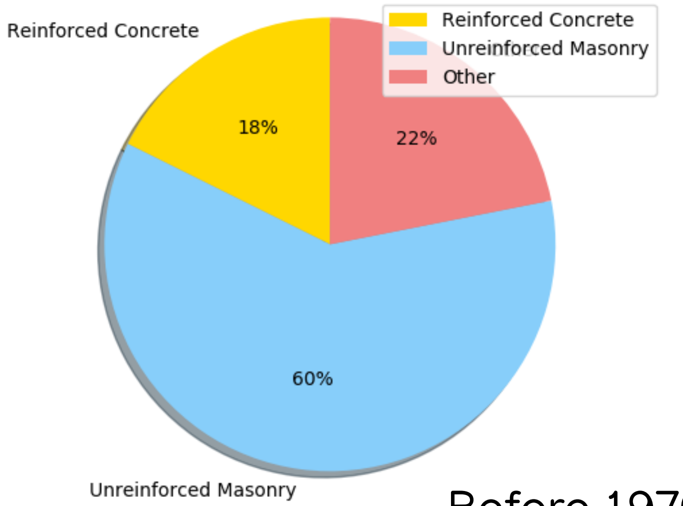


Night lights as proxy for settlements

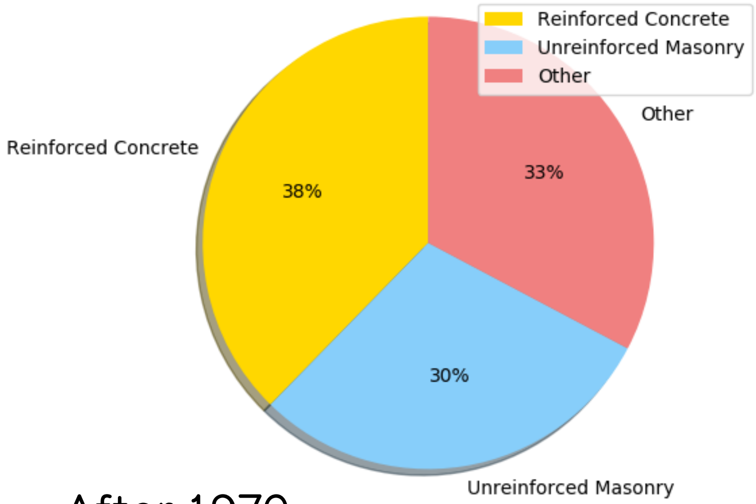
An Exposure Model for NE Italy

In our analysis, we focus on population and residential buildings of the Friuli Venezia Giulia and Veneto. The analysis is performed at two scales: municipalities and census units.

The starting point is the Istat 2011 database, which contains the number of buildings for each combination of height, material and age.

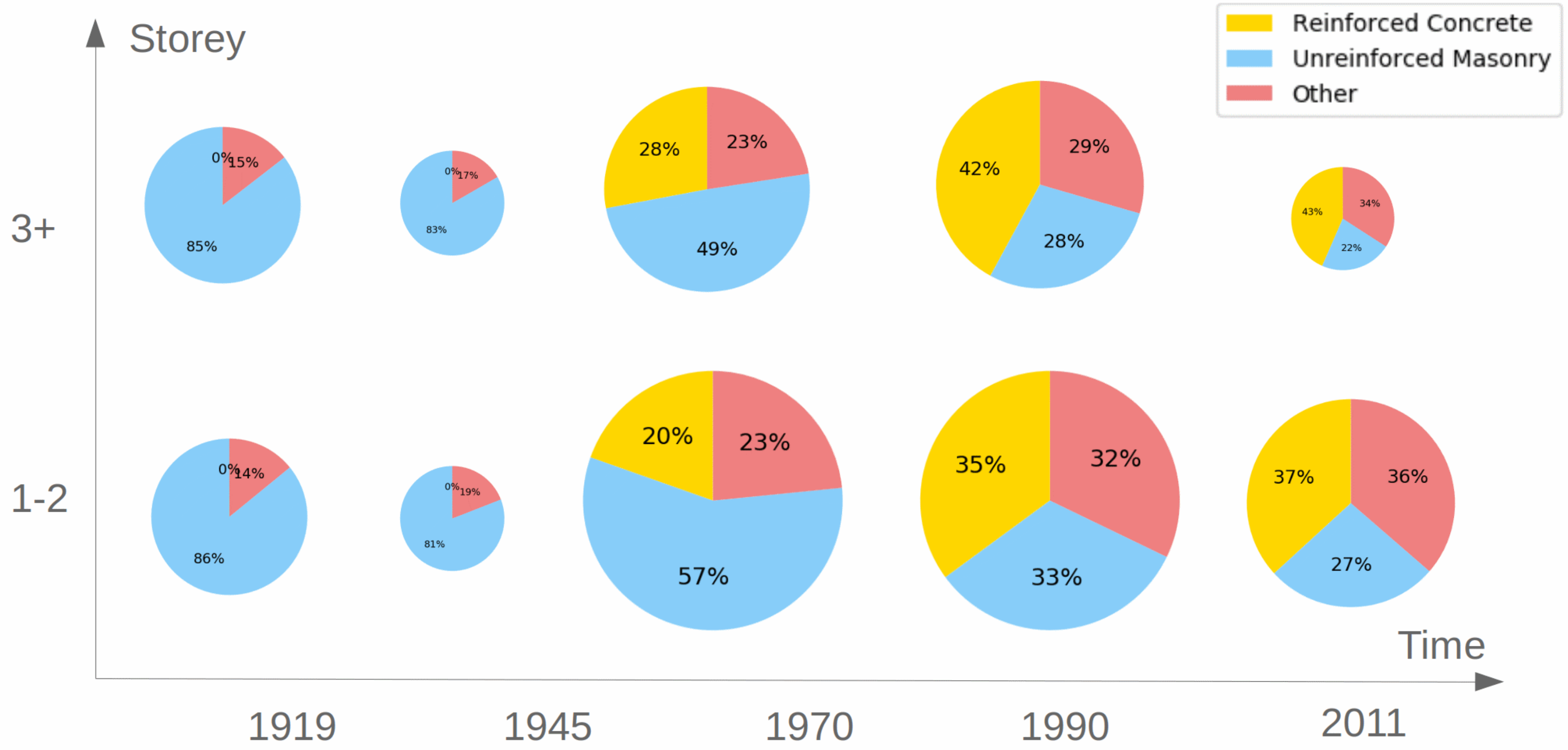


Before 1970

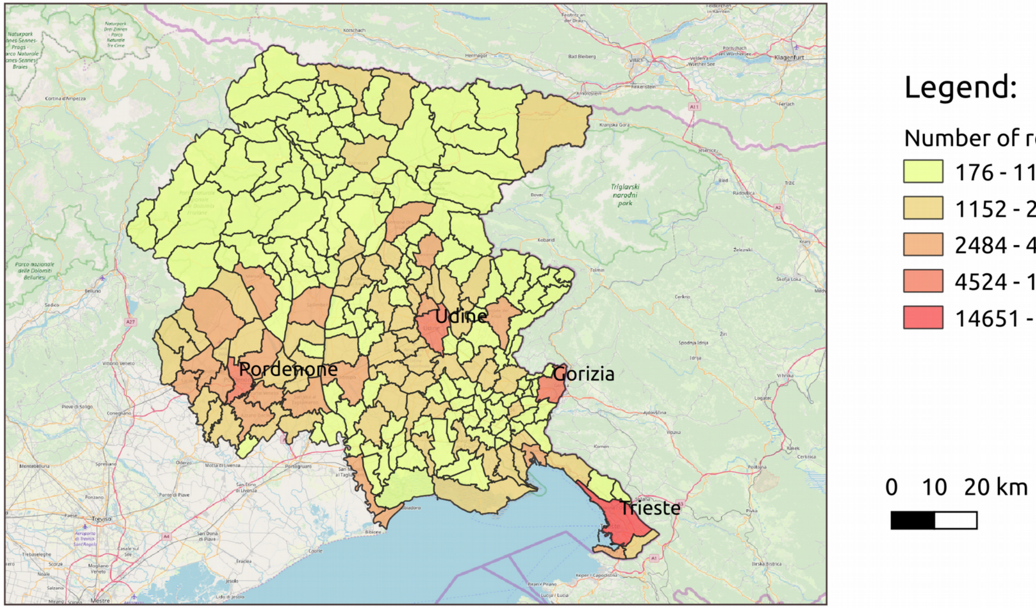


After 1970

Evolution of Exposure

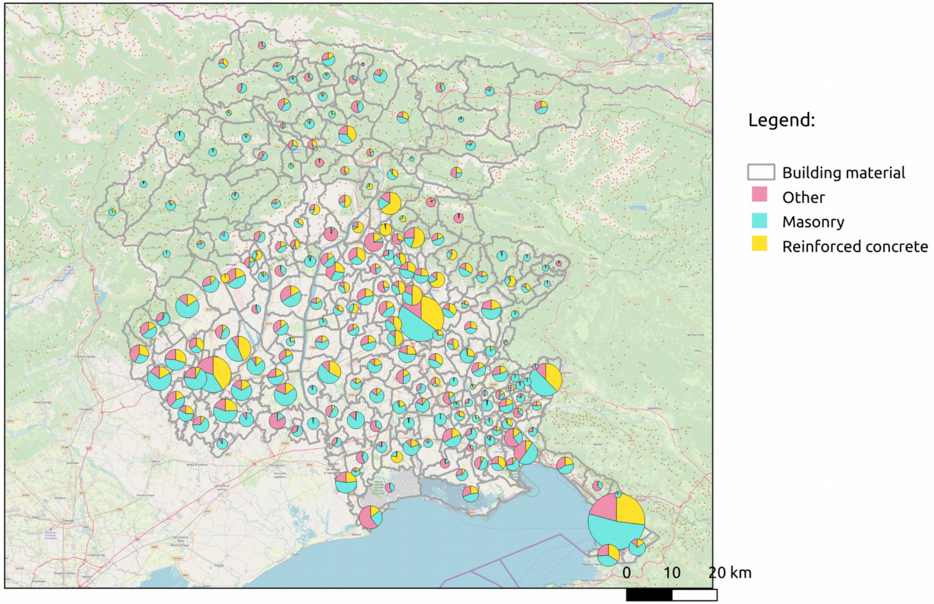


Residential Buildings (Istat 2011)



Number of residential buildings as for 2018, classified by Jenks natural breaks method (Jenks, 1967). Names of municipalities with more than 5000 buildings are shown.

Building material for each municipality (based on Istat 2011 census). Pie charts size is proportional to the total number of residential buildings.



Improving the Exposure Database

The exposure database is progressively enriched by including more and more refined information about those buildings characteristics that are relevant to the damage assessment:

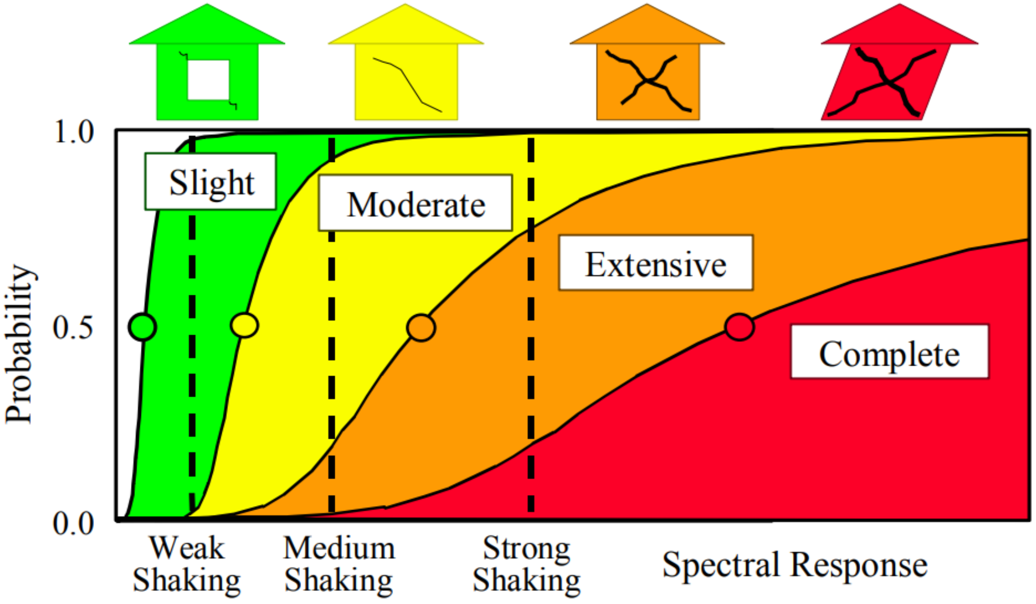
We do this by:

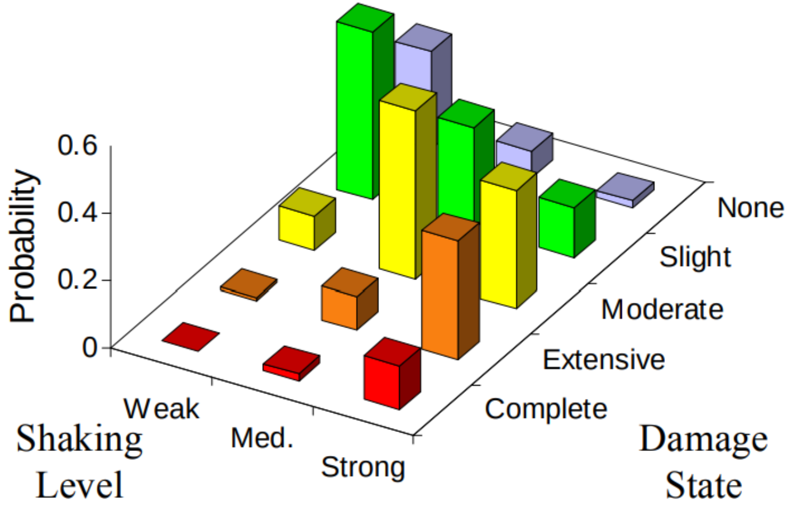
1) inspecting buildings and interviewing municipality officers
2) extracting the information available on numerical cartography (ex. if buildings are aggregated or isolated, if they are regular in shape).
3) **defining existing building typologies** defined by faceted taxonomies
4) characterizing the fundamental period of each typologies (*noise* measurements)

Structural Fragility

Fragility curves describe the probability of exceeding some limit states given a level of ground shaking, such as PGA, PGD, etc.

Limit states for buildings are the conditions of potential failure (ex. of non-structural or structural elements).



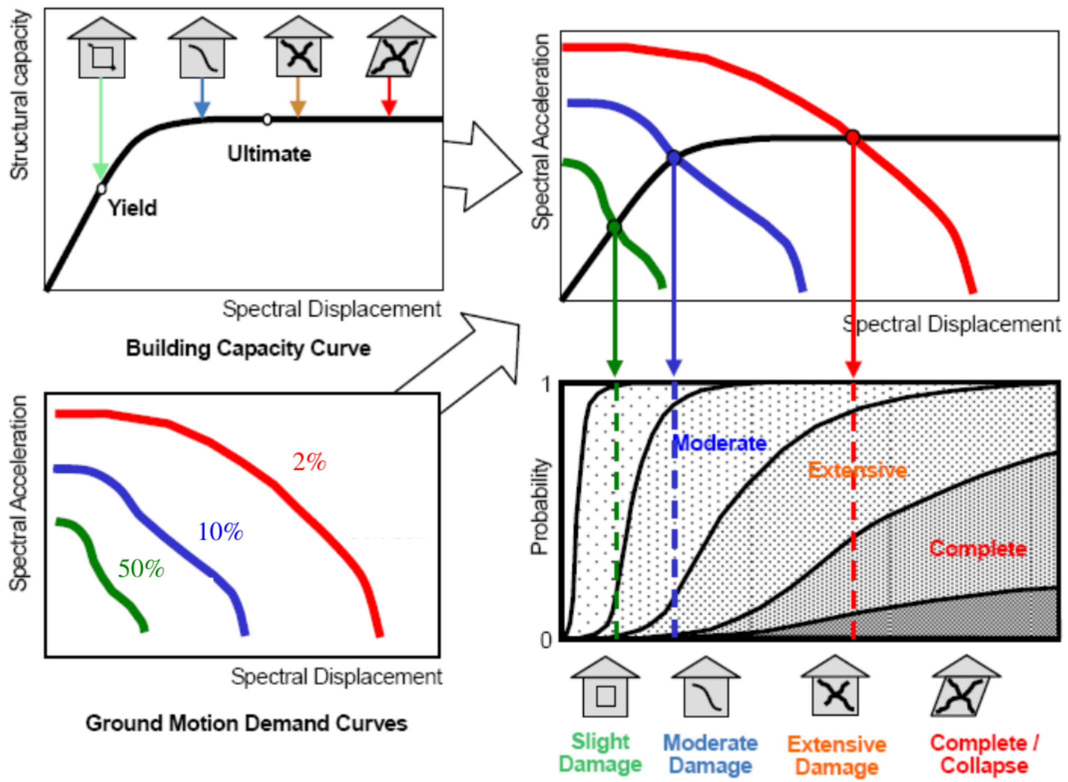


From HAZUS Earthquake, AEBM, Technical Manual

Fragility Curve Calibration

They can be derived:

- **analytically** (ex. creating a set of models of buildings and performing the analysis)
- **based on empirical data** (e.g. damage forms from past events).

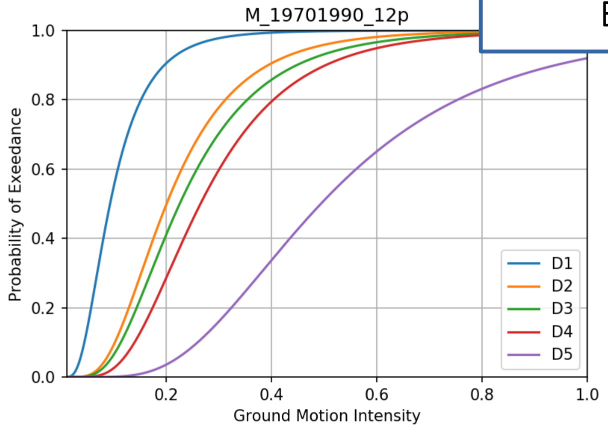


From Duan & Pappin, 14th WCEE

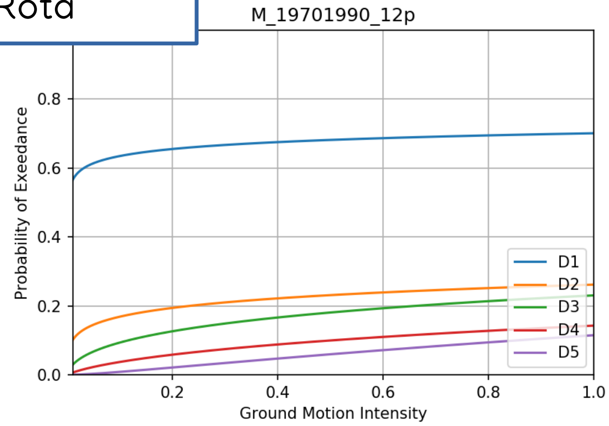
Selected Fragility Models

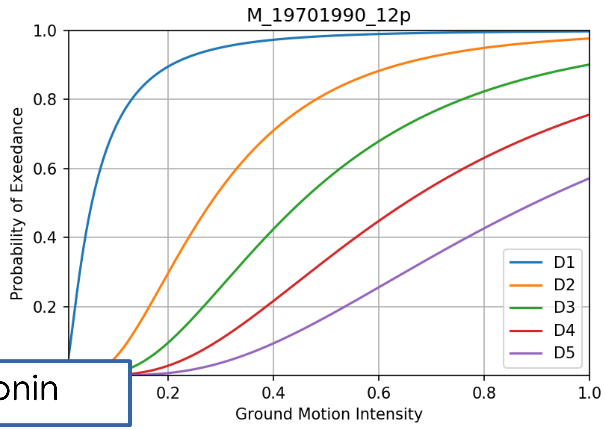
We selected a number of fragility models from literature (e.g. Borzi, Ahmad, Karantoni) as most representative of the building typologies in the Friuli Venezia Giulia region.

Borzi



Rota





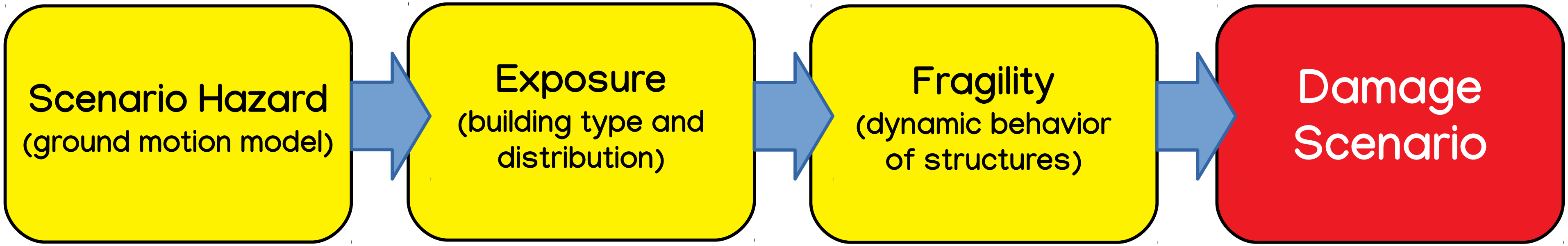
Karantonin

Fragility curves based on PGA

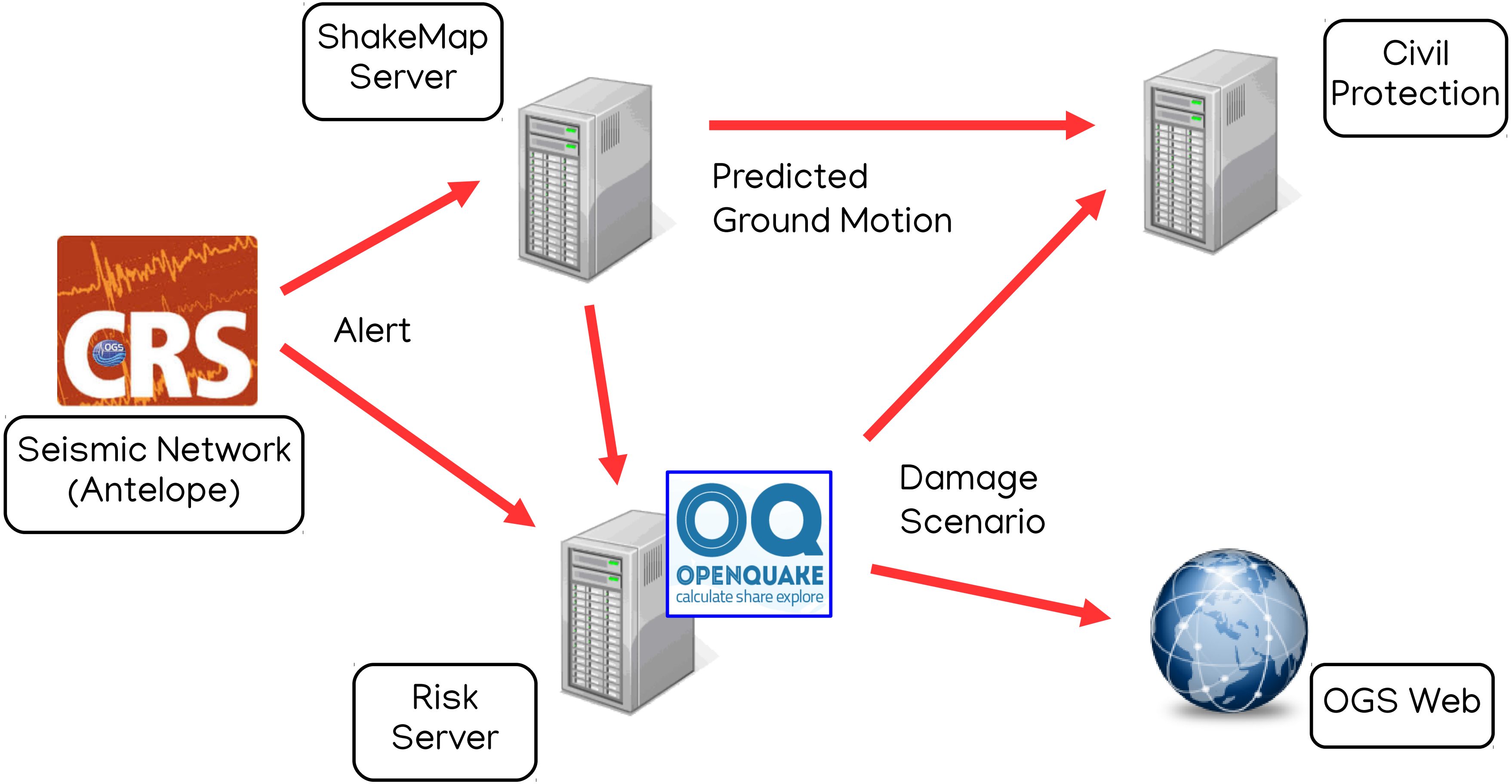
Damage Levels: D1–D5 (EMS98)

A real-time damage scenario calculator

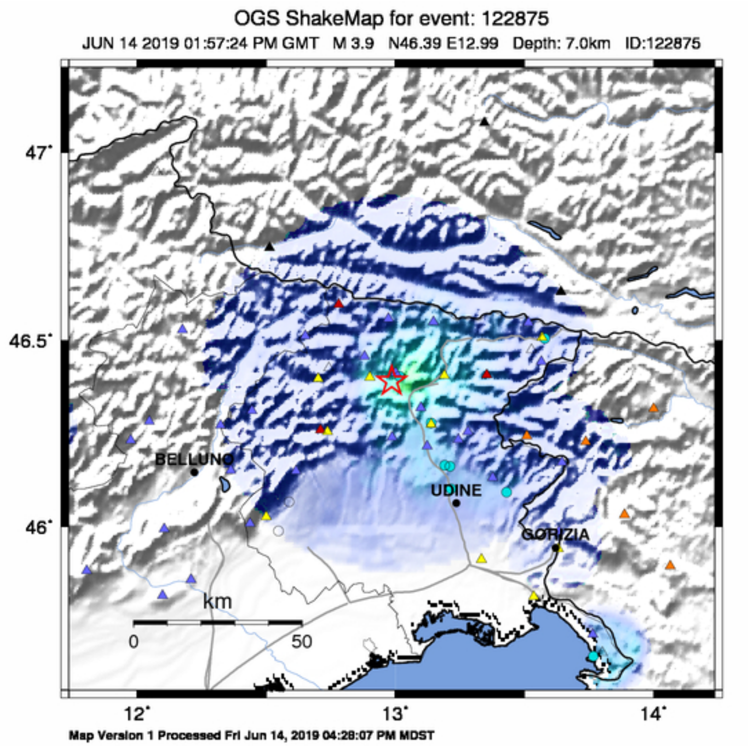
All previous ingredients can then be merged together to predict the expected damage during a known (e.g. after a real earthquake) or hypothetical event (e.g. for training purposes).



Processing Infrastructure



Input Ground Motion



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.06	0.2	0.8	2.0	4.8	12	29	70	>171
PEAK VEL.(cm/s)	<0.02	0.08	0.3	0.9	2.4	6.4	17	45	>120
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

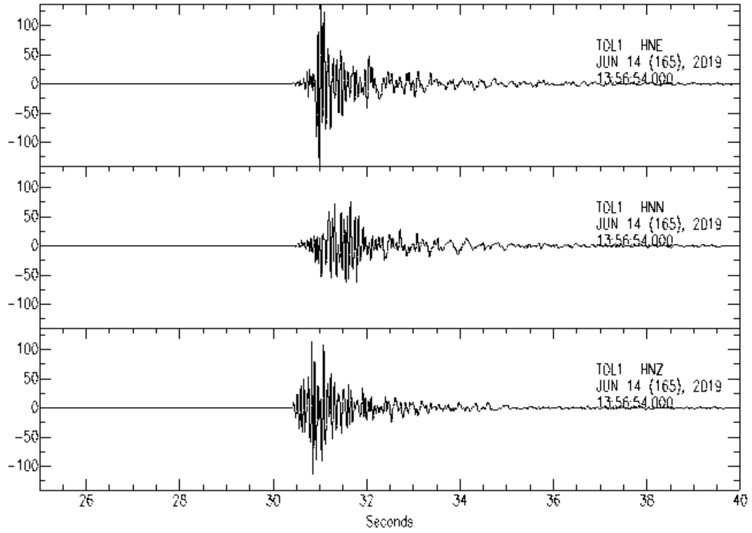
Scale based upon Faenza and Michelini, 2010

Input Ground Motion is computed from an Empirical Prediction Model, constrained by local data from the CRS network and instrumented building (SENTINELLA, ARMONIA)

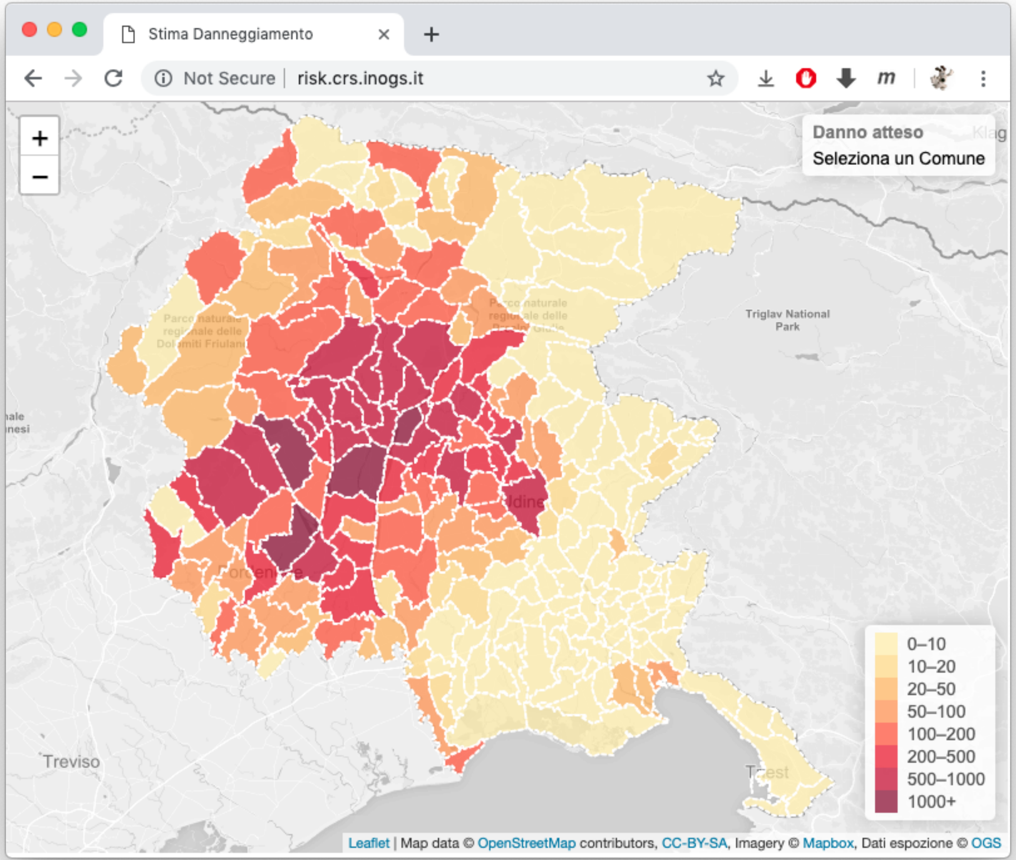
Verzegnis earthquake (ML=3.9; 14/6/2019)

Signals recorded at Tolmezzo (ground floor)

PGA=140 cm/s2=>0.15 g PGV=3 cm/s

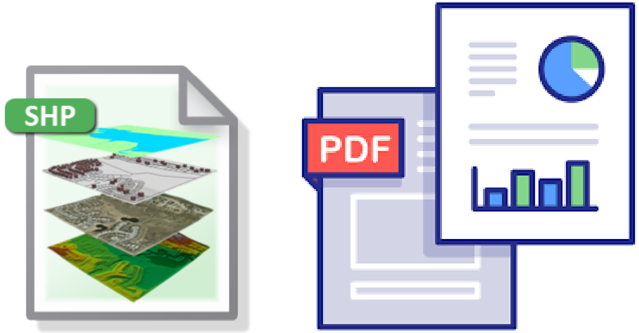


Damage Map



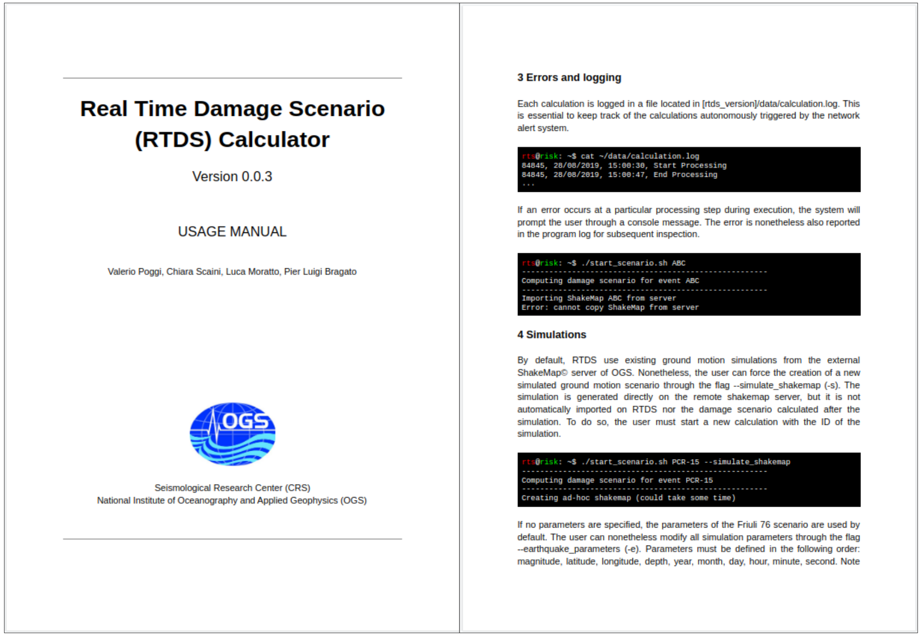
On the maps are the number of damaged building by aggregating severe damage (level D4) and total collapse (level D5) of the EMS98 scale.

A first guess of the number of people impacted is also provided (based on simplified relationships)



The RTDS User Interface

Great attention is give to development of the user interface and the documentation of the calculation system.



Real Time Damage Scenario (RTDS) Calculator

Version 0.0.3

USAGE MANUAL

Valerio Poggi, Chiara Scaini, Luca Moratto, Pier Luigi Bragato

Seismological Research Center (CRS)
National Institute of Oceanography and Applied Geophysics (OGS)

3 Errors and logging

Each calculation is logged in a file located in [rtds_version]/data/calculation.log. This is essential to keep track of the calculations autonomously triggered by the network alert system.

```
rts@risk: ~$ cat ~/data/calculation.log
84845, 28/08/2019, 15:00:30, Start Processing
84845, 28/08/2019, 15:00:47, End Processing
...
```

If an error occurs at a particular processing step during execution, the system will prompt the user through a console message. The error is nonetheless also reported in the program log for subsequent inspection.

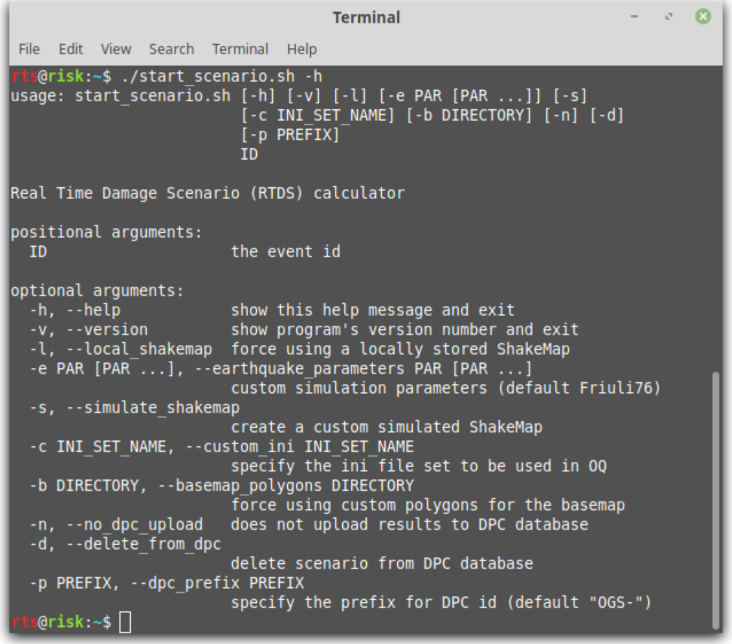
```
rts@risk: ~$ ./start_scenario.sh ABC
----------------------------------------------------------------
Computing damage scenario for event ABC
----------------------------------------------------------------
Importing ShakeMap ABC from server
Error: cannot copy ShakeMap from server
```

4 Simulations

By default, RTDS use existing ground motion simulations from the external ShakeMap© server of OGS. Nonetheless, the user can force the creation of a new simulated ground motion scenario through the flag --simulate_shakemap (-s). The simulation is generated directly on the remote shakemap server, but it is not automatically imported on RTDS nor the damage scenario calculated after the simulation. To do so, the user must start a new calculation with the ID of the simulation.

```
rts@risk: ~$ ./start_scenario.sh PCR-15 --simulate_shakemap
----------------------------------------------------------------
Computing damage scenario for event PCR-15
----------------------------------------------------------------
Creating ad-hoc shakemap (could take some time)
```

If no parameters are specified, the parameters of the Friuli 76 scenario are used by default. The user can nonetheless modify all simulation parameters through the flag --earthquake_parameters (-e). Parameters must be defined in the following order: magnitude, latitude, longitude, depth, year, month, day, hour, minute, second. Note



Terminal

File Edit View Search Terminal Help

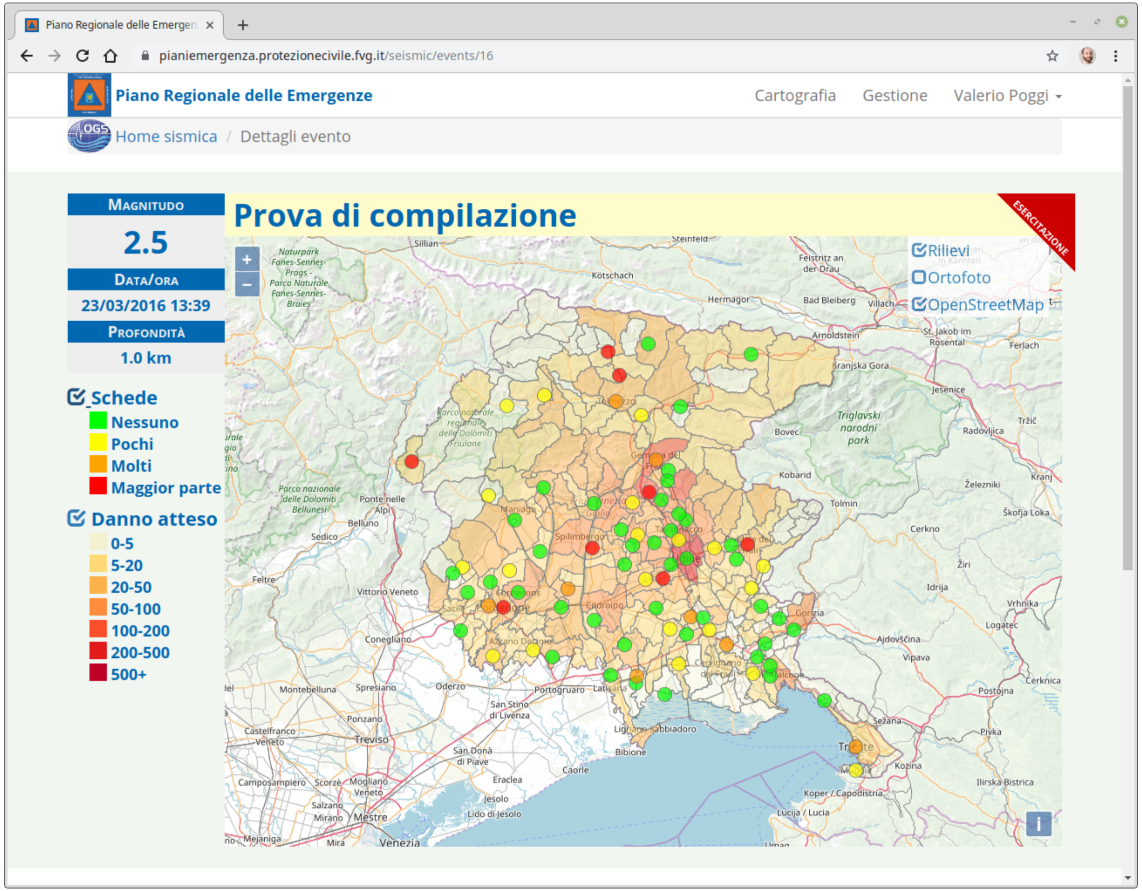
```
rts@risk:~$ ./start_scenario.sh -h
usage: start_scenario.sh [-h] [-v] [-l] [-e PAR [PAR ...]] [-s]
                         [-c INI_SET_NAME] [-b DIRECTORY] [-n] [-d]
                         [-p PREFIX]
                         ID

Real Time Damage Scenario (RTDS) calculator

positional arguments:
  ID                    the event id

optional arguments:
  -h, --help            show this help message and exit
  -v, --version         show program's version number and exit
  -l, --local_shakemap  force using a locally stored ShakeMap
  -e PAR [PAR ...], --earthquake_parameters PAR [PAR ...]
                        custom simulation parameters (default Friuli76)
  -s, --simulate_shakemap
                        create a custom simulated ShakeMap
  -c INI_SET_NAME, --custom_ini INI_SET_NAME
                        specify the ini file set to be used in OQ
  -b DIRECTORY, --basemap_polygons DIRECTORY
                        force using custom polygons for the basemap
  -n, --no_dpc_upload   does not upload results to DPC database
  -d, --delete_from_dpc
                        delete scenario from DPC database
  -p PREFIX, --dpc_prefix PREFIX
                        specify the prefix for DPC id (default "OGS-")
rts@risk:~$
```

python™

Interaction with Civil Protection

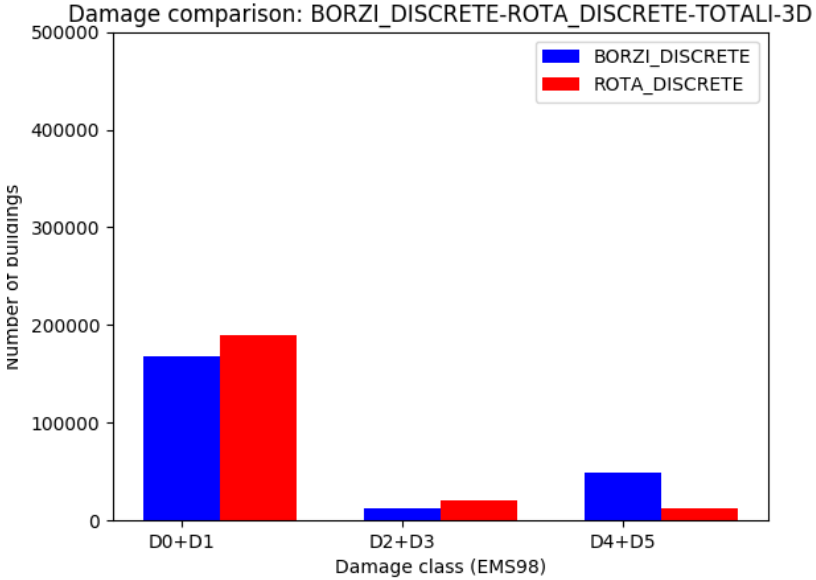
As for the case of predicted ground motion, the expected damage distribution is sent to Civil Protection for operational purposes using a dedicated channel:

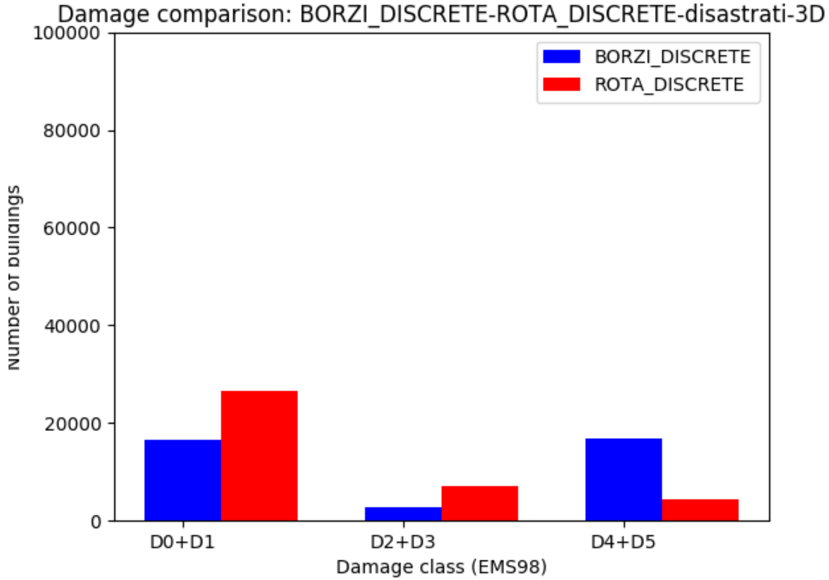
- Training
- Emergency planning
- Post-event response organization
- Etc…



Calibration of the model

We perform different Openquake runs initialized with different fragility curves and compare the results.

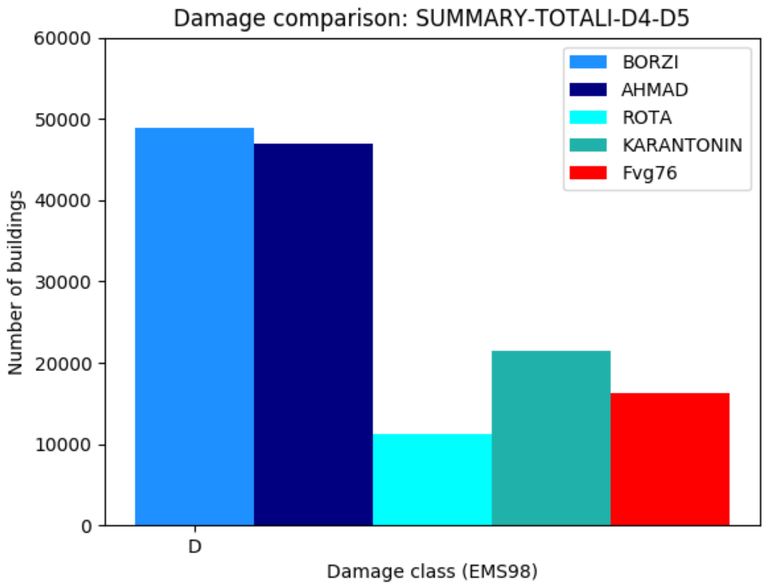


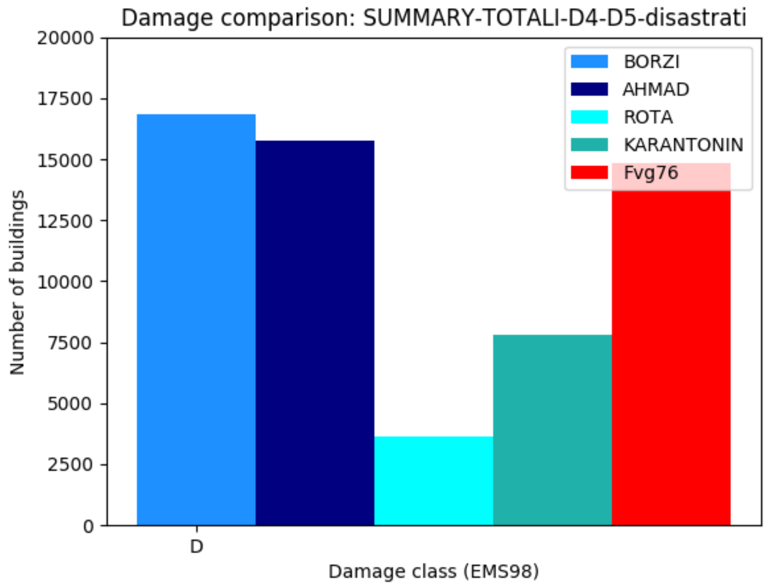


The main difference is in the estimation of high damage levels (D4–D5). Differences are more evident in epicentral areas.

Validation of the model

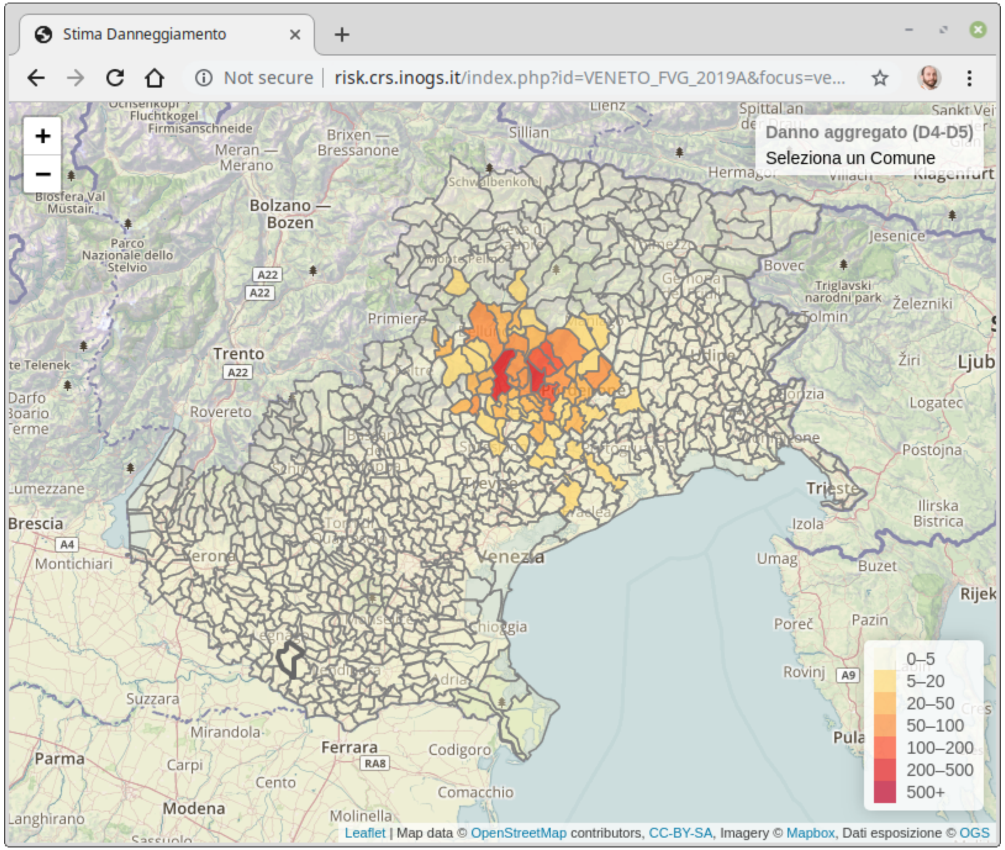
We tested four independent models with different fragility curves and with the buildings older than 1976. The number of highly-damaged buildings is compared with the number of destroyed buildings from post-1976 damage statistics (Friuli Venezia Giulia, 1986).





Karantonin works better in general, but Borzi and Ahmad perform better in epicentral areas.

Next steps: Extension to Veneto



We are presently extending the target area to Veneto.

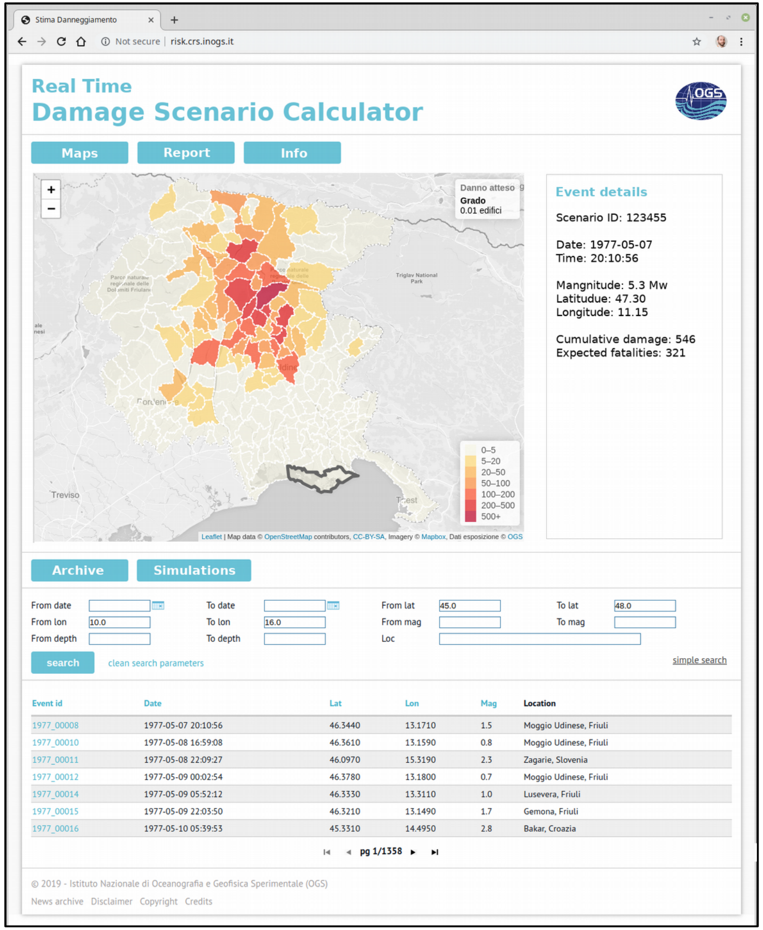
The model is preliminary, and will be better calibrated based on the acquisition of local data.

We are nonetheless interested in including neighborhood regions.

What's needed? CRS Web Interface

- Different Layers (ground motion, aggregated damage, casualties, economic losses)
- Different zooming levels
- List of previous and simulated events
- Possibility to run an ad-hoc scenario

Access through credentials



Retrieving Building Response

So far, we did not consider that different buildings might react differently to the same input ground motion.

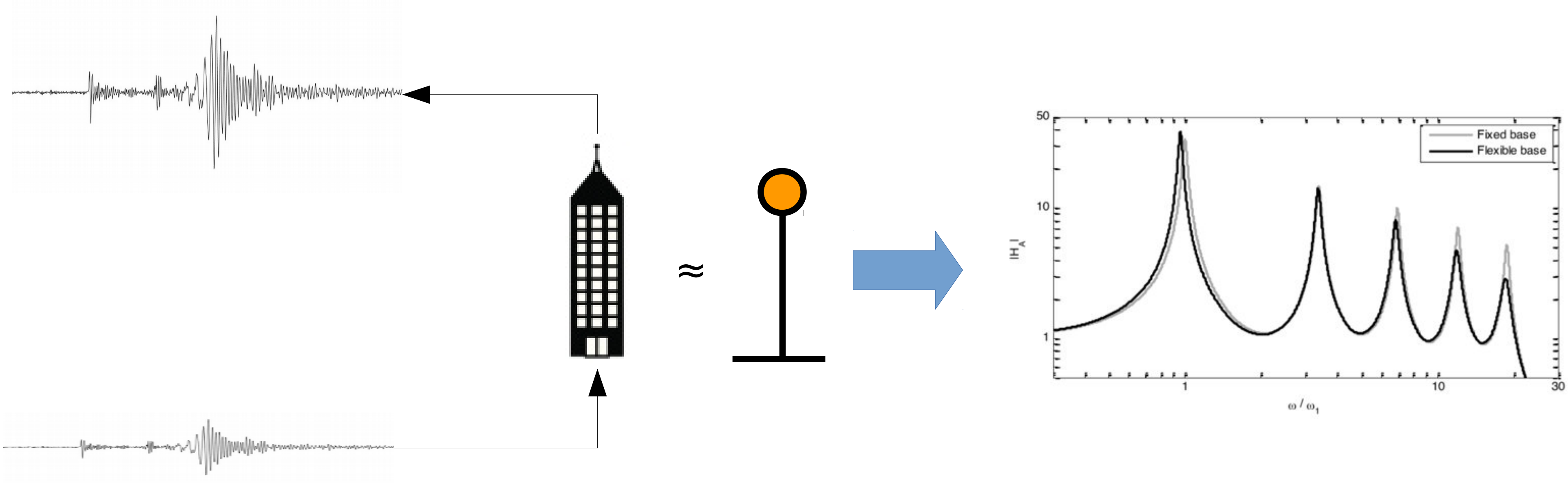
For a more realistic definition of the expected damage it is therefore necessary to include ad-hoc information about the dynamic behavior of the different building typologies.

This can be done by characterizing their **structure response...**

The Harmonic Oscillator Approximation

In engineering It is often useful to represent ground motion as it would be experienced by a structure (building, bridges).

A convenient simplification is obtained by convolving the acceleration time-histories with the theoretical response of a damped one-dimensional harmonic oscillator (representing the structure).



Analytical Response: Duhamel's Integral

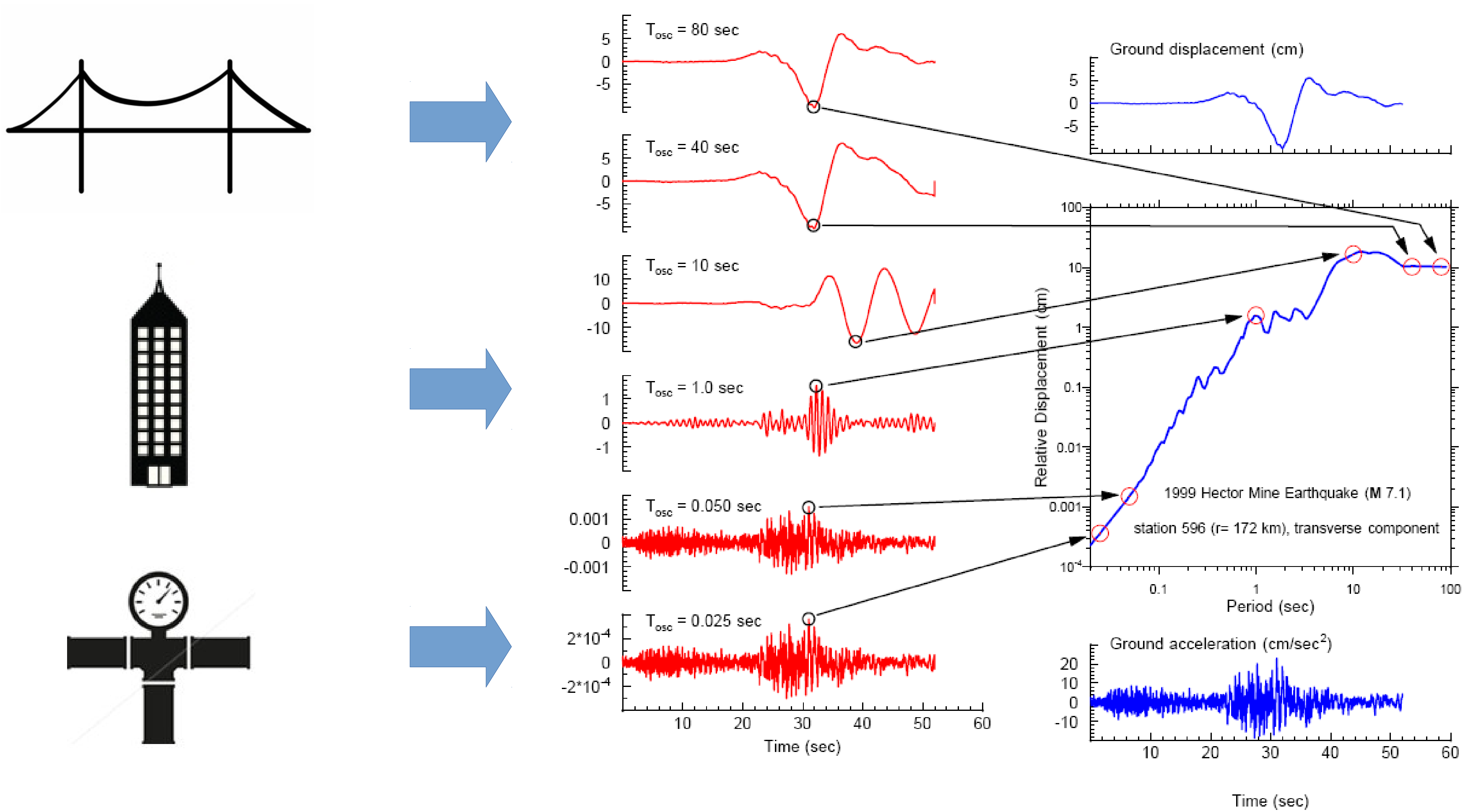
When a building is approximated to a simple (damped) s.d.o.f system, the result of the interaction with input ground motion can be obtained analytically by means of the Duhamel's integral.

$$\boxed{u(t)} = -\frac{1}{\omega_d}\int_0^t \boxed{\ddot{u}(\tau)}\,\boxed{e^{-\zeta\omega_n(t-\tau)}\sin\left(\omega_d(t-\tau)\right)}\,d\tau$$

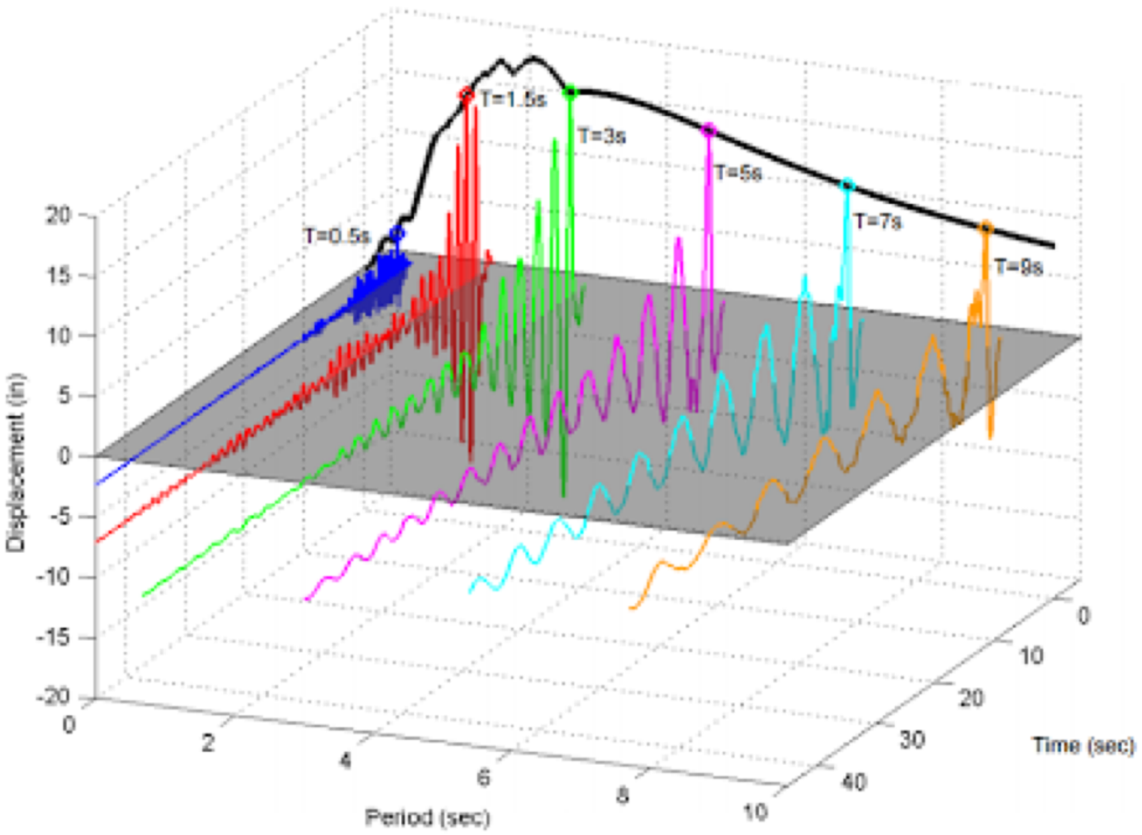
$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

Here, the convolution with the system response function with an acceleration time history produces the displacement response of the system.

The Response Spectrum

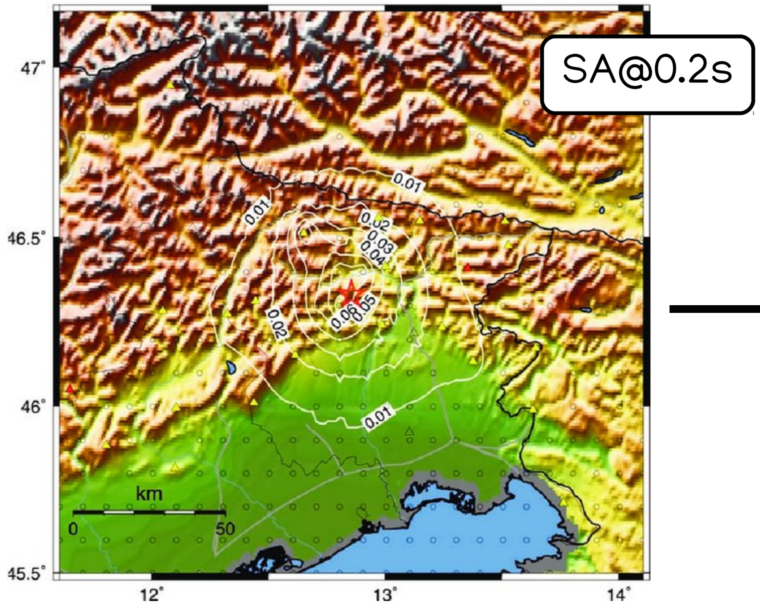


The Response Spectrum



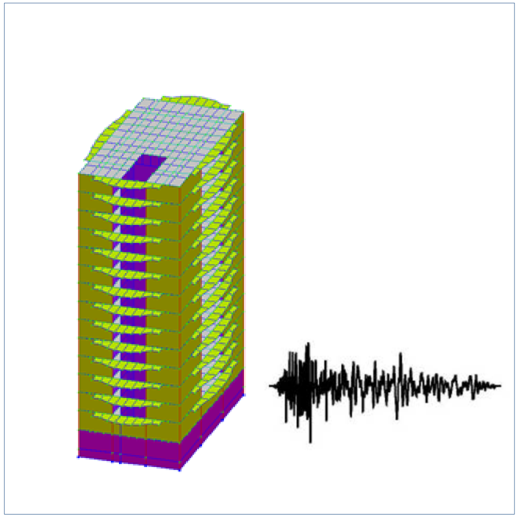
Period Dependent Damage

Ground motion prediction can also be done for various <u>response spectral ordinates</u> (e.g. T=0.1s, 0.2s, 0.5s etc.) other than PGA (T=0s). This allows the damage scenario to be period-dependent, and therefore specific for a specific building typology.

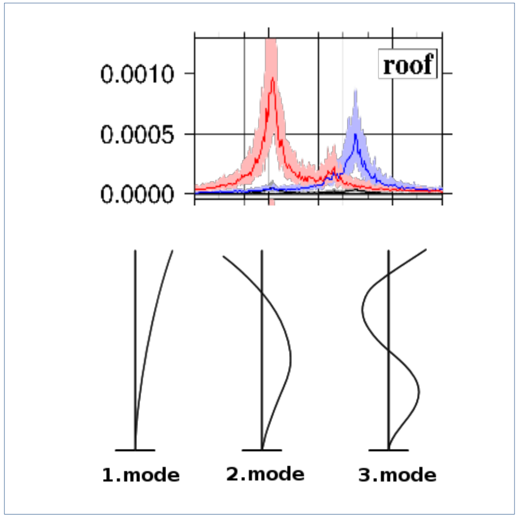


Question: how to identify the typical period of these buildings?

Experimental Characterization of the Response

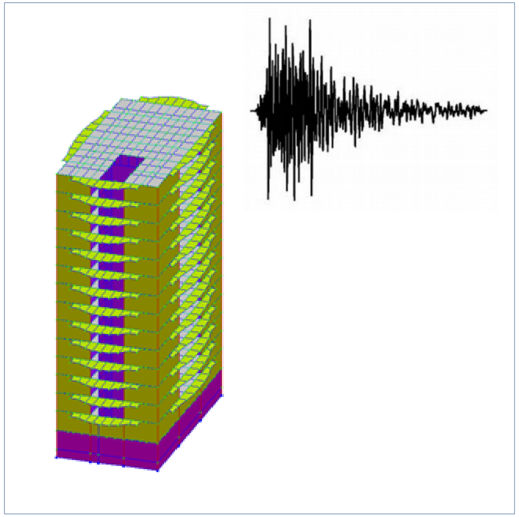


Acceleration recorded by a sensor installed at the bottom of a building



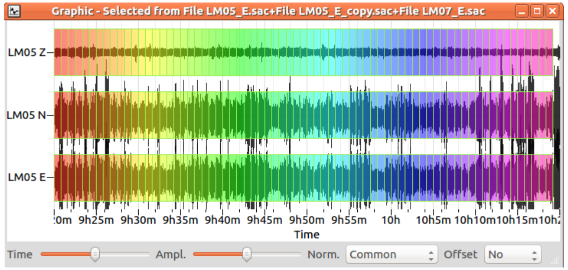
Definition of the vibrational modes by characterization of resonance frequencies (e.g. from ambient vibration)

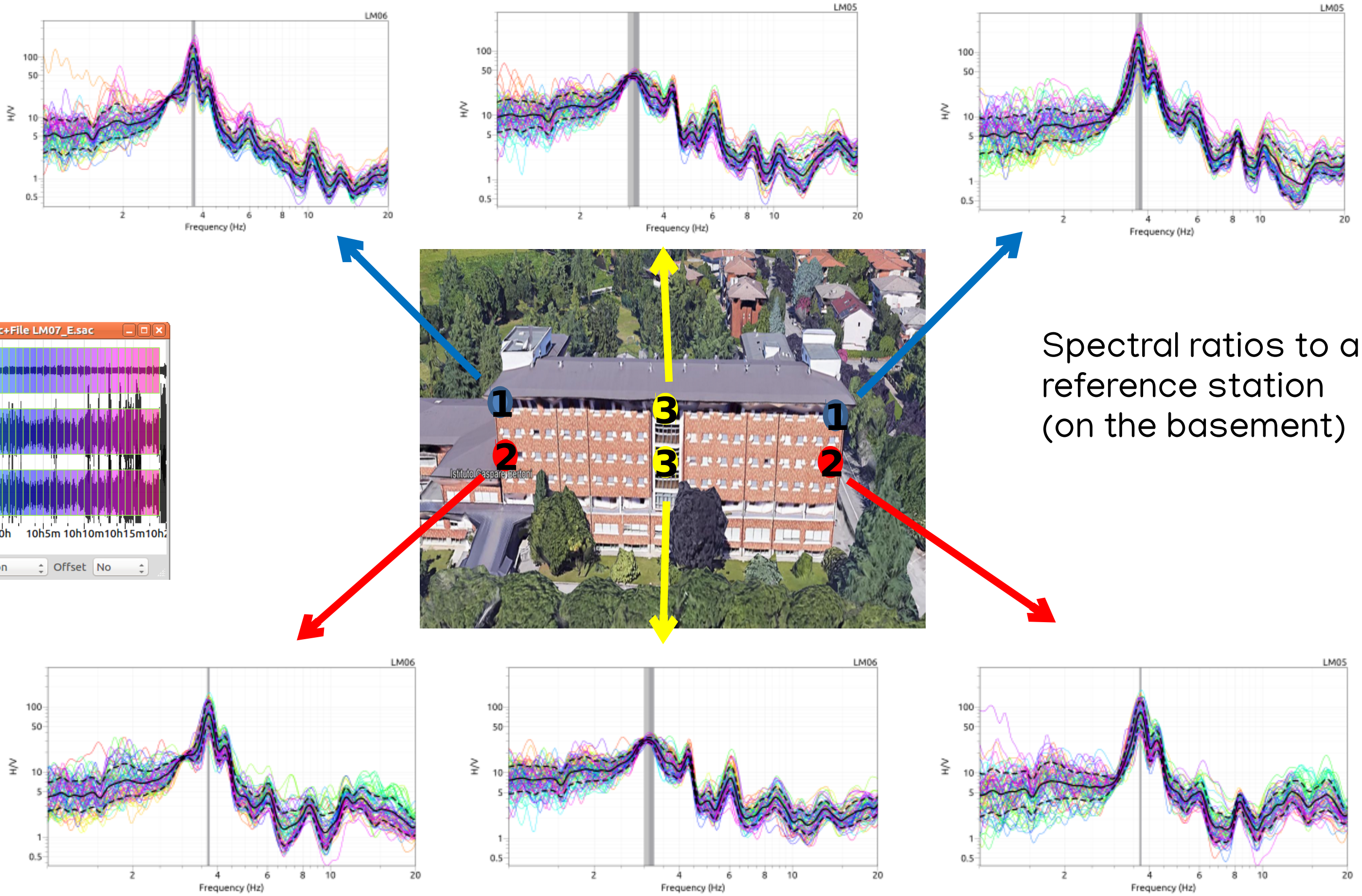
Building is assumed to behave as a SDOF oscillator



Recursive calculation of expected acceleration on the top of the building

Characterization of Specific Buildings





Spectral ratios to a reference station (on the basement)

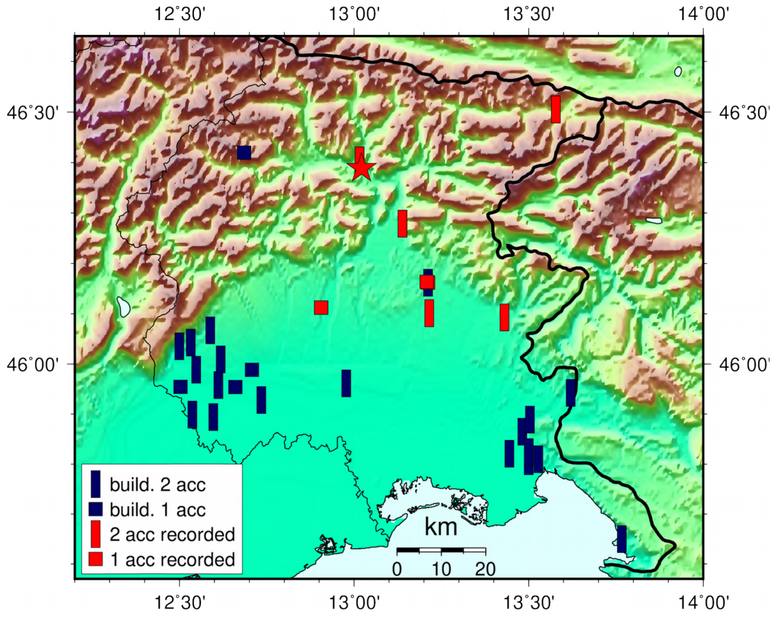
The Structural Monitoring Network

A Monitoring network on buildings (Sentinella, Armonia), in collaboration with civil protection, university of Udine and Trieste.

The network is constituted by 51 sensors on 29 buildings, and few earthquakes of magnitude greater than 3 have been already recorded.

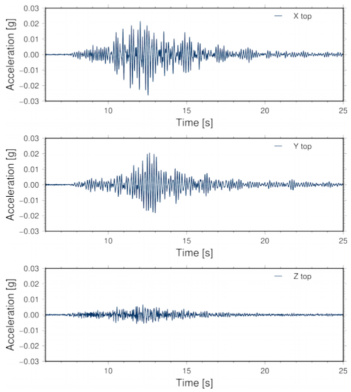
The network allows to refine the ground motion prediction, but also to acquire relevant information on the shaking on buildings.

Verzegnis Event from SentiNet-FVG Network



Distribution of instrumented buildings recording of the M3.9 event of 14.06.2019 (near Verzegnis)

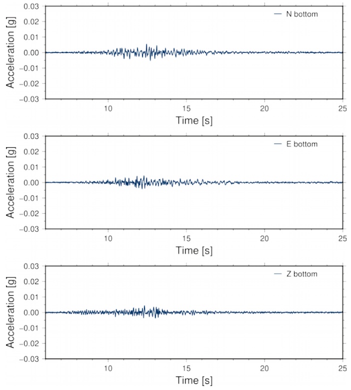
A building in Gemona (UTI) installed with a sensor on the top and one on the bottom.



H1

H2

V



H1

H2

V

The Structural Monitoring Network

Impact on Target Areas

Objective: characterization of areas surrounding the monitored building (*target areas*), in order to estimate the expected displacement at the building (and, subsequently, give information on the expected damage).

Methodology: perform noise measurements on several buildings of the same typology and extract the fundamental frequency. Need to analyze many buildings in order to obtain a statistically robust dataset.

Expected result: an average value of fundamental period for each typology, and its standard deviation.

Work in progress: we intend to perform measurements in the whole region.

Aviano Testing Site

- City hall monitored with two sensors (bottom and top)
- Presence of representative building typologies
- Scarcely damaged during the events of 1936 (Cansiglio) and 1976 (Friuli)

Conclusions

The damage scenario calculator is already up and running, therefore it can be used to support emergency management, training activities and territorial planning.

The implemented system is state-of-art and it has to be intended as a starting point for further scientific development.

We are currently improving the overall methodology by:

- Enriching exposure and fragility information
- Testing and verifying the model reliability through validation against observed damage
- Implementing a locally calibrated ground motion model, accounting for site effects
- Collecting feedback from stakeholders