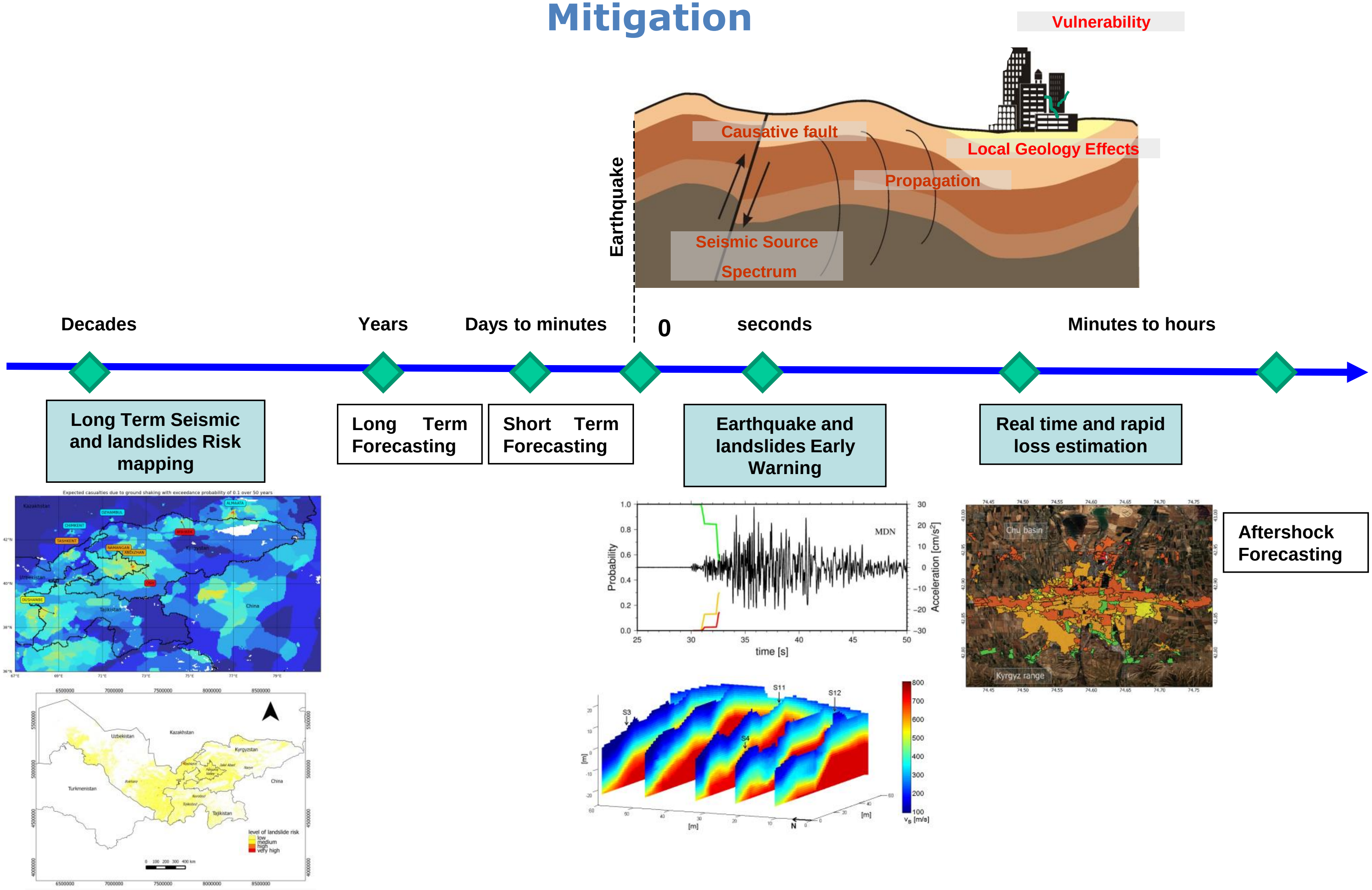
Earthquake Early Warning

S. Parolai

Seismic Risk Assessment and Mitigation



Objective

The goal of an EEW system is the estimation in a fast and reliable way an earthquake's damage potential before the strong shaking hits the target

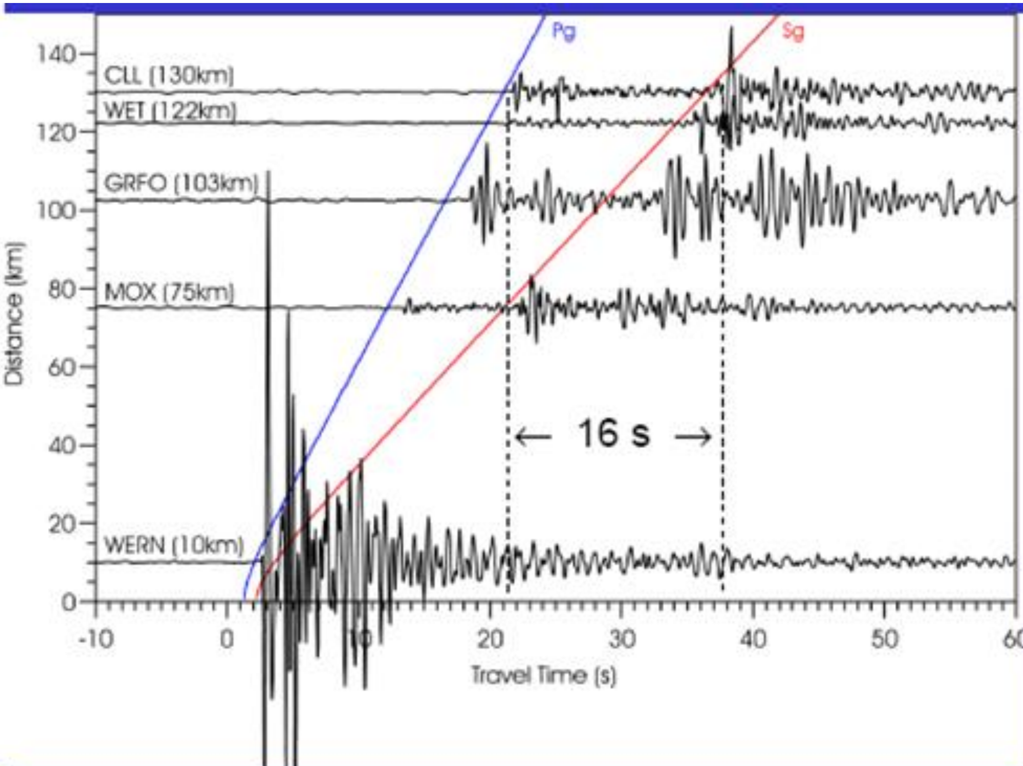
Principles

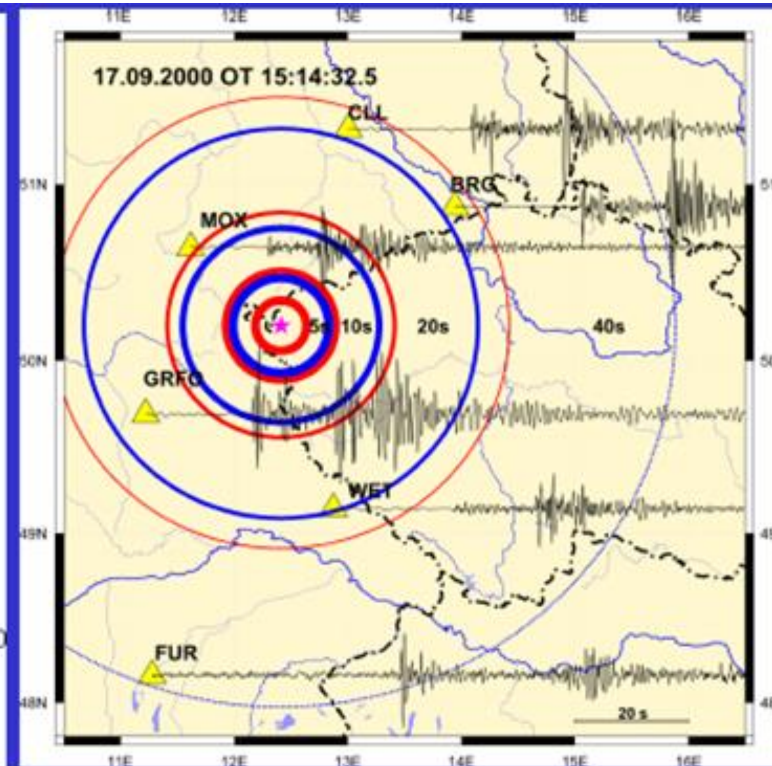
The idea of developing systems for launching early alert messages about incoming ground shaking dates back to 1868 (*Cooper JD, Letter to the Editor, San Francisco Daily Evening Bulletin, November 3, 1868*). It is based on the fact that information spread through electromagnetic signals travels faster (about 300,000 km/s) than seismic waves (a few km/s). Moreover, most of the radiated seismic energy is carried by S- and surface-waves, which travel slower than P-waves.

Early examples

The first early warning systems were developed and installed during the cold war to detect incoming intercontinental ballistic missiles. These early warning systems were designed to alert target areas as soon as a missile was detected by a radar or a launch discovered by satellite systems.

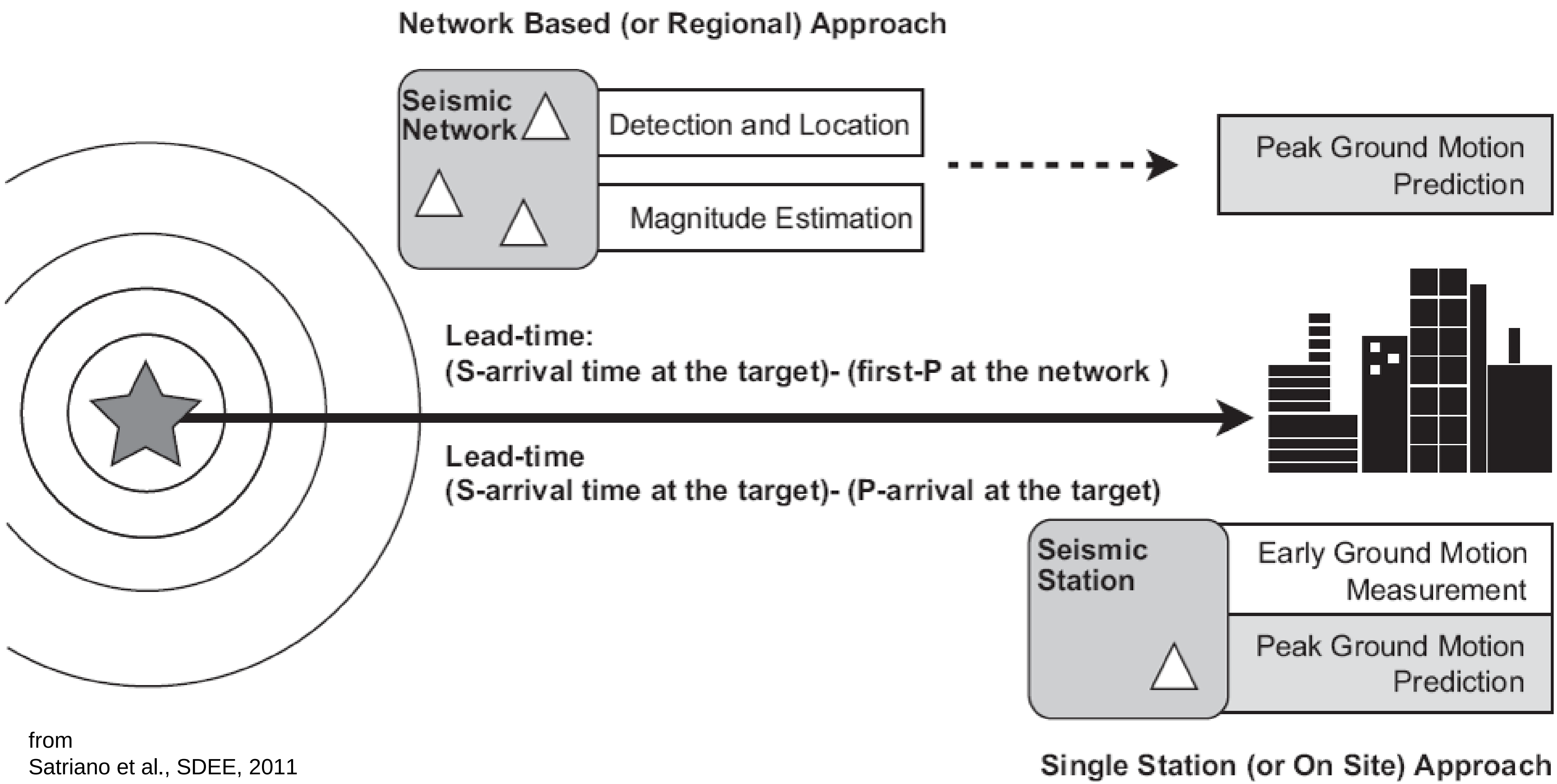
from
Satriano et al., SDEE, 2011


Pg
Sg
CLL (130km)
WET (122km)
GRFO (103km)
MOX (75km)
WERN (10km)
← 16 s →
Distance (km)
Travel Time (s)
140
120
100
80
60
40
20
0
-10
0
10
20
30
40
50
60


17.09.2000 OT 15:14:32.5
CLL
BRG
MOX
GRFO
WET
FUR
5s
10s
20s
40s
20 s
11E
12E
13E
14E
15E
16E
51N
50N
49N
48N

Approaches

There are two main approaches: **Regional** (or network-based) EEW systems and **Onsite** (or single-station) EEW systems.



from
Satriano et al., SDEE, 2011

Methodology

Regional network EEW system

Event detection and location

Magnitude estimation

Peak ground motion prediction at target site

Alert notification

Onsite approaches predict the ground shaking associated with S-wave starting from the ground shaking recorded for P-waves.
Some Onsite (or single station) EEW systems also estimate the location and magnitude of the event (e.g., Nakamura approach; Odaka approach; etc).

Starting from the Regional and Onsite schemes, more complex and hybrid systems can be established. For example, Onsite systems can be composed of several nodes communicating witheach others and fed with information coming from a Regional networks. The Regional scheme may in turn simplified into a concept involving a front-detection scheme when the source region is known.

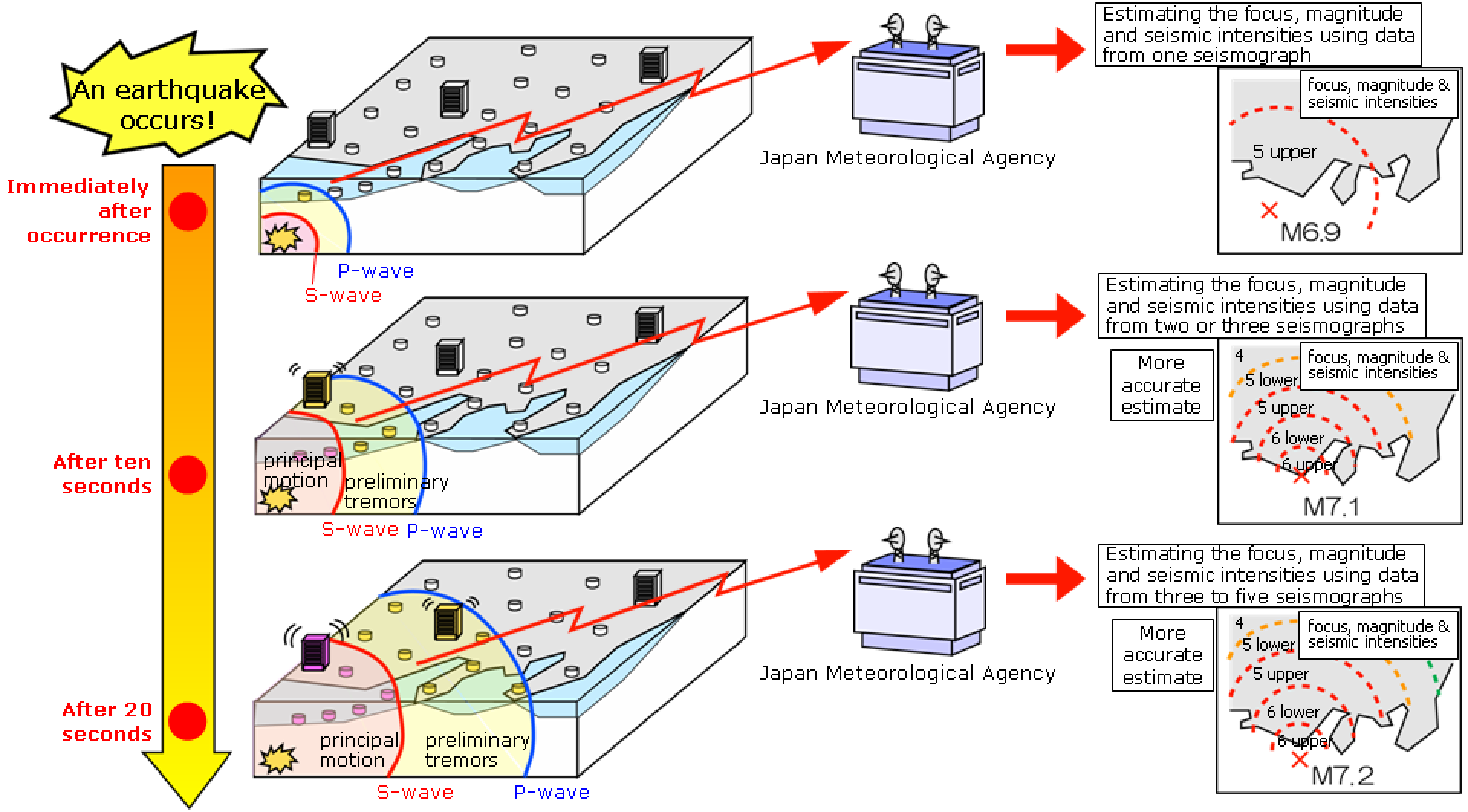
Time is a critical parameter in any EEW system. The system and procedures have to be designed in such a way as to maximize the **lead time** for the target area.

	Regional	**Onsite**
Network deployment	Source region	Target area
Data analysis	Network based	Single station
Output parameters	Location, magnitude	Location, magnitude or expected intensity
Accuracy on source parameter estimation	Good to high	Moderate
Lead-time	Ts at the target–Tp at the source	Ts at the target–Tp at the target

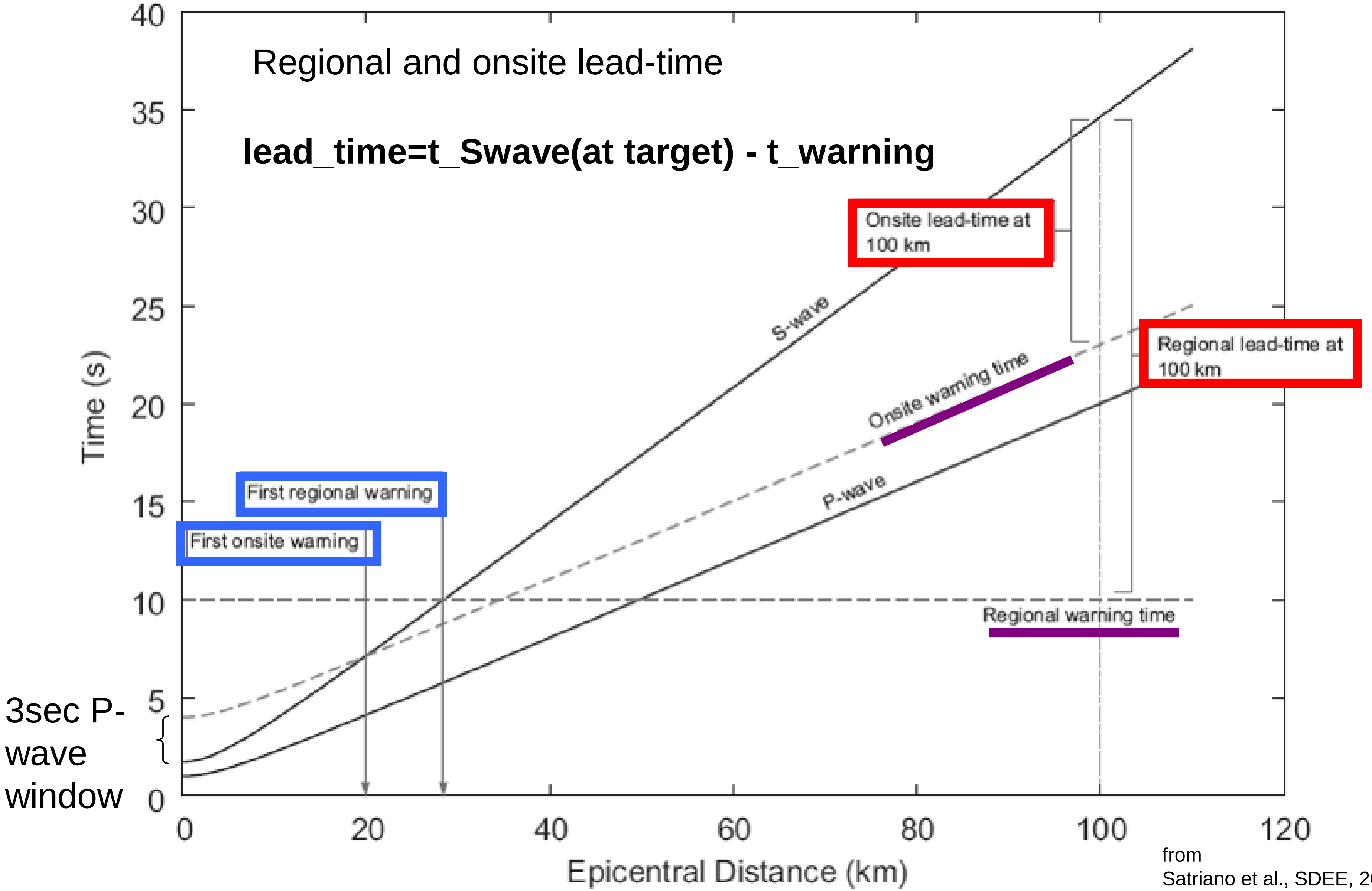
from
Satriano et al., SDEE, 2011

Lead time maximization and improvements in the estimation of parameters (such as magnitude, location) however involve a trade-off. The minimization of the false alarms is also crucial.

Therefore, any EEW system has to be tailored to the specific situation at hand.



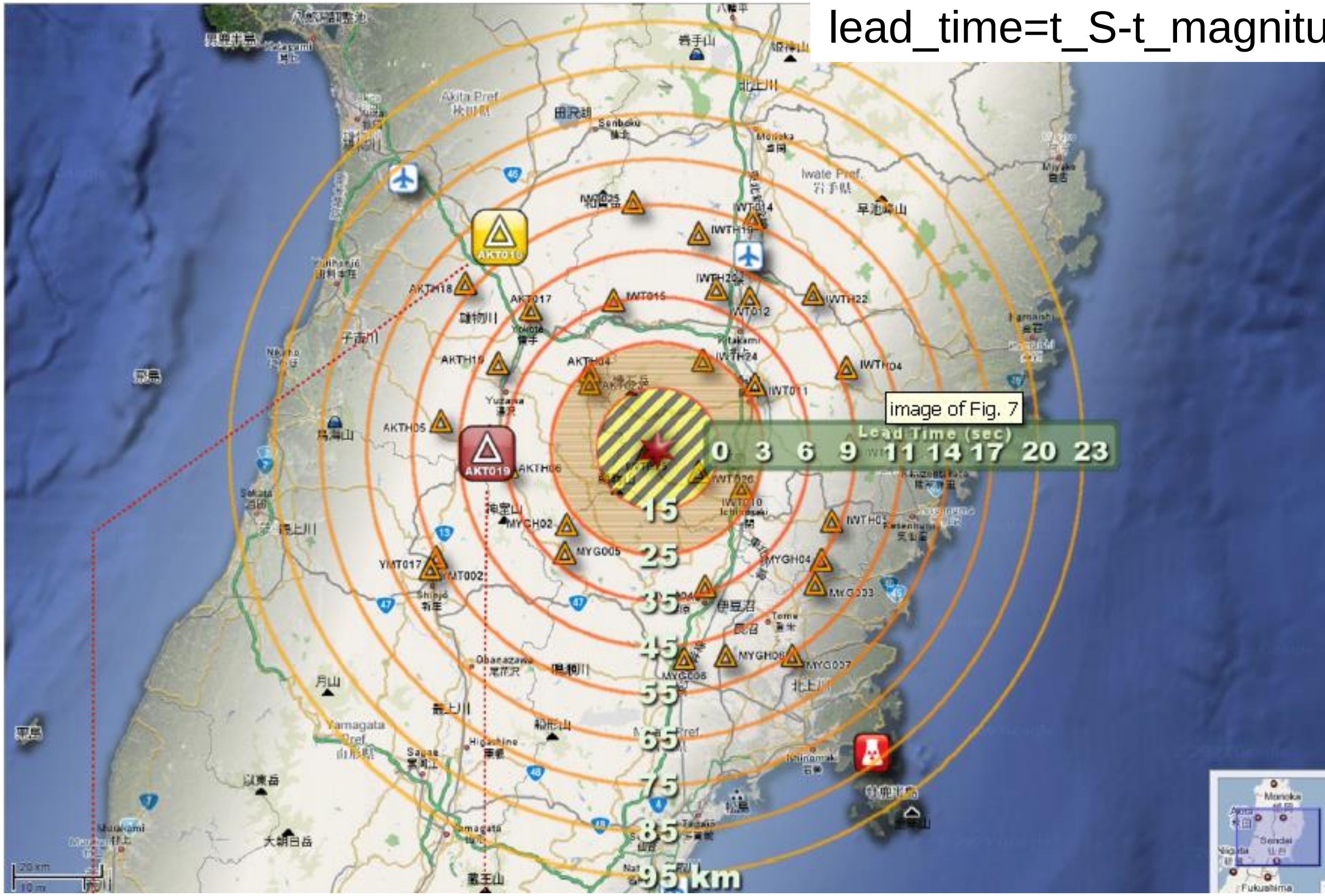
from
JMA webpage



from
Satriano et al., SDEE, 2011

Examples of estimated lead time

2008 Mw 6.9 Iwate earthquake (Japan).
lead_time=t_S-t_magnitude_estimated

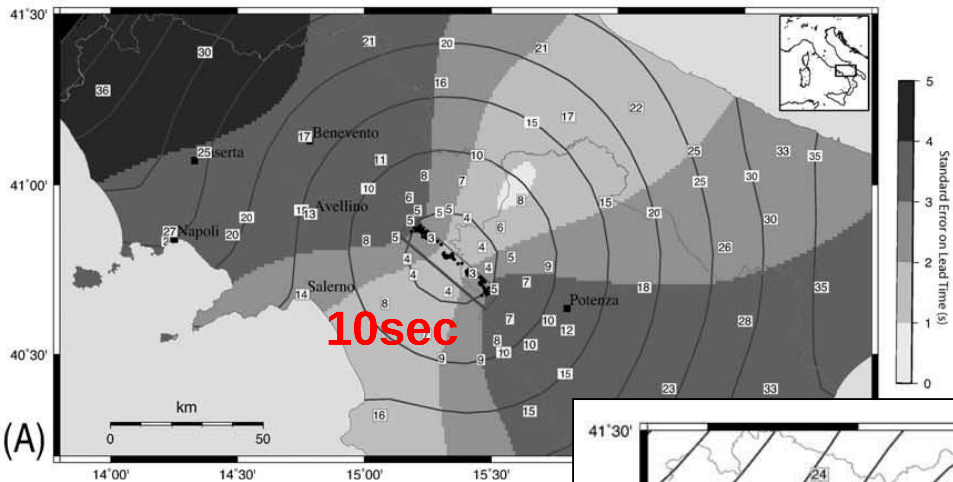


yellow:
blind zone

orange:
blind zone
when robust
magnitude
estimates are
requested

from
Satriano et al.,
SDEE, 2011

Examples of estimated lead time

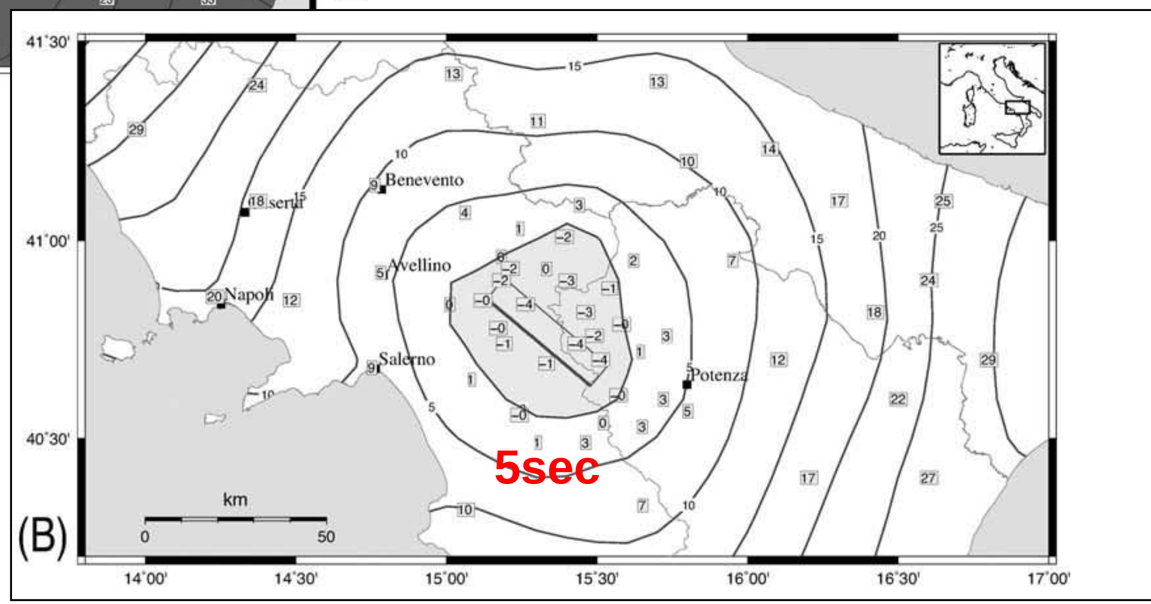


1980 Mw 6.9 Irpinia earthquake

(maximum)**lead_time**=
time_S - **time**_mag&loc_first estimate

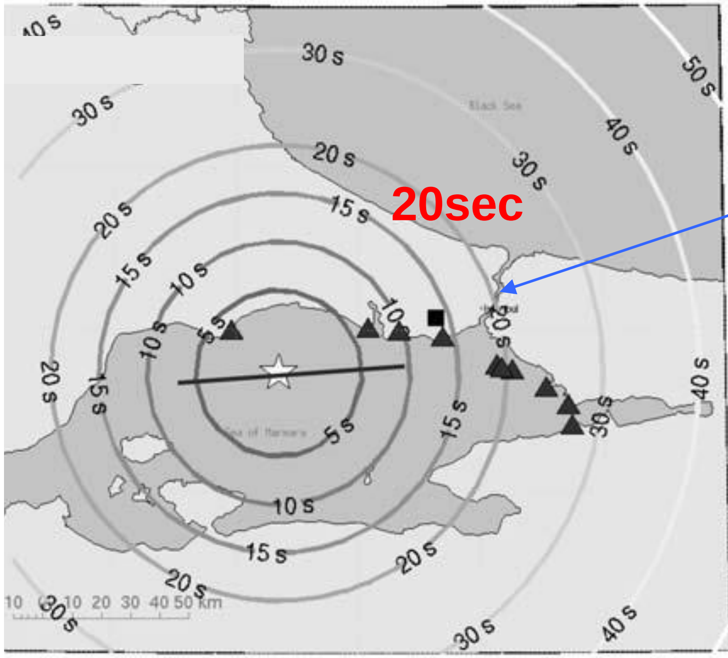
from
Zollo et al GRL, 2009

gray area:
blind zone



(effective)**lead_time**=**time**_S - **time**_EW_parameters_stable estimate

Examples of estimated lead time



Istanbul

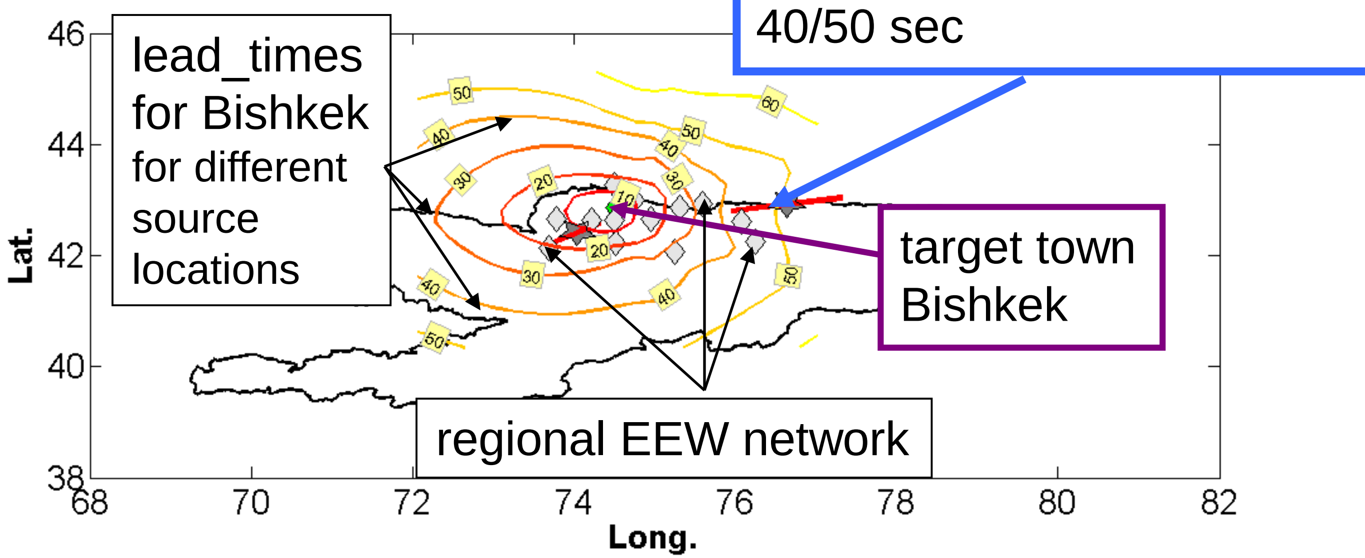
Scenario earthquake in the Marmara sea

from
Böse et al, BSSA, 2008

Feasibility study for

Kyrgyzstan

from
Picozzi et al, JOSE, 2012



Earthquake location

Procedures for estimating early warning parameters are generally based on evolutionary (time-dependent) schemes: the “quick & dirty” estimates obtained by analyzing information gathered by a single station are constantly updated as soon as new data are acquired by the system.

Example:

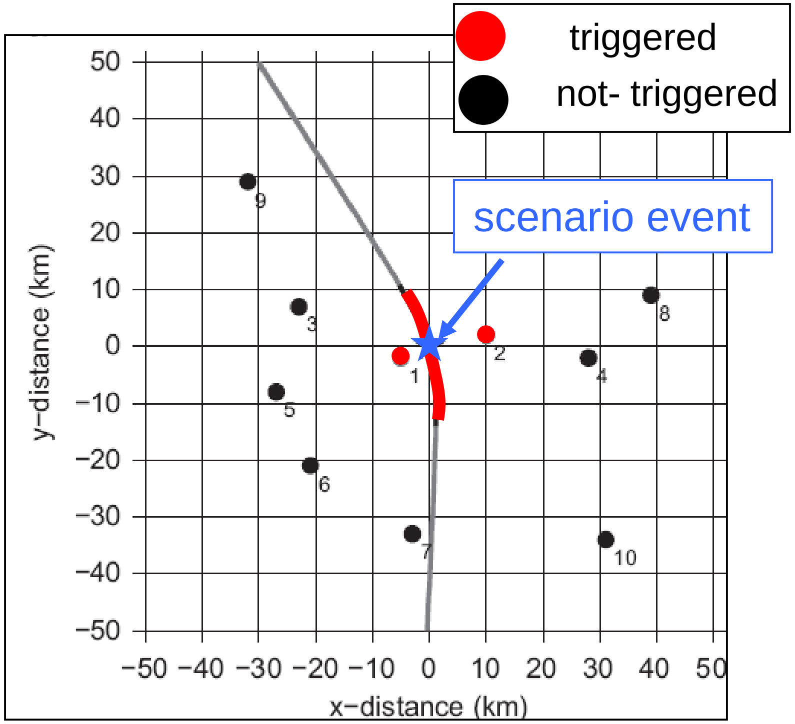
ElarmS (California, Wurman et al 2007):

A) Detection based on STA(0.5sec)/LTA(5sec) ratio at each individual station.
B) Initial hypocenter placed with respect to the triggered station (depth fixed according to the regional tectonic regime).
C) When a second station is triggered, the epicenter is moved between the two stations.
D) With three or more triggers, event location and origin time are estimated using a grid search algorithm.

Earthquake location

Recently, new earthquake location procedures have been introduced.
These make use of the concept of **not-yet-triggered** stations.

Ryedelek & Pujol (2004) constrained the epicentral location using only two triggered stations and a set of not-yet-triggered ones.



Stations 1 and 2 triggered:

$$t_2 - t_1 = \frac{1}{V}(d_2(\mathbf{x}) - d_1(\mathbf{x})) = tt_2(\mathbf{x}) - tt_1(\mathbf{x}) \qquad (1)$$

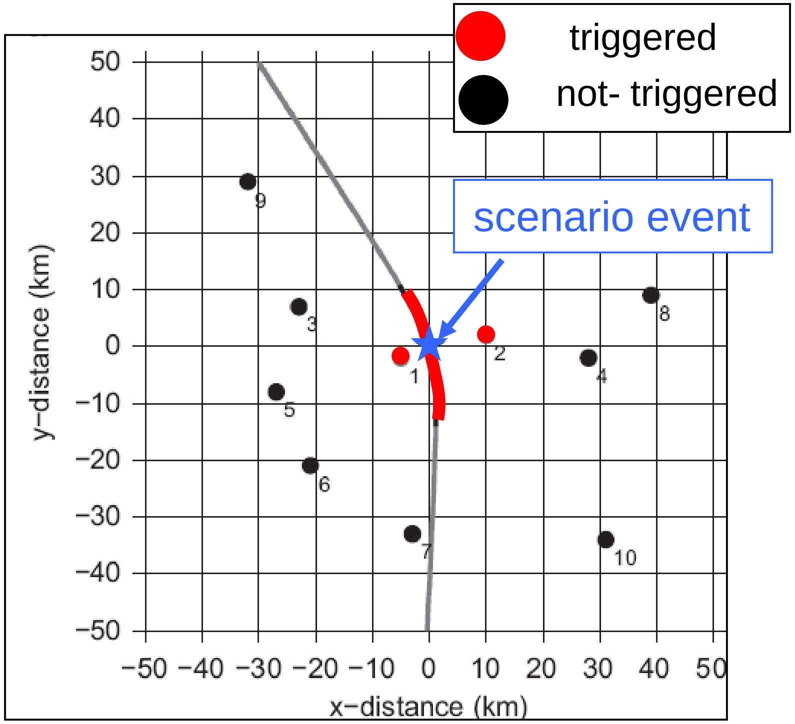
Equation (1) defines a hyperbola (open curve).
Station 3 has not yet triggered, therefore

$$\frac{1}{V}(d_3(\mathbf{x}) - d_i(\mathbf{x})) = tt_3(\mathbf{x}) - tt_i(\mathbf{x}) \geq 0, \quad i = 1,2 \qquad (2)$$

and similar inequalities can be set up for the other not-triggered stations. This set of inequalities identifies a segment (shown in red in Figure) over the hyperbola.

Earthquake location

Recently, new earthquake location procedures have been introduced. They make use of the concept of **not-yet-triggered** stations.



$$\frac{1}{V}(d_3(\mathbf{x})-d_i(\mathbf{x})) = tt_3(\mathbf{x})-tt_i(\mathbf{x}) \geq 0, \quad i = 1,2 \qquad (2)$$

Horiuchi et al. (2005) extended this approach considering that, as time passes since the first two triggers: a) the constraint on the earthquake location given by (2) increases and b) other stations will trigger. Equation (2) can be generalized to

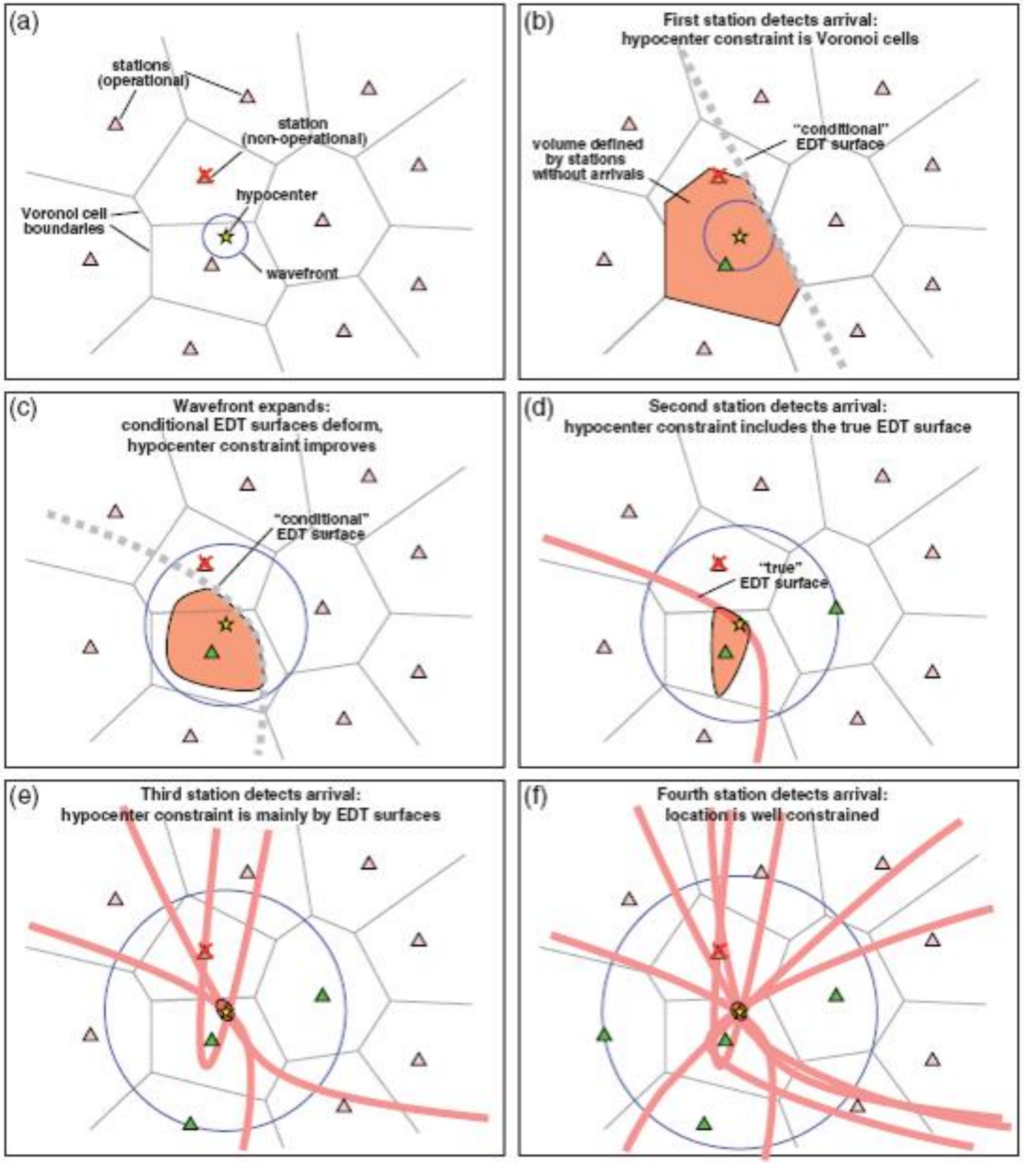
$$tt_j(\mathbf{x})-tt_i(\mathbf{x}) \geq t_{now}-t_i \qquad (3)$$

where i is a triggered-station and j not-trig-station. This inequalities identifies a volume containing the hypocenter which shrinks when t_now is running

Earthquake location

Cua & Heaton (2007) extended the previous approach by introducing Voronoi cells, in order to start the location determination with only one triggered station.

The approach has been further developed by Satriano et al. (2008) and Rosenberg (2009).

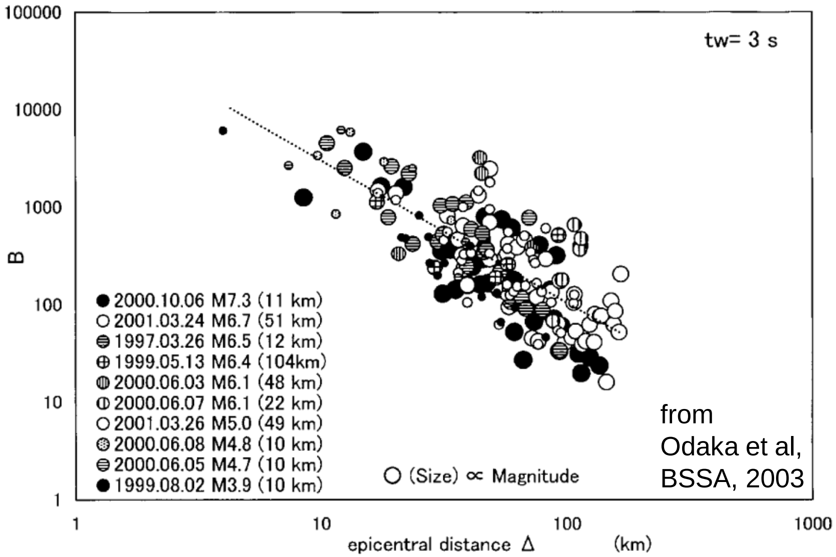


Earthquake location

Regarding the **Onsite** approaches, there are some examples of location (and magnitude) **estimation using a single station**.

Nakamura (1984). The UrEDAS system first estimates the magnitude on the basis of the predominant period of the P-waves.
Then, the hypocentral distance is inferred from the peak P-wave amplitude using an empirical magnitude-amplitude relation that includes the hypocentral distance as a parameter. The azimuth of the epicenter is determined by polarization analysis over the three components.

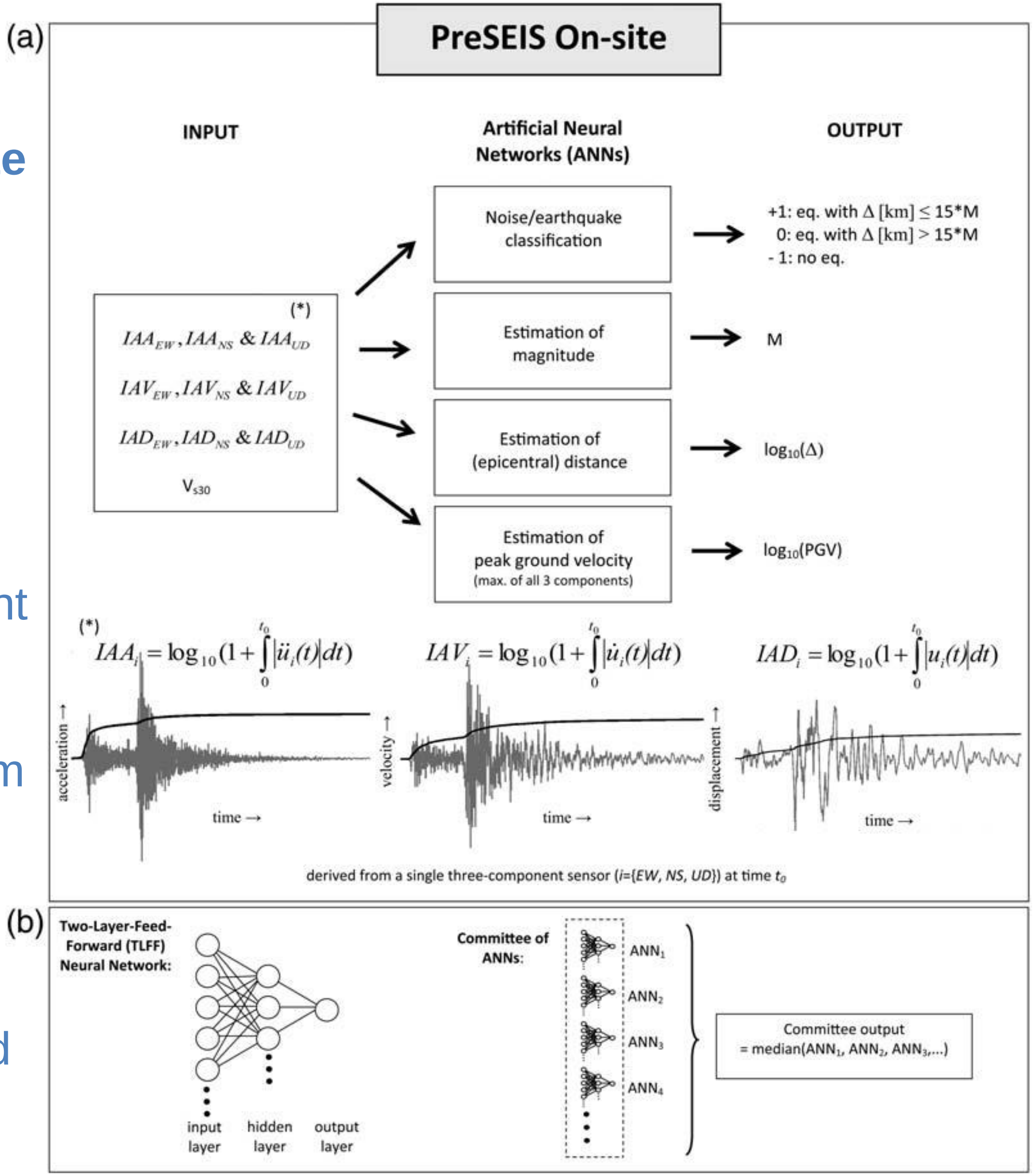
Odaka et al (2003). The function B t *exp*(-A t) is fitted to the envelope of the vertical component of acceleration (considering the first 3 sec). It has been observed that log(B) is proportional to – log(distance). The distance is first found using the measured B value, then the magnitude is determined using empirical equations for P-wave amplitude as in the Nakamura method.



from Odaka et al, BSSA, 2003

Earthquake location

Böse et al (2012). The **PreSeis On-site** approach provides a rapid earthquake/noise discrimination, a near/far source classification, and estimates the moment magnitude, the epicentral distance, and the peak ground velocity at the site of observation. PreSeis uses the seismic acceleration, velocity, and displacement waveforms recorded at a single three-component Strong Motion (SM) or Broad-Band (BB) sensor. The algorithm is based on Artificial Neural Networks (ANNs). Moreover, it uses global data sets of BB and SM records for the training phase. This makes the approach more general and less linked to a specific region.



Earthquake magnitude estimation

Rapid magnitude estimation for EEW is based on the observation that quantities like peak displacement, characteristic period, etc., estimated in the first few seconds of the recorded P- or S-signal, can be correlated to the final earthquake size. The EEW magnitude estimation is therefore based on empirical relationships between early-measured parameters and the earthquake's size.

from
Satriano et al., SDEE, 2011

Examples:

The use of the initial portion of recorded P-wave for magnitude determination was introduced by Nakamura (1988). The **predominant period** is computed from the initial 2-4 sec of P-wave. It is called τ_p after Allen and Kanamori(2003). It is computed in real time from the vertical component of velocity (V) and acceleration (A):

$$\tau_{p,i} = 2\pi\sqrt{\frac{V_i}{A_i}}$$

where

$$V_i = \alpha V_{i-1} + v_i^2$$

$$A_i = \alpha A_{i-1} + a_i^2$$

and a is a smoothing parameter from 0 and 1.

Earthquake magnitude estimation

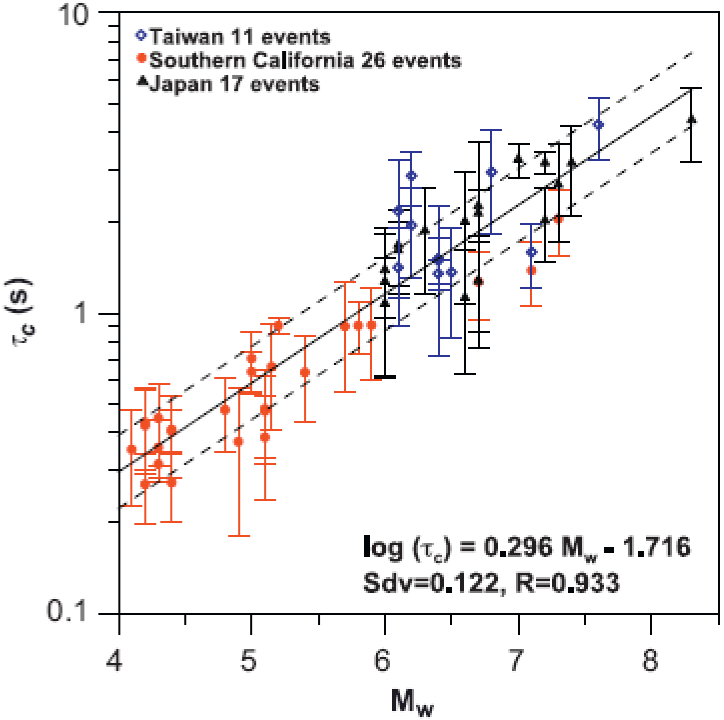
Nakamura (1988) and Allen and Kanamori(2003) observed that the predominant period linearly scales with the earthquake size.
Kanamori (2005) introduced the parameter τ_c which is similar to τ_p but defined as

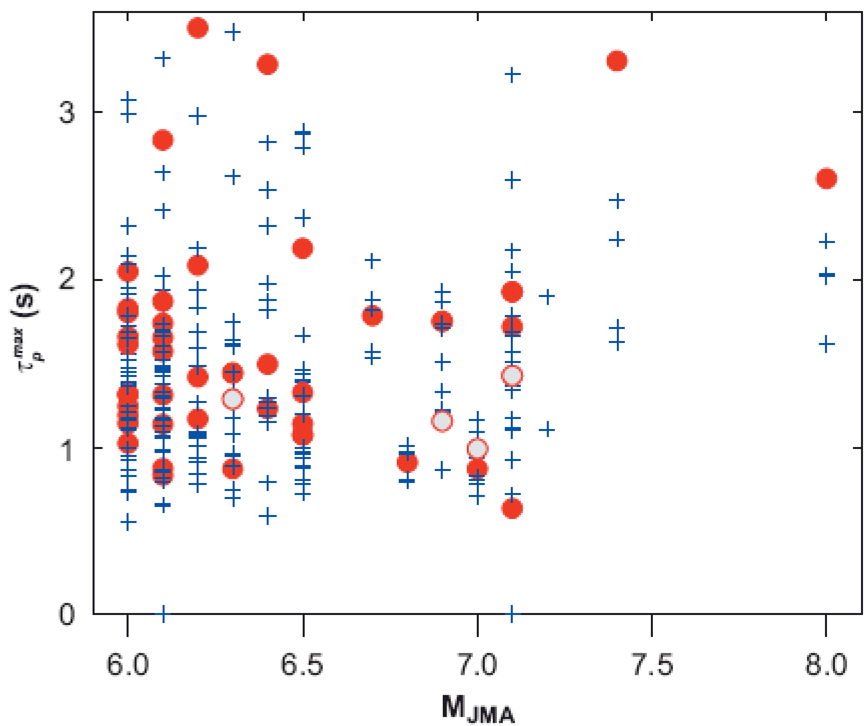
$$r = \frac{\int_0^{\tau_0} \dot{u}^2(t)\,dt}{\int_0^{\tau_0} u^2(t)\,dt} \qquad \tau_c = \frac{1}{\sqrt{\langle f^2 \rangle}} = \frac{2\pi}{\sqrt{r}}$$

With τ_0 generally equal to 3 sec, and with displacement obtained by numerical integration and high-pass filtered at 0.075 Hz.

The effectiveness of this approach is still under debate.

Earthquake magnitude estimation





Wu and Kanamori (2008): Correlation between τ_c and Mw of earthquakes in Japan, Southern California, and Taiwan.

Rydelek and Horiuchi (2006): No-Correlation is seen between τ_p and M_{JMA} of earthquakes in Japan (Hi-Net)

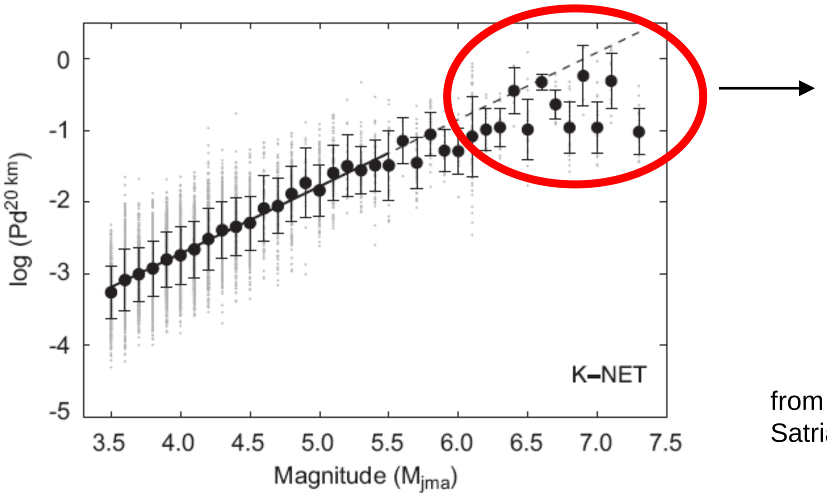
from
Satriano et al., SDEE, 2011

Earthquake magnitude estimation

Different parameters from the predominant period have been introduced.
Wu & Zhao(2006) and Zollo et al. (2006) investigated the peak displacement amplitude measured on the early P (and S) phases.
Wu and Zhao called this parameters Pd, measured on the vertical component, using the first 3 sec after the P arrival. They studied the attenuation of Pd with magnitude and distance in southern California:

$$\log P_d = A + BM + C \log R$$

where the constants A, B, and C are determined trough regression analysis for the studied area. Once the distance is determined by the EEW algorithm, this empirical model is used to estimate M from the measured Pd.



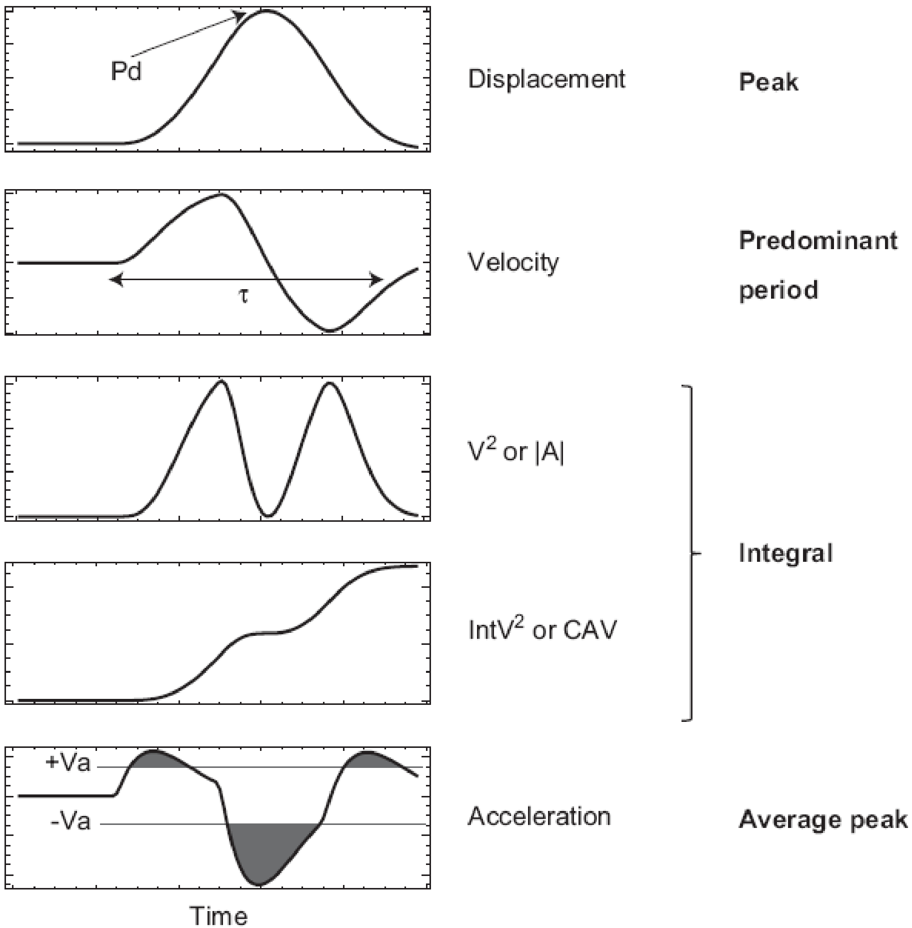
The saturation effect is removed by considering larger windows (4sec of P-wave) or using the peaks read from the S-waves (Zollo et al, 2996; Lancieri and Zollo, 2008).

from
Satriano et al., SDEE, 2011

Earthquake magnitude estimation

Another class of EEW parameters used for estimating the earthquake size involves **integral measurements** (e.g. Festa et al., 2008)

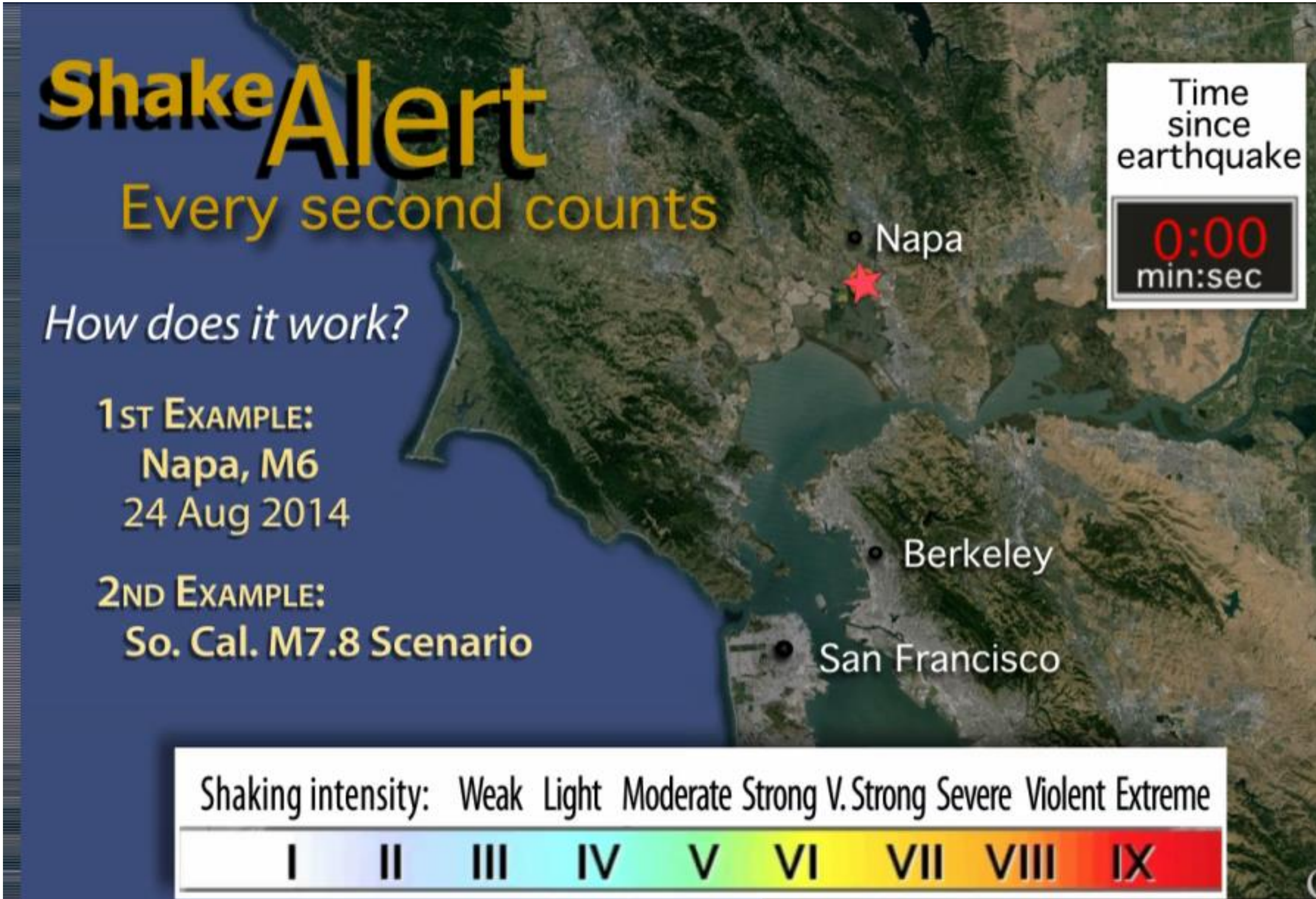
from
Satriano et al., SDEE, 2011



$$CAV = \int_0^{t_{max}} \left| a(t) \right| dt$$

$$IV2_c = \int_{t_c}^{t_c + \Delta t_c} v_c^2(t)\, dt$$

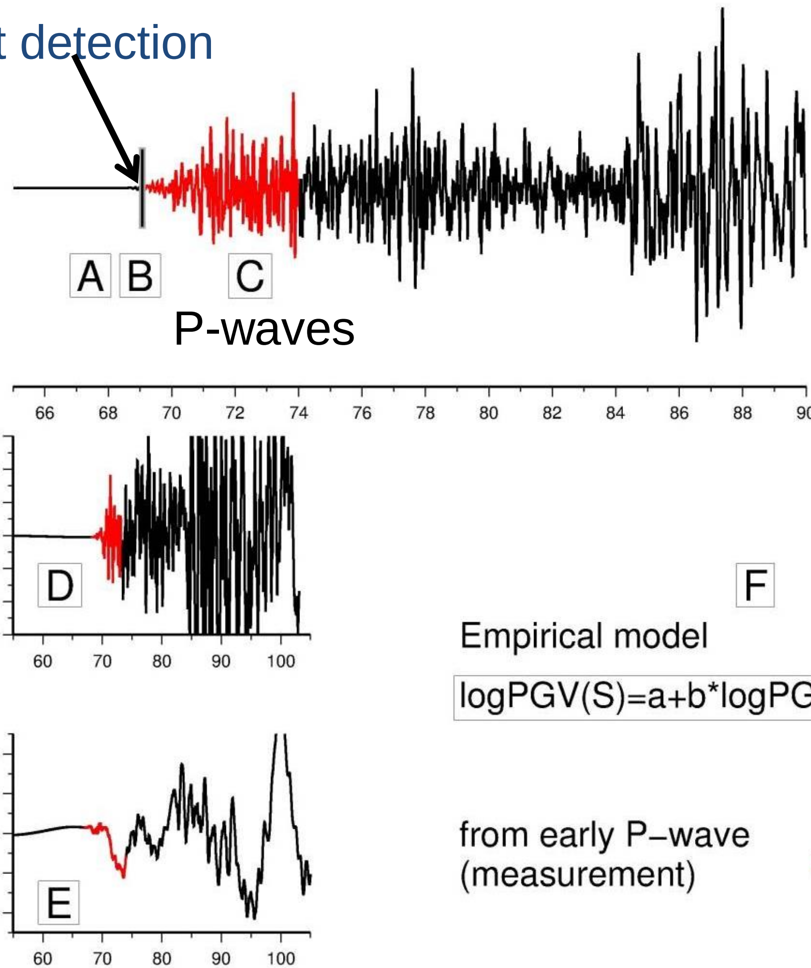
with c= P or S phases


ShakeAlert
Every second counts
How does it work?
1st Example:
Napa, M6
24 Aug 2014
2nd Example:
So. Cal. M7.8 Scenario
Time since earthquake
0:00
min:sec
Napa
Berkeley
San Francisco
Shaking intensity: Weak Light Moderate Strong V. Strong Severe Violent Extreme
I II III IV V VI VII VIII IX

Decentralised Onsite Early warning

Real-time acceleration

Event detection

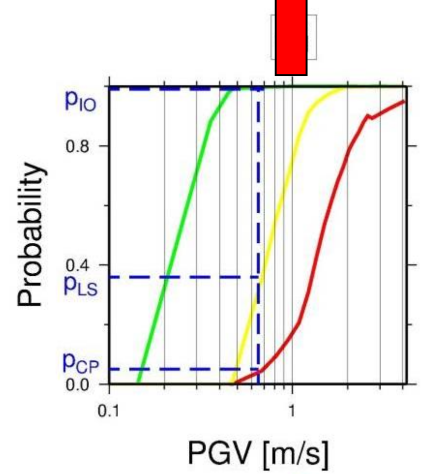


Peak Displacement over 3s P-wave

Empirical model

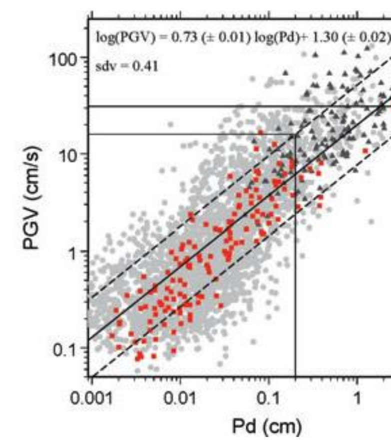
logPGV(S)=a+b*logPGD(P)

from early P–wave (measurement) → to S–wave (prediction)



Alert protocols based on PGV thresholds & expected damage levels

Alert protocols based on PGV thresholds



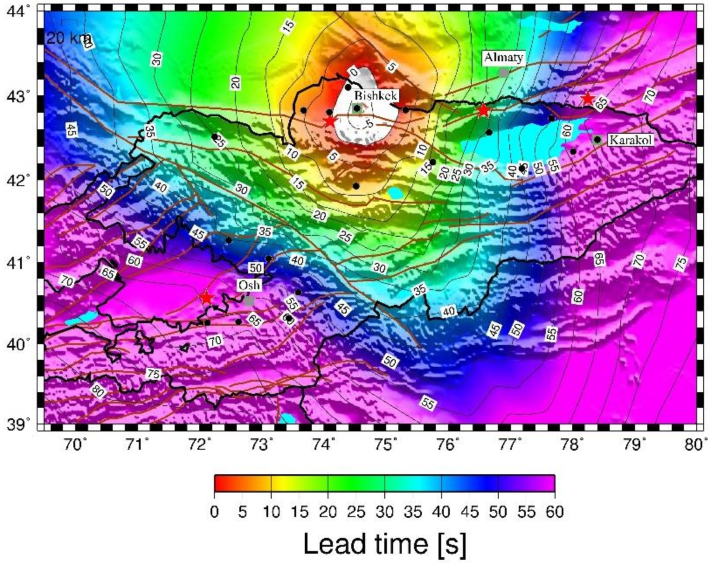
[Zollo et al 2010]

Recursive filters

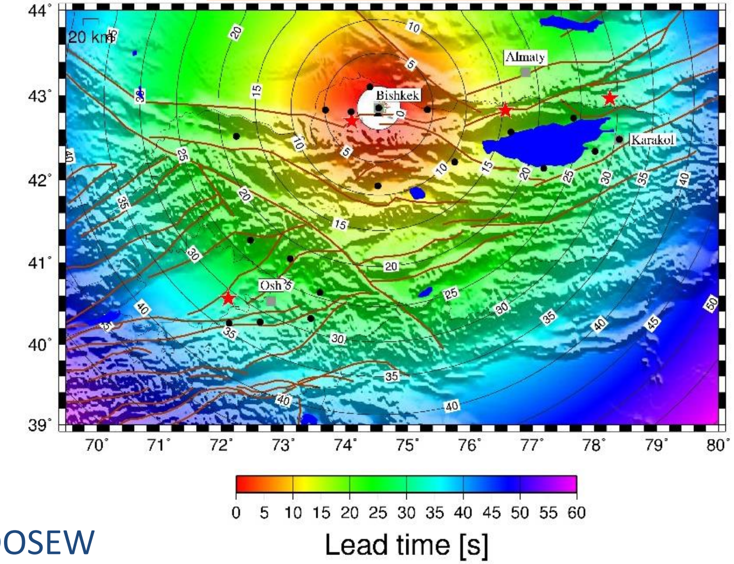
http://www.dspguide.com/CH19.PDF

Online application to Kyrgyzstan: Lead time for Bishkek

ACROSS Network

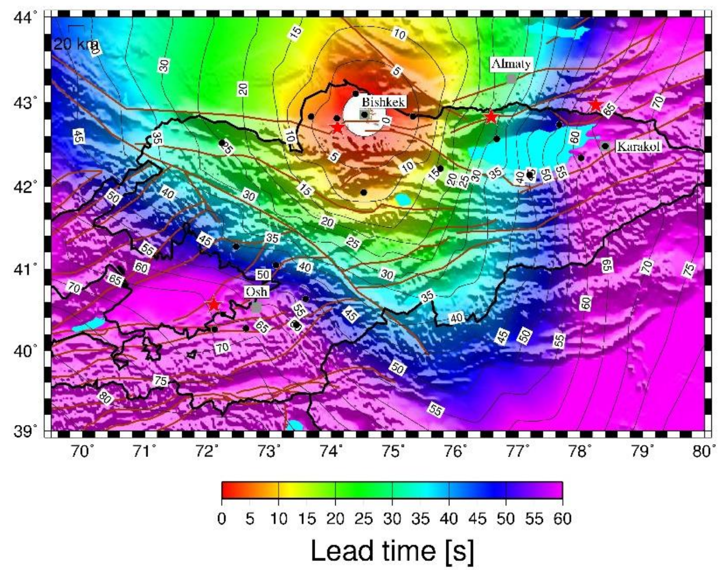


DOSEW



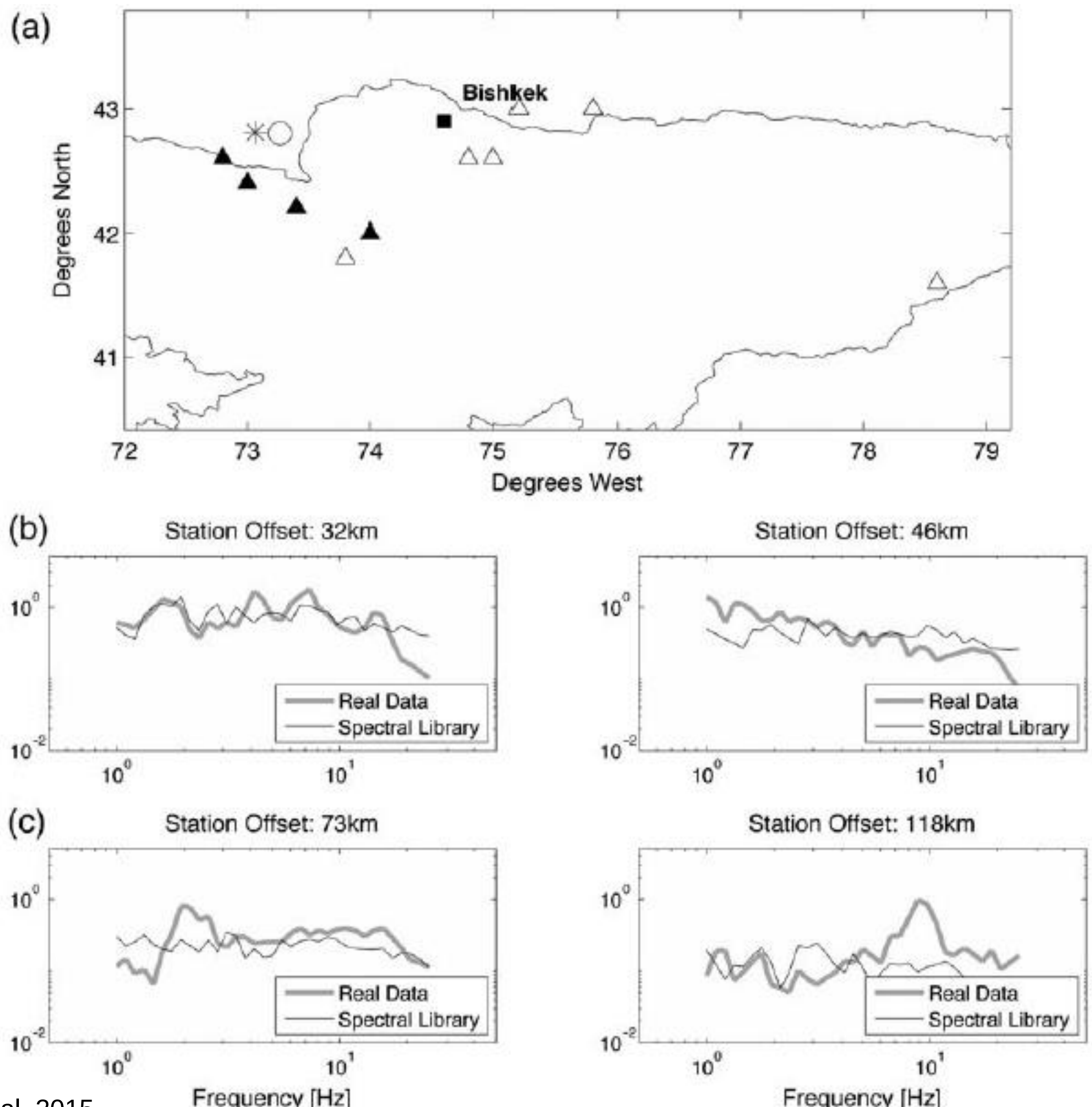
ACROSS + DOSEW

The **Presto** (Regional) and **GFZ-Sentry** (Decentralised on Site) softwares are running in a testing phase on the network



from
Parolai et al.,2017, Frontiers

Are magnitude and location necessary?



from
Stankiewicz et al.,2015

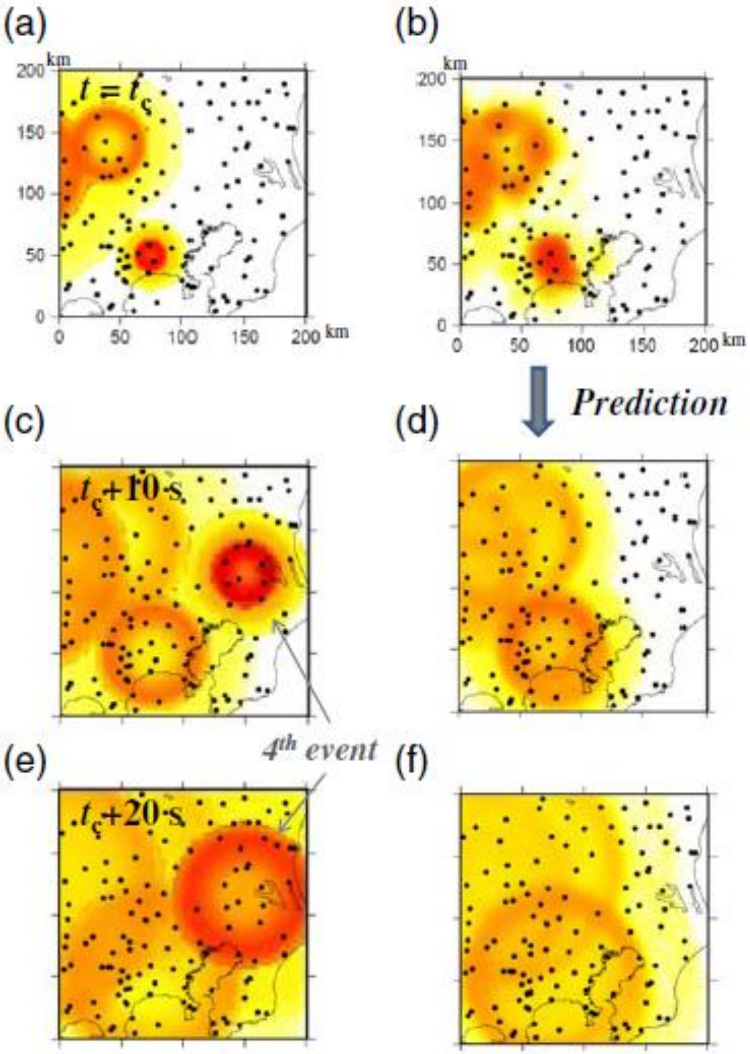
Spectral content used to improve Earthquake Early Warning Systems Bishkek

Timely warning than was possible using a threshold on ground motion

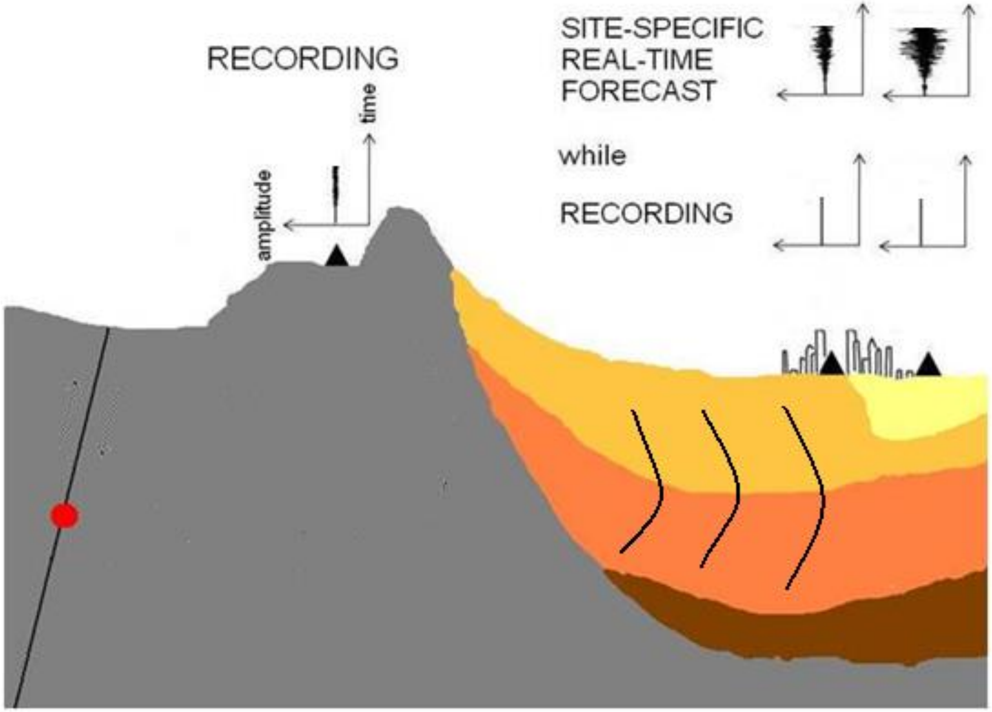
Improvement should come from a **combination with On-Site Early Warning**

Some Emerging questions

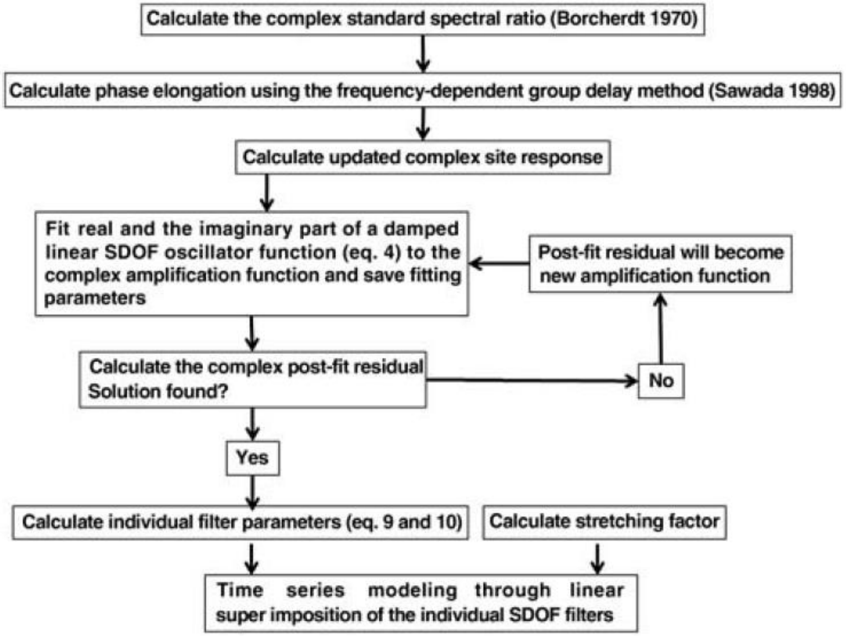
How to deal with nearly simultaneous aftershocks?
How to include site effects in real time shaking forecasting?



Hoshiba and Aoki (2015):



Pilz and Parolai (2016), Hoshiba (2020)

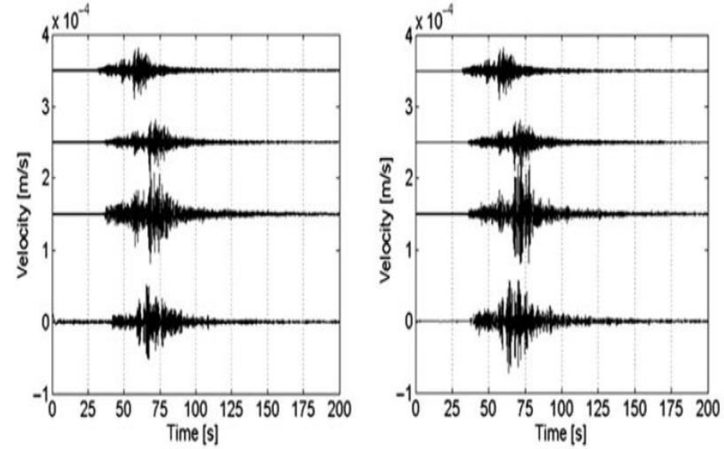


Reference

stretched

+ site

observed

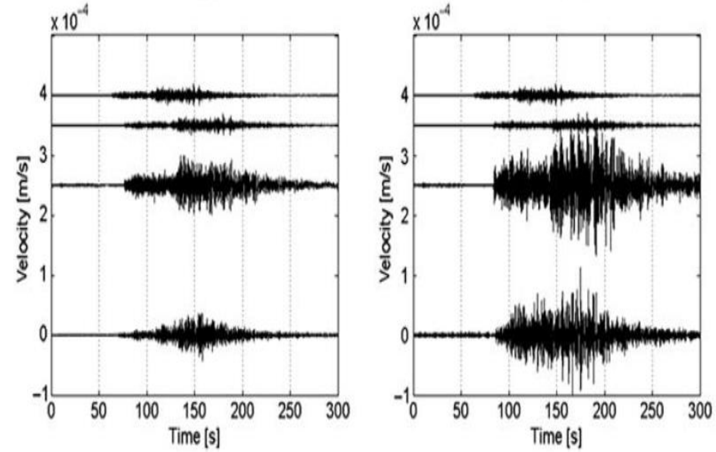


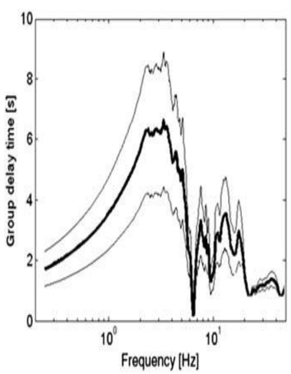
Reference

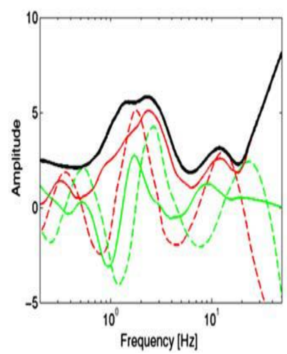
stretched

+ site

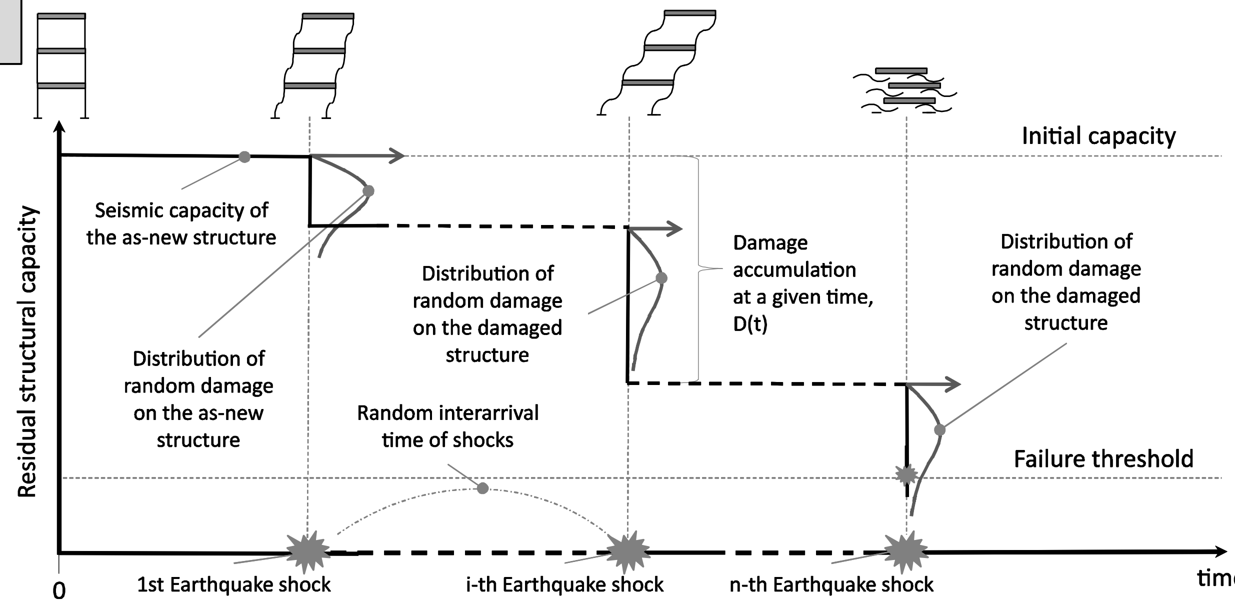
observed





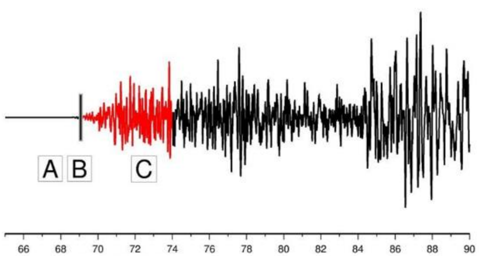


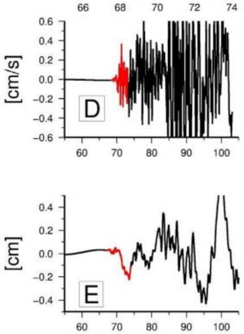
Emerging questions



Aftershocks early warning and monitoring: time dependent vulnerability

Non structural damage:
Induced seismicity





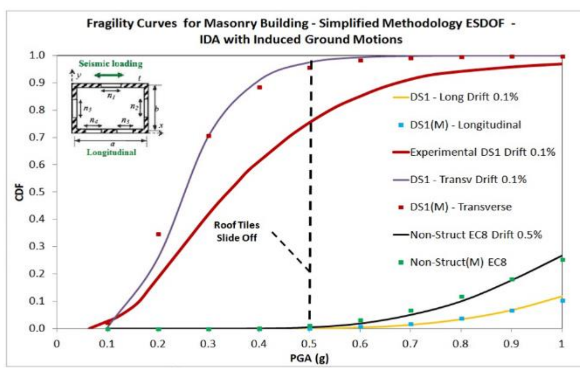
F

Empirical model

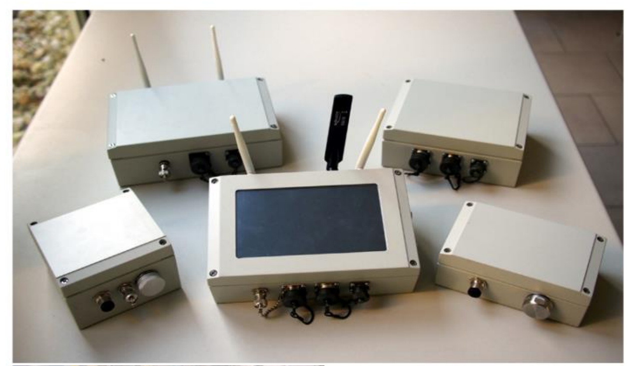
logPGV(S)=a+b*logPGD(P)

from early P–wave (measurement)

to S–wave (prediction)

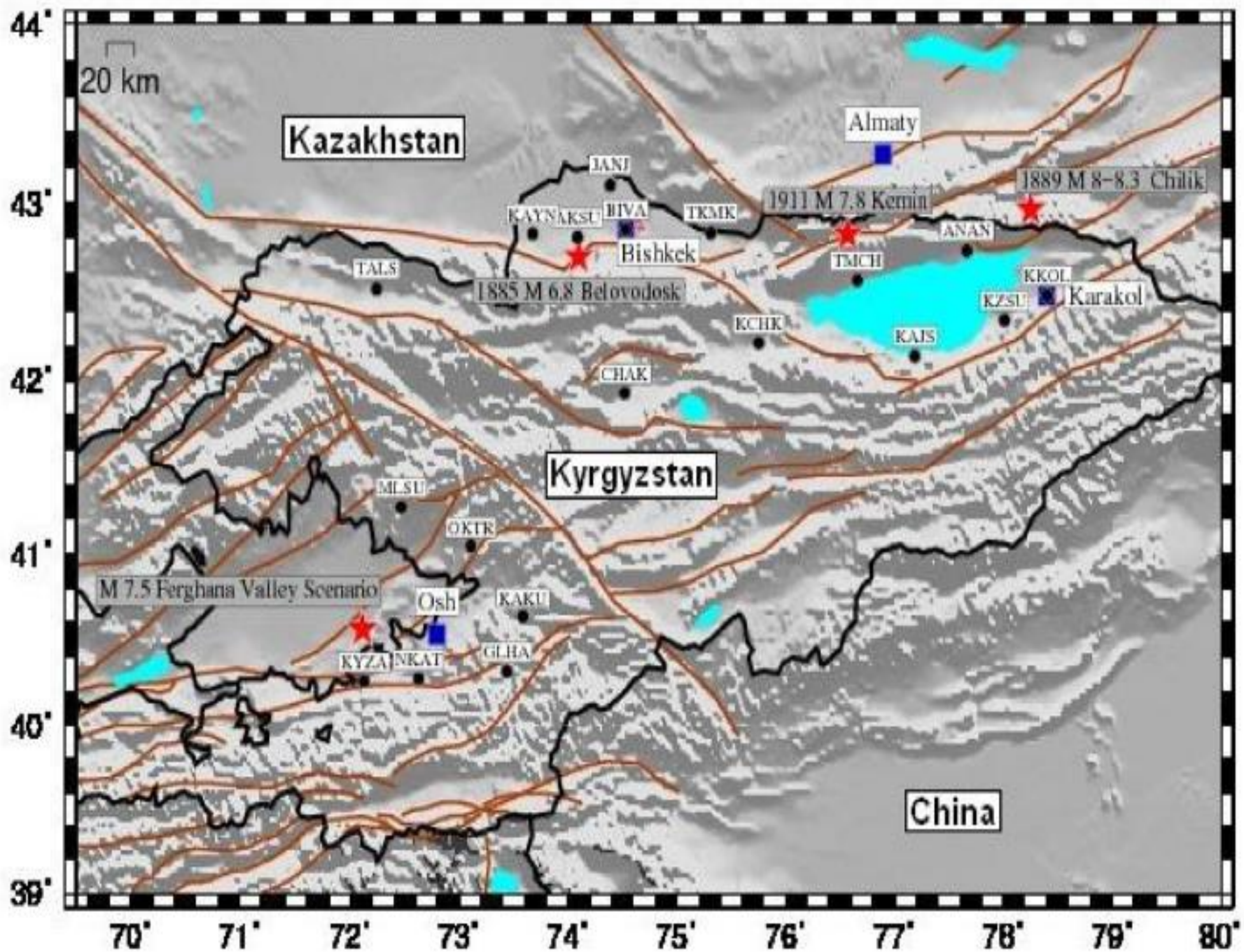


Developed for Drift Sensitive Brittle Non-Structural Components of URM buildings.

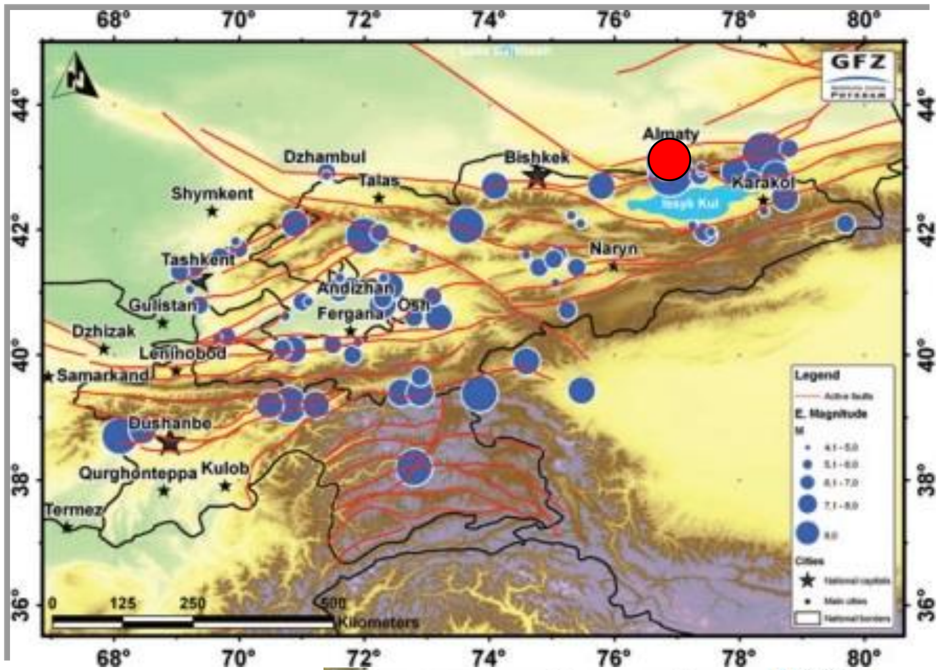


MP-Wise (Multi-Parameter Wireless Sensing System)

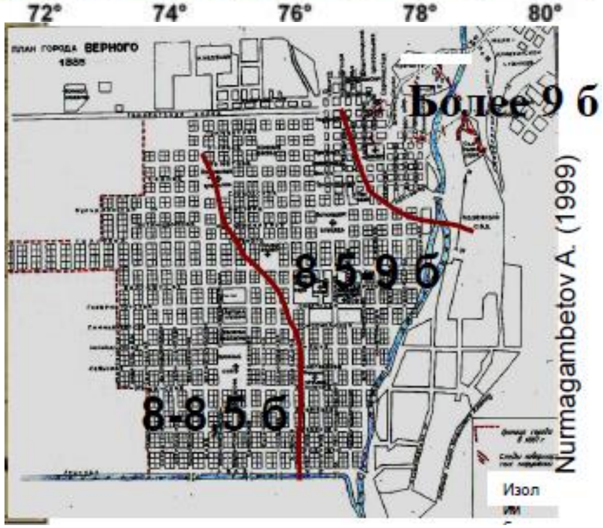
ACROSS Network



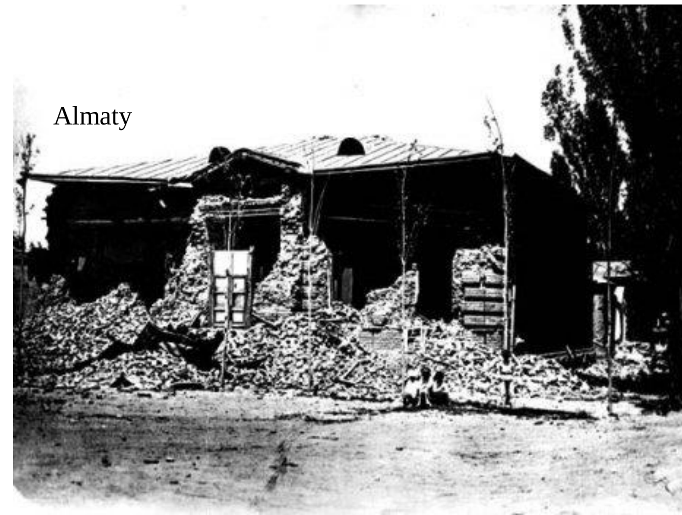
1887 Verny Earthquake M=7.3



Macroseismic Intensities in Almaty



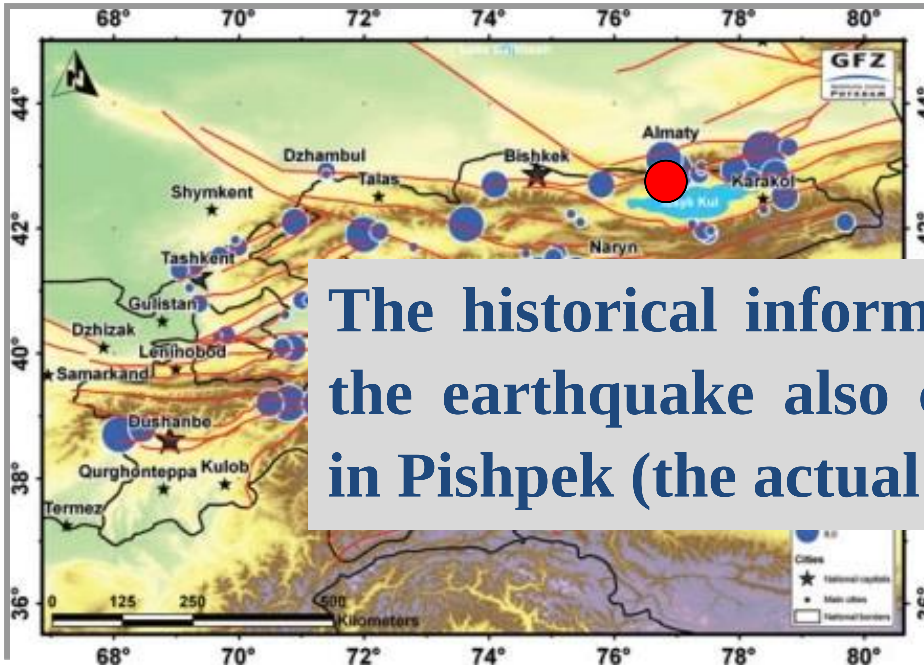
~300 death



Nurmagambetov (1999)

Nurmagambetov (1999)

1911 Kemin Earthquake M=7.8-8.0

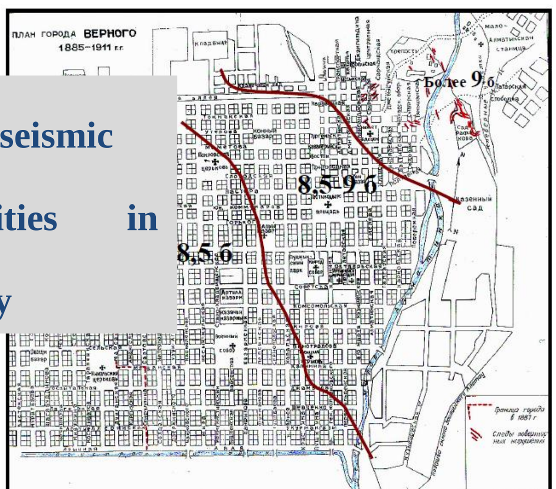


The historical information suggests that the earthquake also created devastation in Pishpek (the actual Bishkek)

Almaty

Nurmagambetov (1999)

Macroseismic Intensities in Almaty

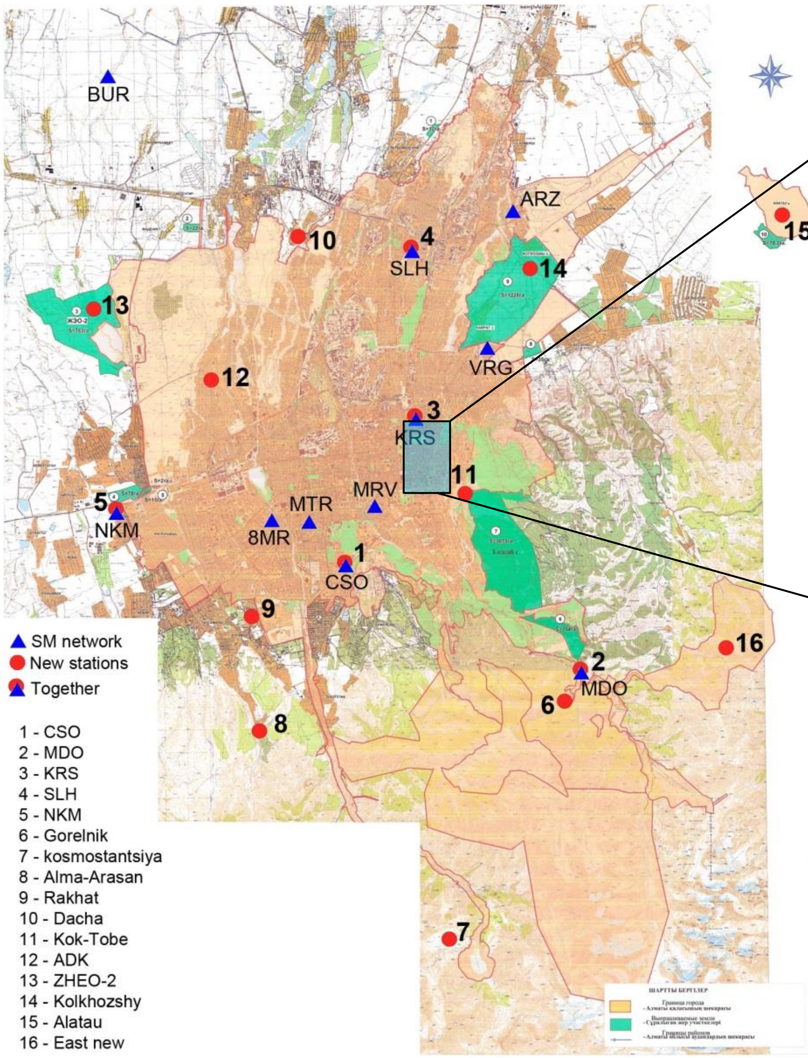


Almaty

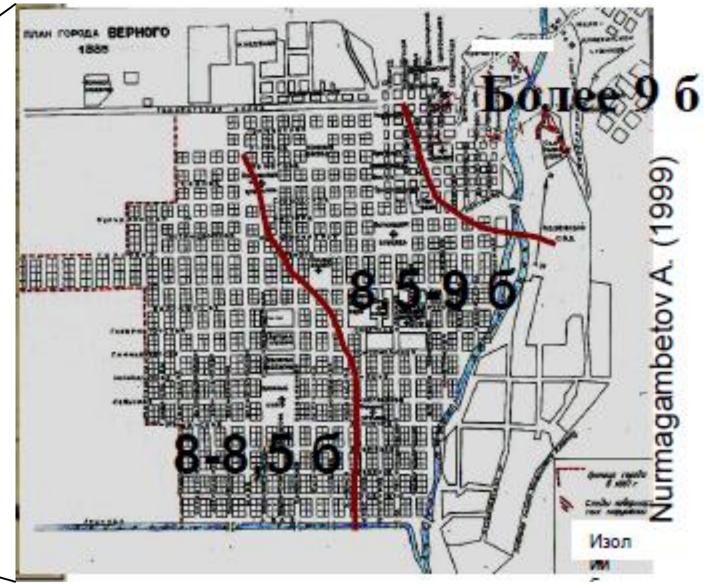
Nurmagambetov (1999)

Nurmagambetov (1999)

High risk considering the urban dynamic



Parolai et al (2018) in preparation



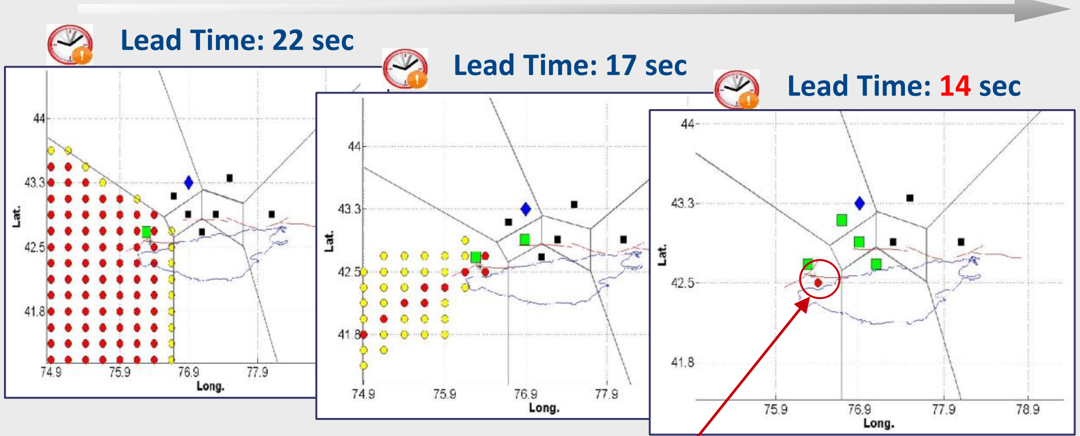
City	Population (millions)	Estimated deaths (thousands)	Estimated Injuries (thousands)
Almaty	1.5	75	300
Bishkek	0.8 (now ~1)	40	160

GeoHazards Int. B.Tucker, pers. comm.

Earthquake risk early warning

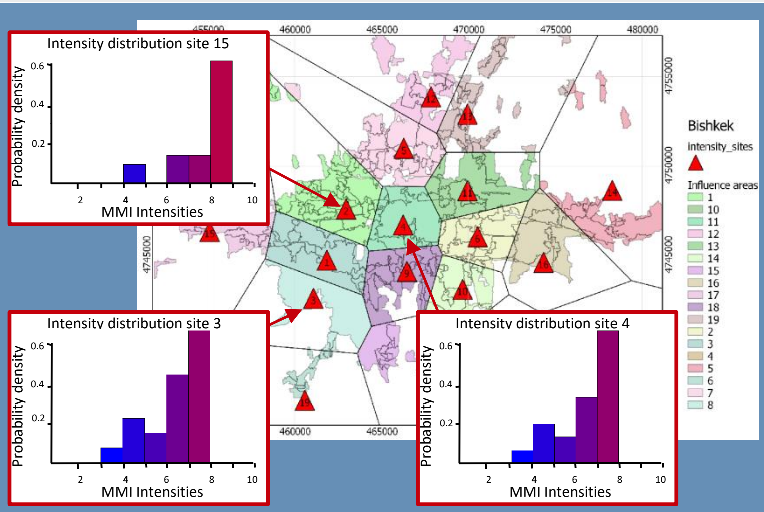
Picozzi et al (2013)

- P-wave arrival time data set → Evolutionary Earthquake Localization
- Stochastic Event data set → Evolutionary Event Size Characterization
- Site Effects → Intensity Scenario at the Target Site
- Physical Vulnerability Model → Real Time Loss Map

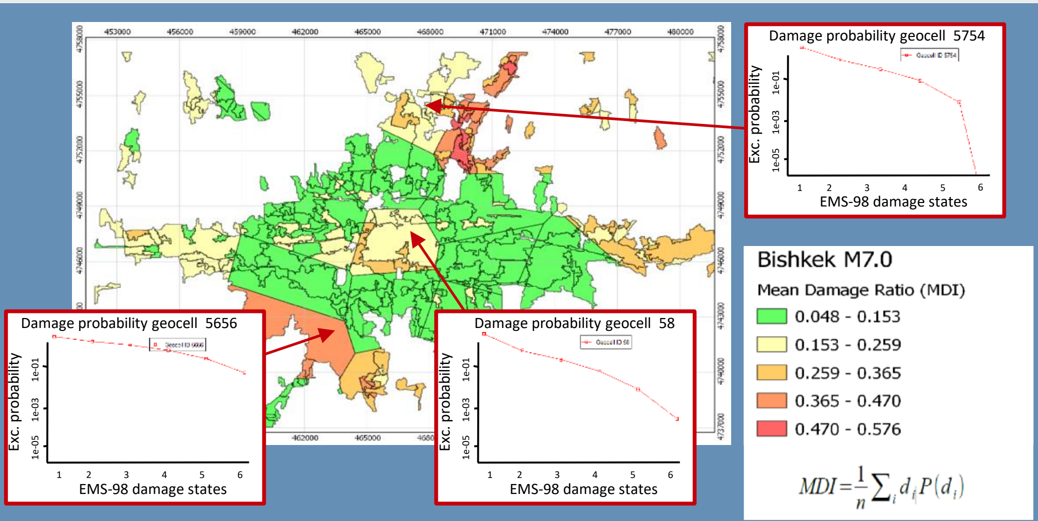


Real-time loss scenario filtering

Event characterized, most probable scenario selected, warning



Spatial distribution of simulated intensity



$$MDI = \frac{1}{n}\sum_i d_i P(d_i)$$

Damage probability of exceedance

Decentralised On Site Early Warning

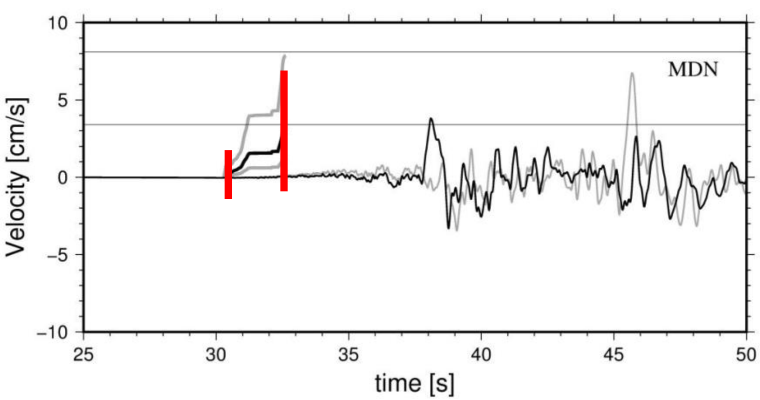
Low pass filtering

Integration in velocity and displacement

Event detection

(possibility of combining info from the low and high pass filtered record or pred period)

PGV estimation (mean +/- s)



M 5.9 20th May 2012 Emilia earthquake

mean + σ > 8.1 cm/sec Intensity ≥VI

	mean – σ >**8.1** cm/sec	**8.1** cm/sec>mean – σ > **3.4** cm/sec	mean – σ <**3.4** cm/sec
Mean >**8.1** cm/sec			
8.1 cm/sec>mean>**3.4** cm/sec			
Mean <3.4 cm/sec			

8.1 cm/sec > mean + σ > 3.4 cm/sec Intensity =V

	mean – σ >**8.1** cm/sec	**8.1** cm/sec>mean – σ > **3.4** cm/sec	mean – σ <**3.4** cm/sec
Mean >**8.1** cm/sec			
8.1 cm/sec>mean>**3.4** cm/sec			
Mean <**3.4** cm/sec			X

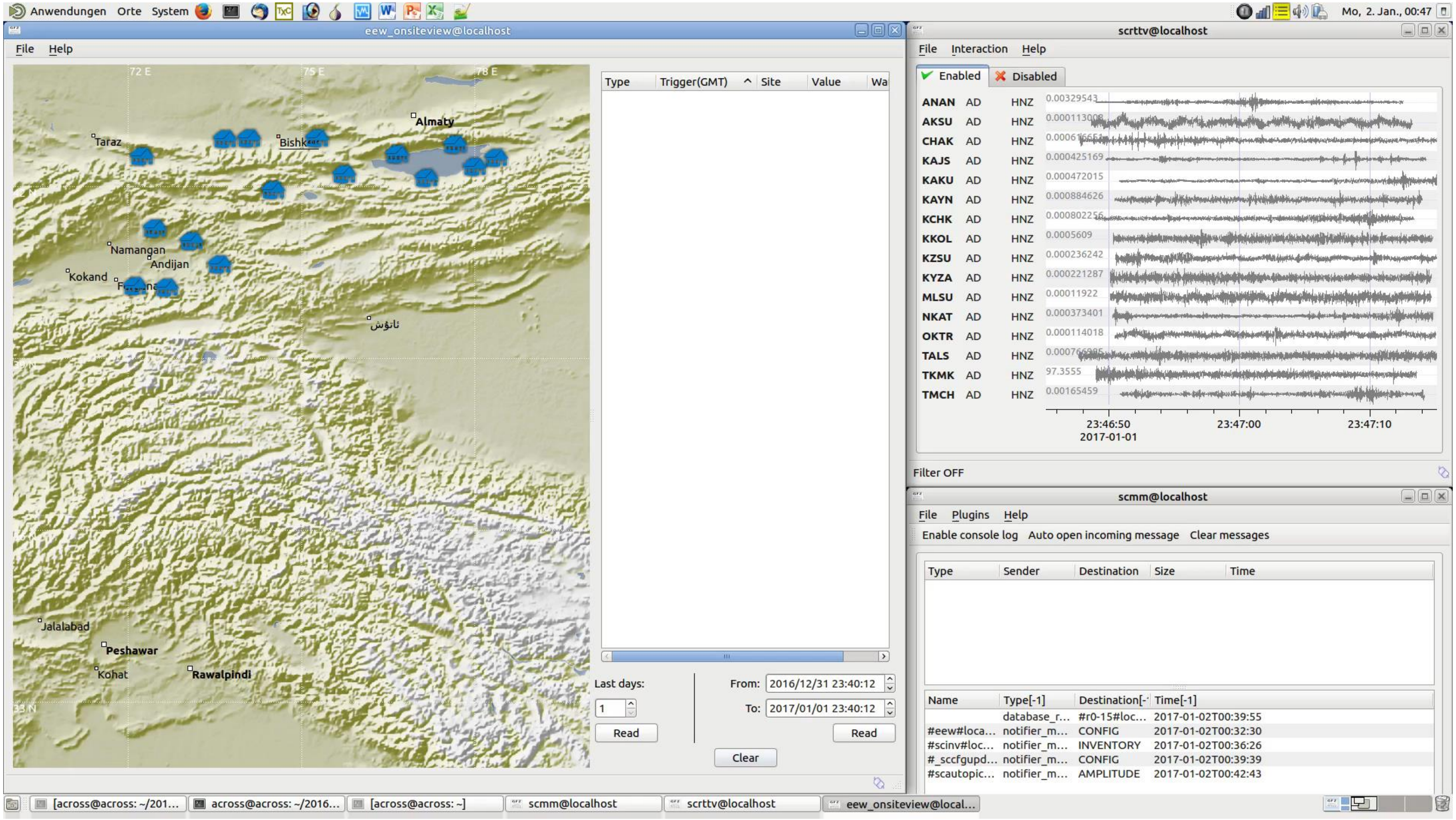
mean + σ < 3.4 cm/sec Intensity ≤IV

	mean – σ >**8.1** cm/sec	**8.1** cm/sec>mean – σ > **3.4** cm/sec	mean – σ <**3.4** cm/sec
Mean >**8.1** cm/sec			
8.1 cm/sec>mean>**3.4** cm/sec			
Mean <**3.4** cm/sec			X

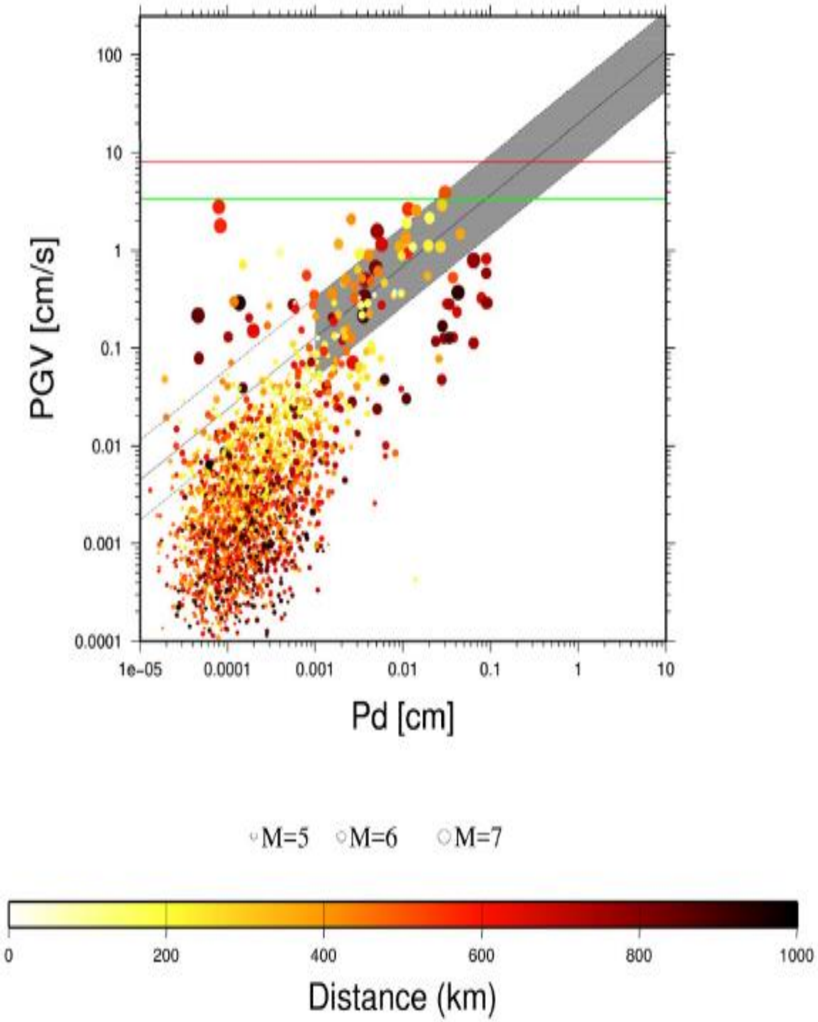
from
Parolai et al.,2015

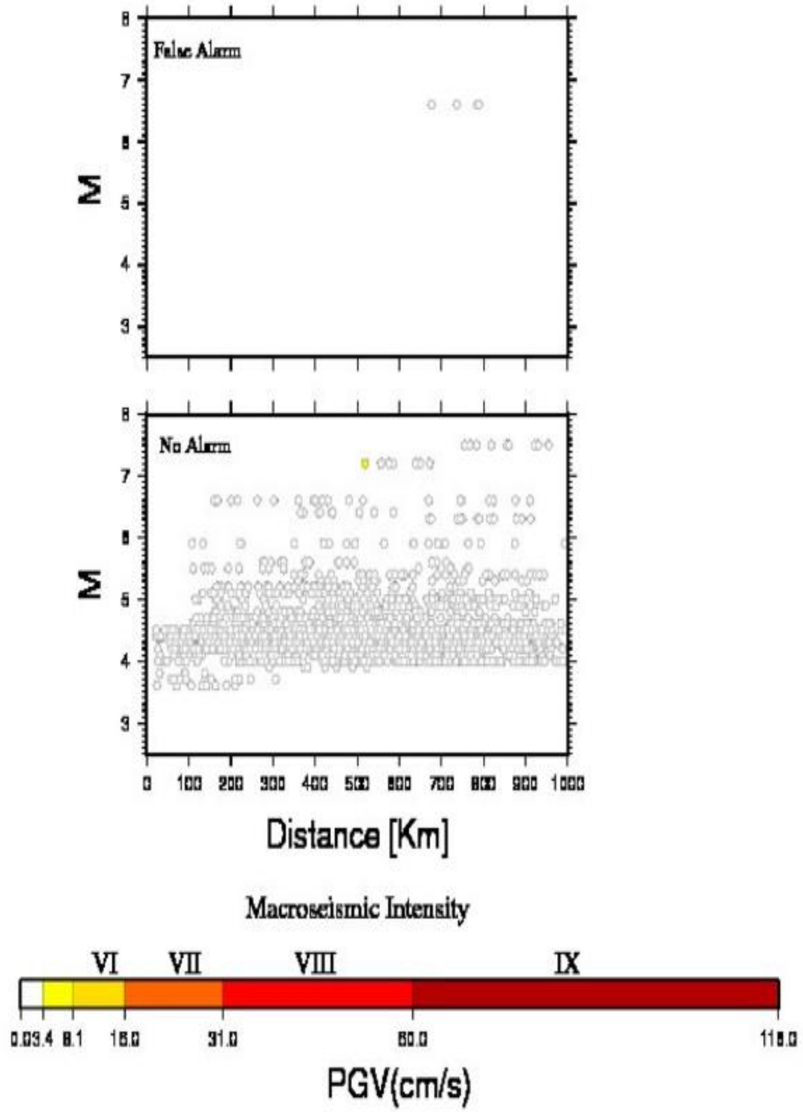
Decentralised Onsite-Early Warning

GFZ-Sentry Software, based on Parolai et al. (2015) and developed in cooperation with GEMPA GmbH.



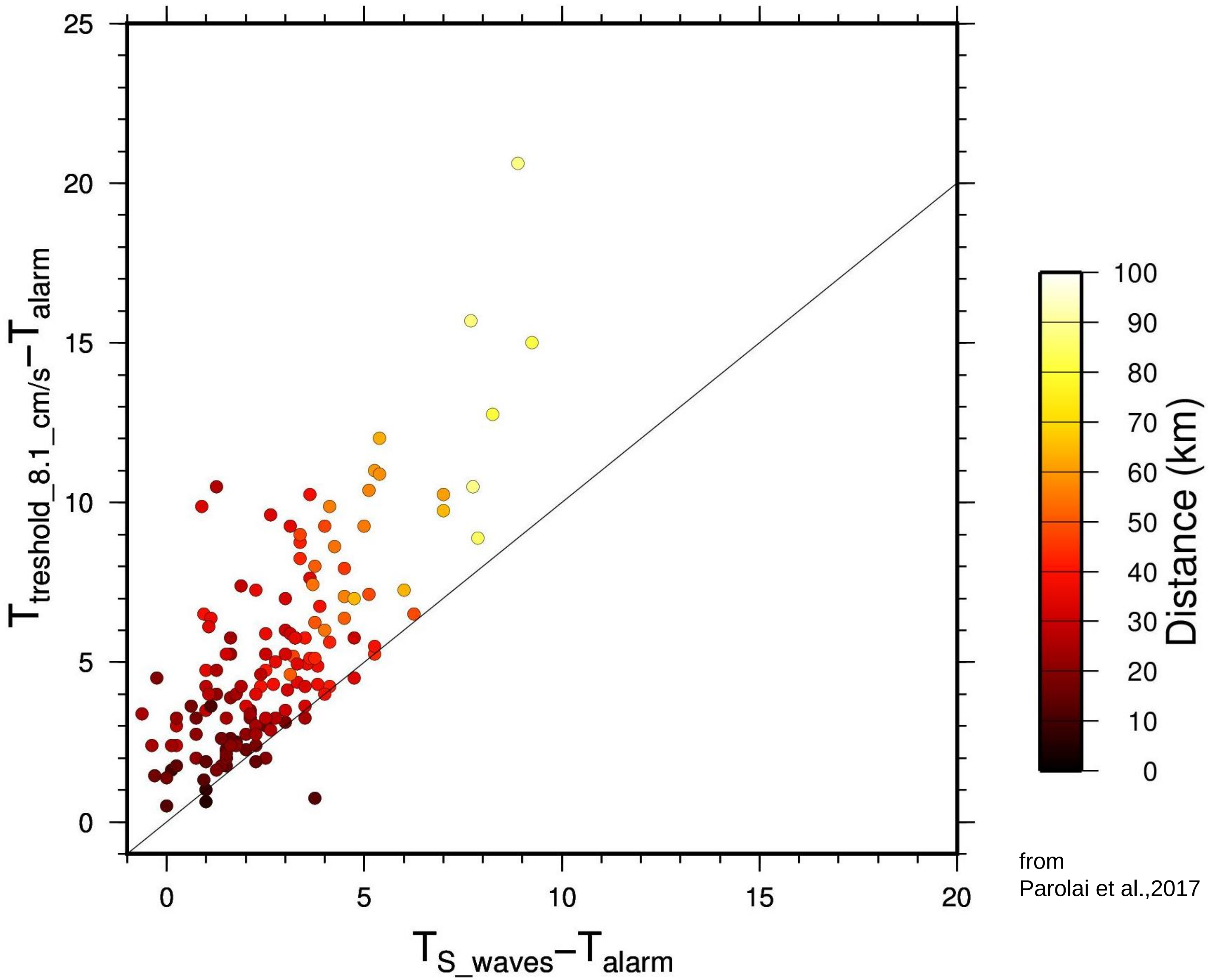
Decentralised OSEW in testing





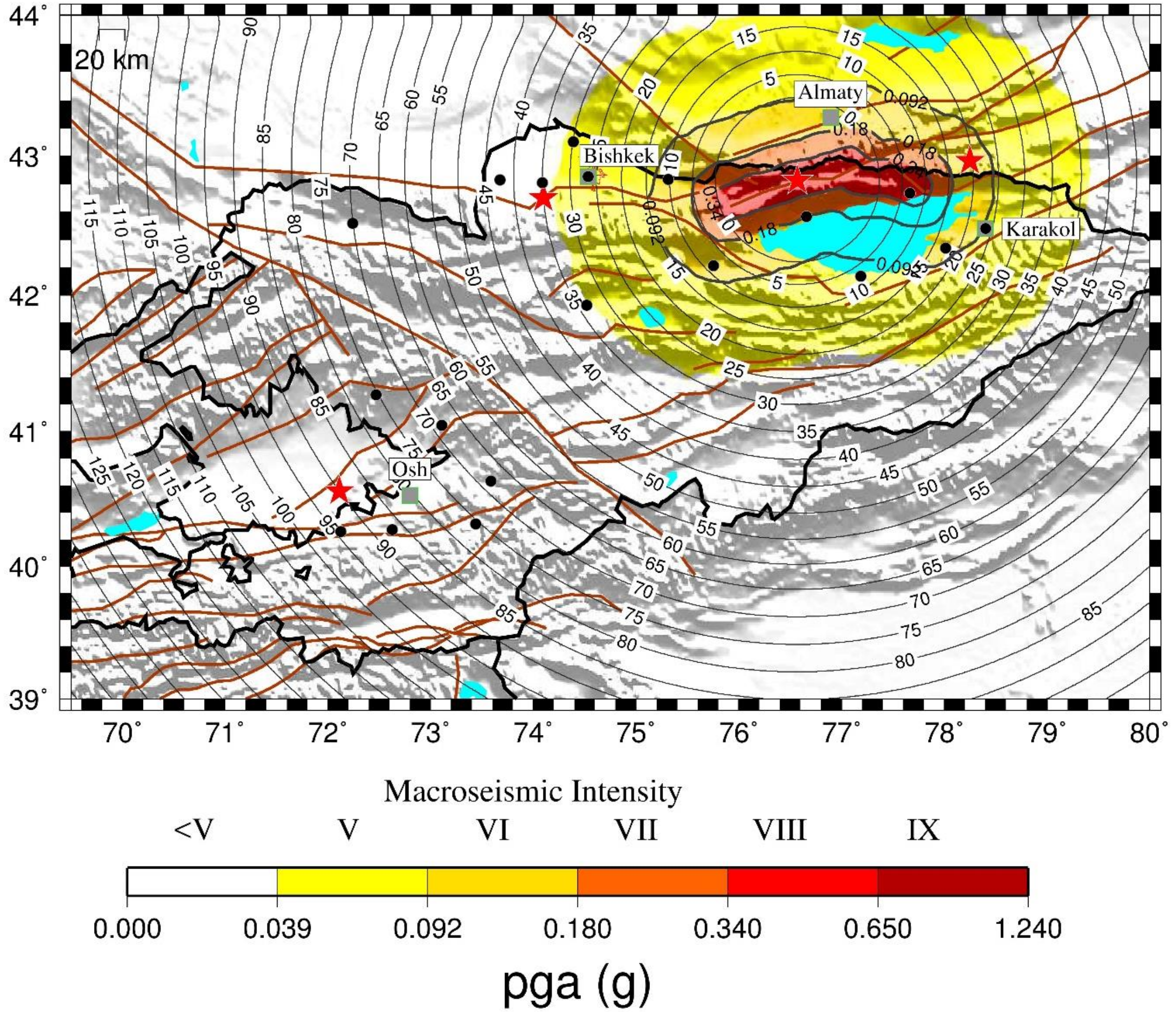
from Parolai et al.,2017, Frontiers

Application to KiK-Net and K-NET recordings



from
Parolai et al.,2017

Offline application to Kyrgyzstan: Lead time for Repetition of the M 7.8 1911 Kemin Earthquake



from
Parolai et al.,2017, Frontiers

1976 Seismic Sequence

MessaggeroVeneto

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

Origin time: 20:00:13 UTC
epicenter 46° 17' N - 13° 17' E
Depth: 5 - 12 km

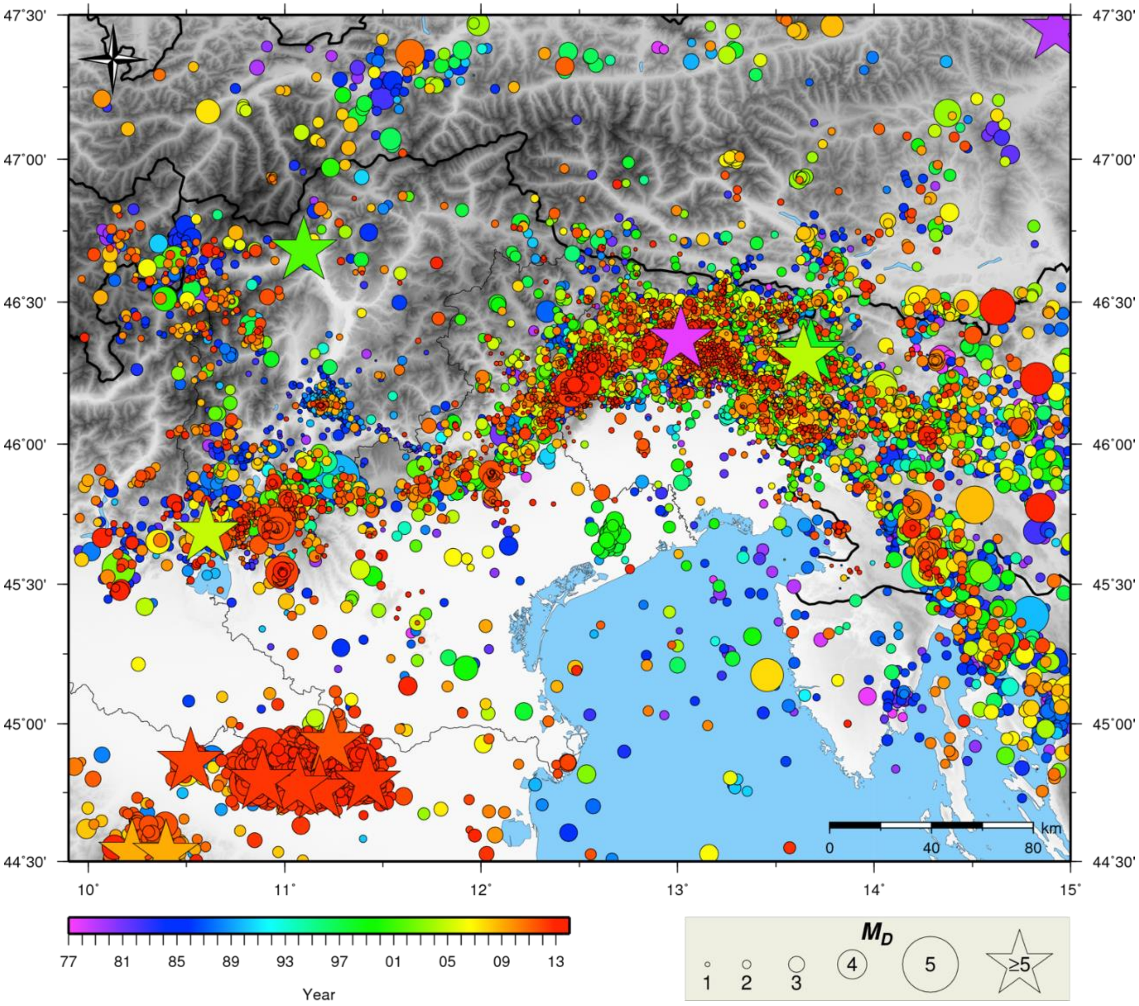
Magnitude: 6.0 mb 6.5 Ms 6.4 ML
Epicentral intensity: X MKS

Max PGA recorded: 0,36 g

Felt at distance of : 579 km
Impact Area : 5.700 km^2
Death toll: 989

People needing shelters: 110.000
Damage: 4.500.000 milions (lire in 1976)

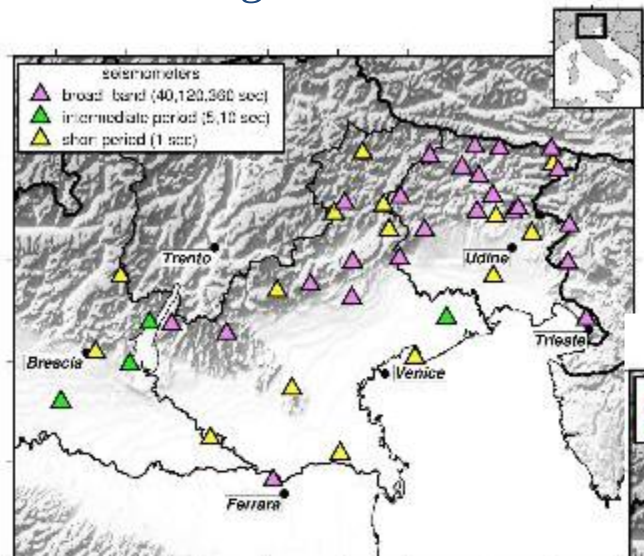
Earthquakes recorded since 1977 (>33.000 events)



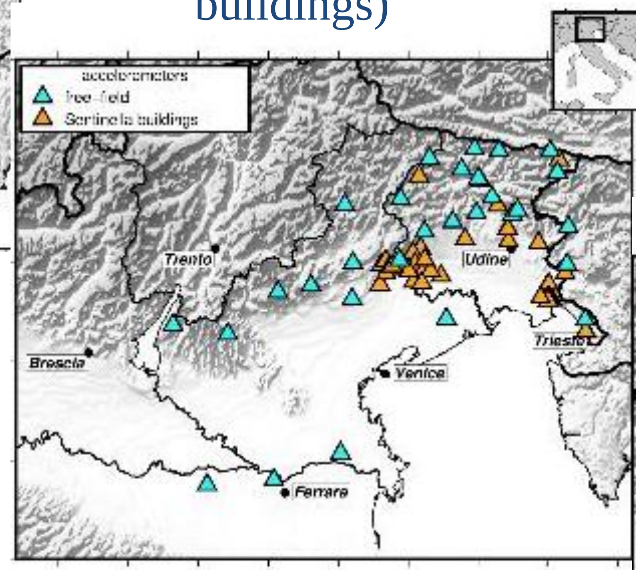
Sistema di Monitoraggio terrestre dell'Italia Nord Orientale (SMINO)

Earth monitoring system in North-Eastern Italy

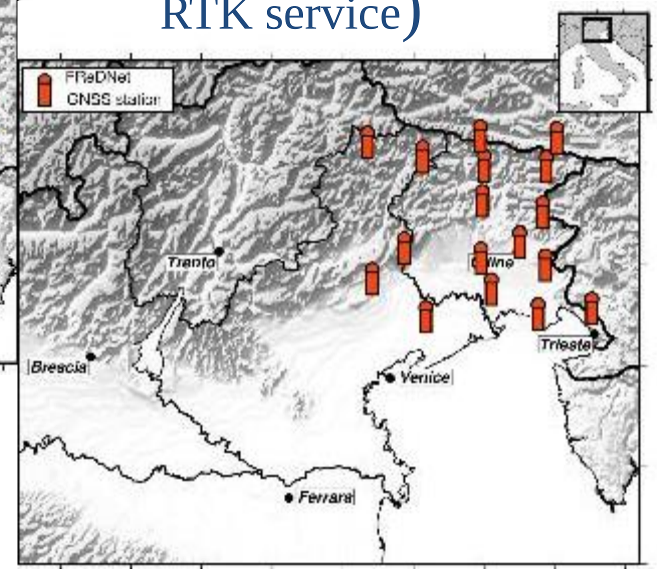
Seismological stations



Strong motion stations (free-field and in buildings)



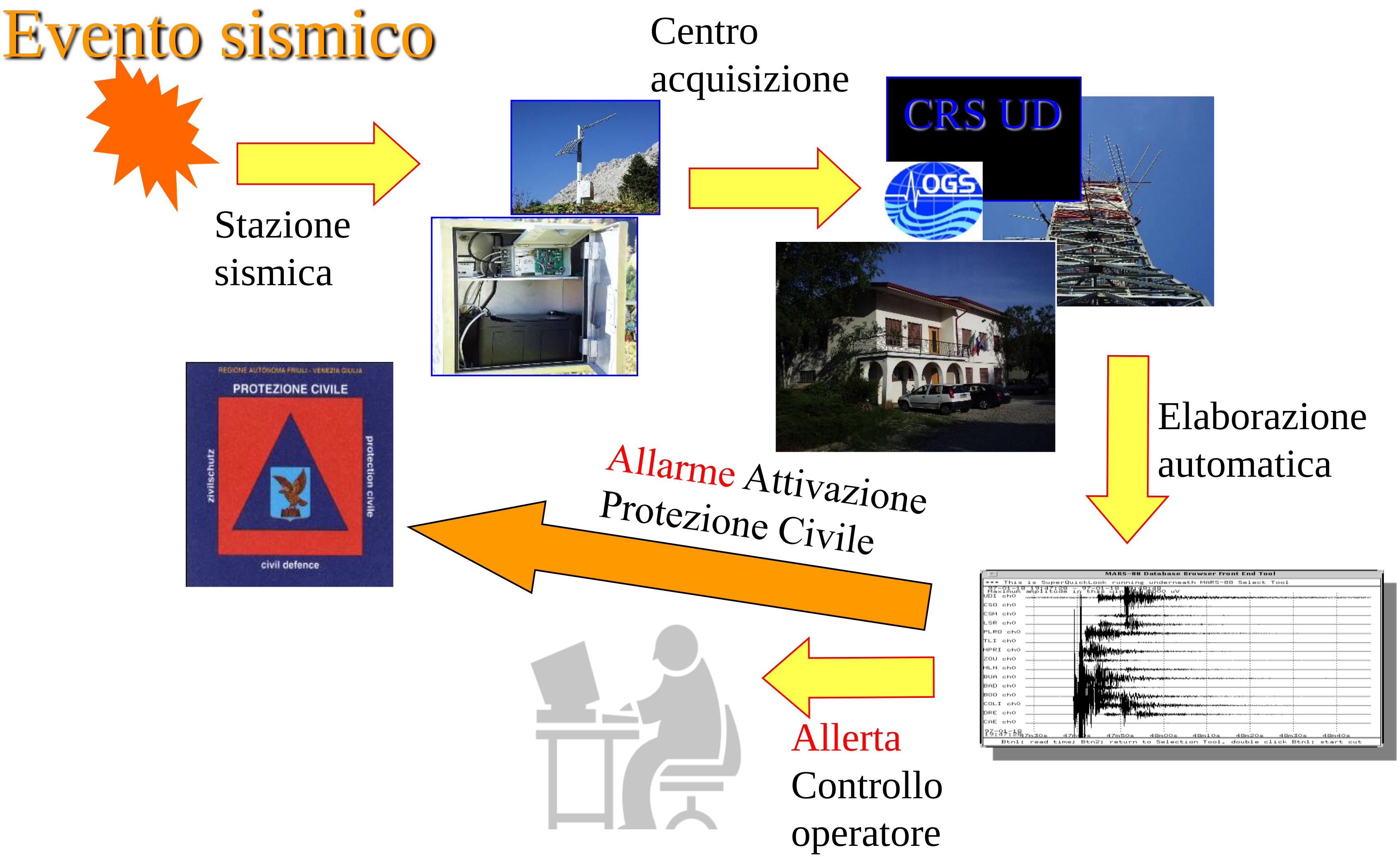
GNSS stations (crustal deformation and RTK service)



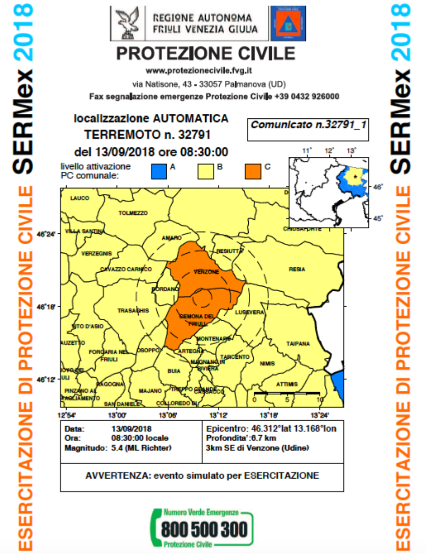
from
Bragato et al.,2020

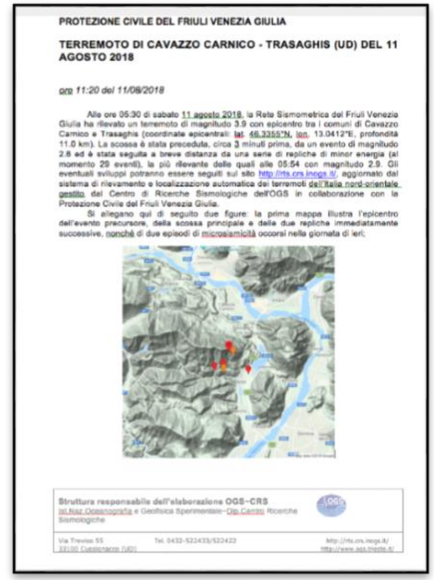
Integrated Trans-boundary network

Information in the immediate post-event phase



Communication towards Institutions




PROTEZIONE CIVILE DEL FRIULI VENEZIA GIULIA

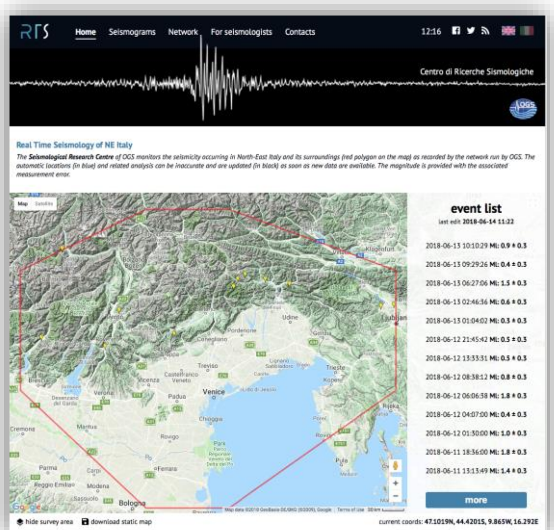
TERREMOTO DI CAVAZZO CARNICO - TRASAGHIS (UD) DEL 11 AGOSTO 2018

ore 11:20 del 11/08/2018

Alle ore 05:30 di sabato 11 agosto 2018, la Rete Sismometrica del Friuli Venezia Giulia ha rilevato un terremoto di magnitudo 3.9 con epicentro tra i comuni di Cavazzo Carnico e Trasaghis (coordinate epicentrali: lat. 46.3355°N, lon. 13.0412°E, profondità 11.0 km). La scossa è stata preceduta, circa 3 minuti prima, da un evento di magnitudo 2.8 ed è stata seguita a breve distanza da una serie di repliche di minor energia (al momento 29 eventi), la più rilevante delle quali alle 05:54 con magnitudo 2.9. Gli eventuali sviluppi potranno essere seguiti sul sito http://rts.crs.inogs.it/, aggiornato dal sistema di rilevamento e localizzazione automatica dei terremoti dell'Italia nord-orientale gestito dal Centro di Ricerche Sismologiche dell'OGS in collaborazione con la Protezione Civile del Friuli Venezia Giulia.

Si allegano qui di seguito due figure: la prima mappa illustra l'epicentro dell'evento precursore, della scossa principale e delle due repliche immediatamente successive, nonché di due episodi di microsismicità occorsi nella giornata di ieri;

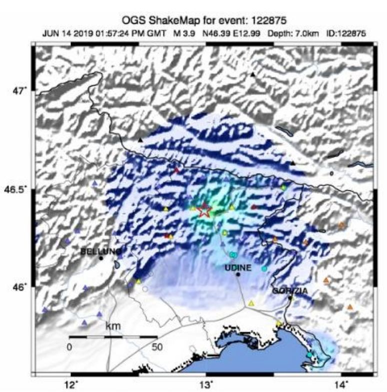
Struttura responsabile dell'elaborazione OGS-CRS

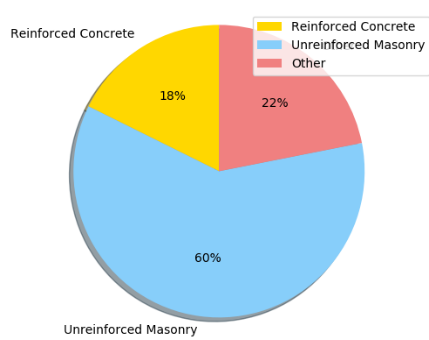


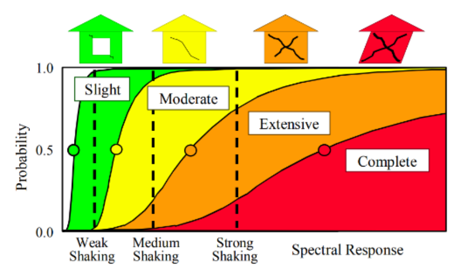
Communication to the public

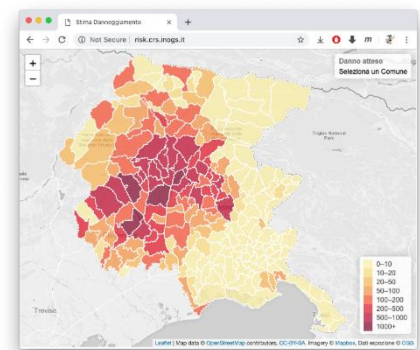
A Real-time Damage Scenario Calculator

Scenario Hazard (ground motion model e.g. shakemap) → Exposure (building type and distribution) → Fragility (dynamic behavior of structures) → **Damage Scenario**









from
Poggi et al.,2020

CARAVAN - earthquake impact forecasting

Description:

- Provides **near-real time <u>ground motion and loss</u>** <u>(fatalities, displaced) estimation</u>
- Stand-alone (client/server), web-based
- multilingual; include mapping
- Currently on-demand: manual event
- characterization and FDSN event query
- Current focus: <u>Central Asia</u>

Which events: manual M5+

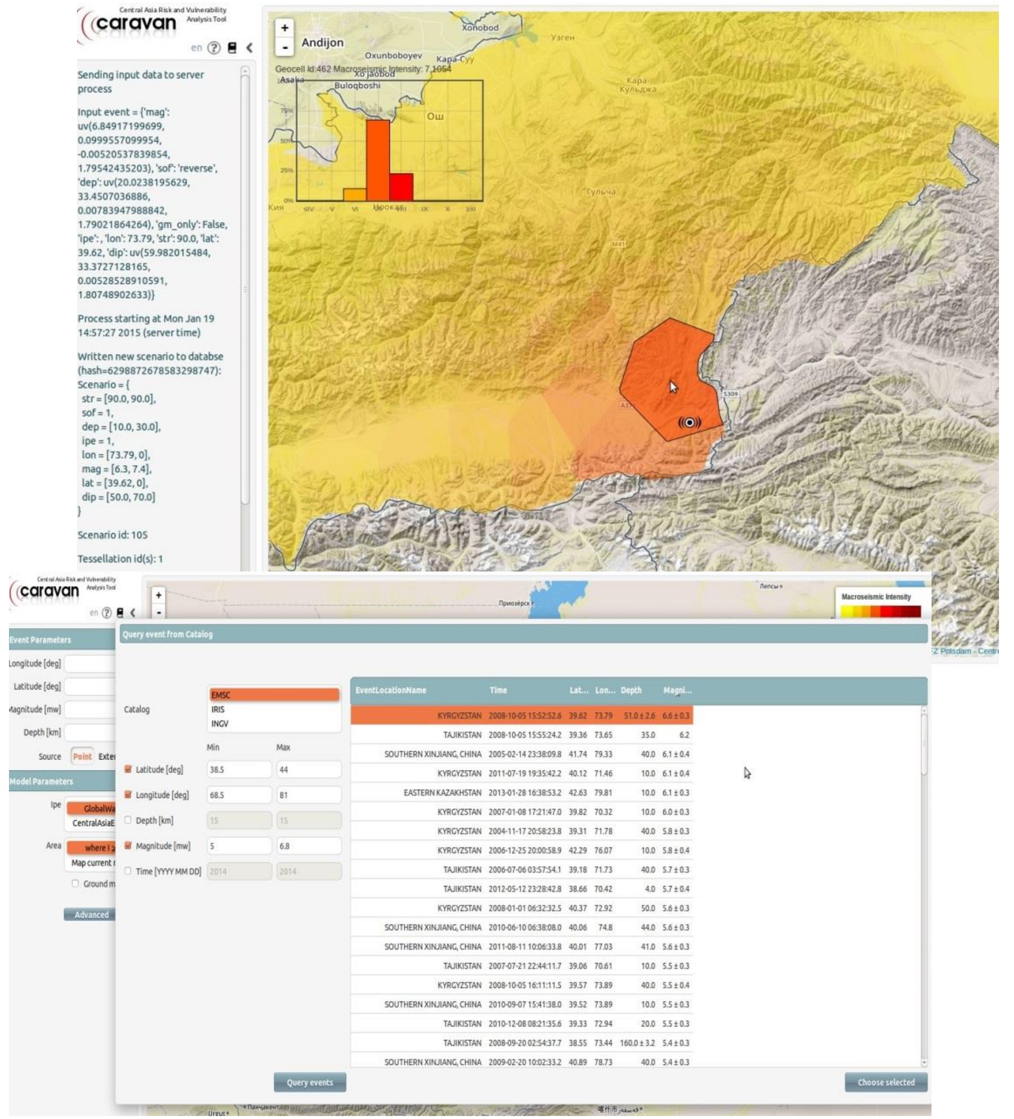
Type: routine (auto mode in preparation)

Dissemination: Centre for Early Warning; (optional: RSS feed; Email list; SMS)

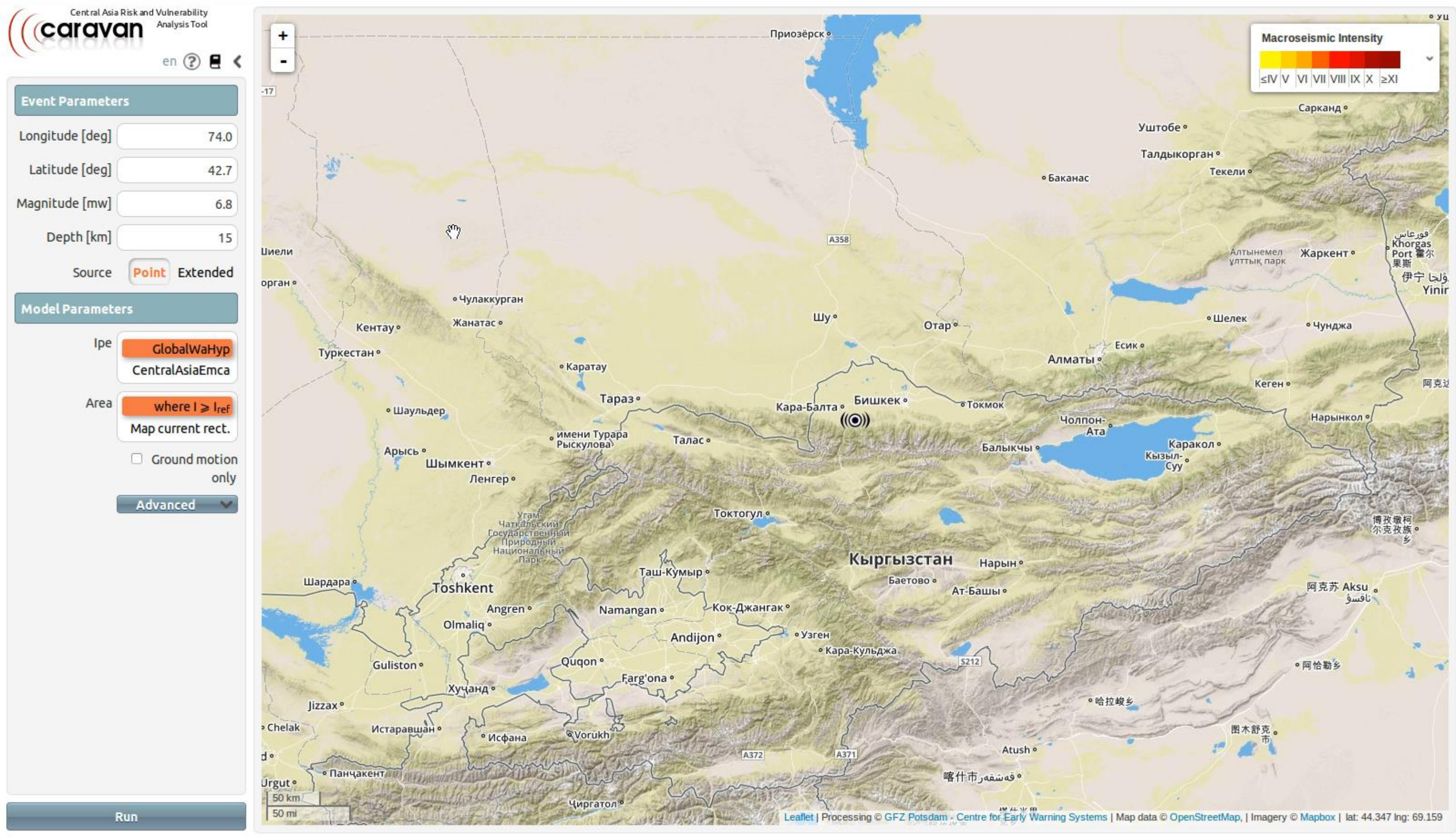
Time lag: <1 minute for first solution; possibly updated in real-time (automatic solution) based on stochastic simulations

Yearly output: 3 (2014), possibly up to 50

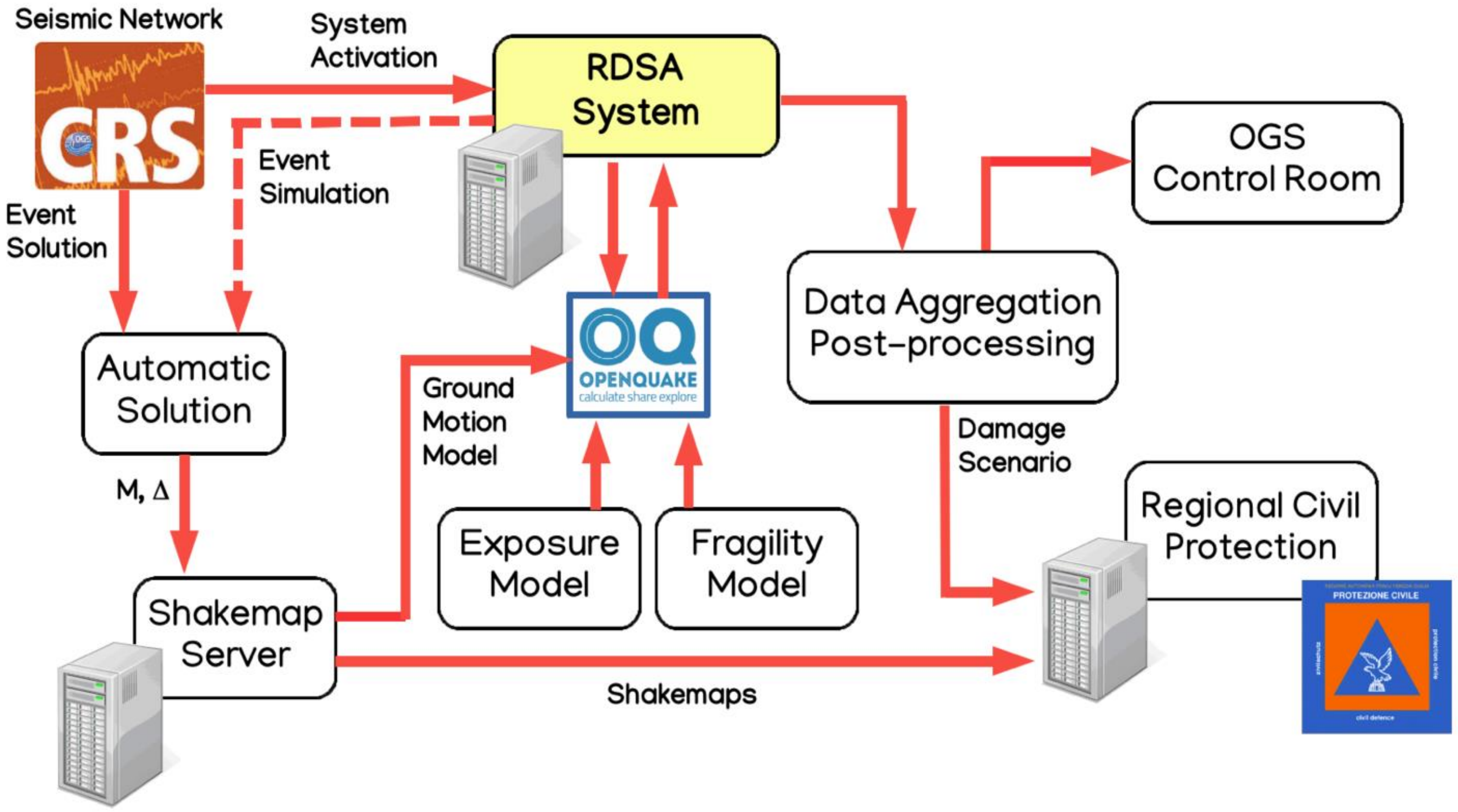
Trigger: manual, GEOFON event, ACROSS



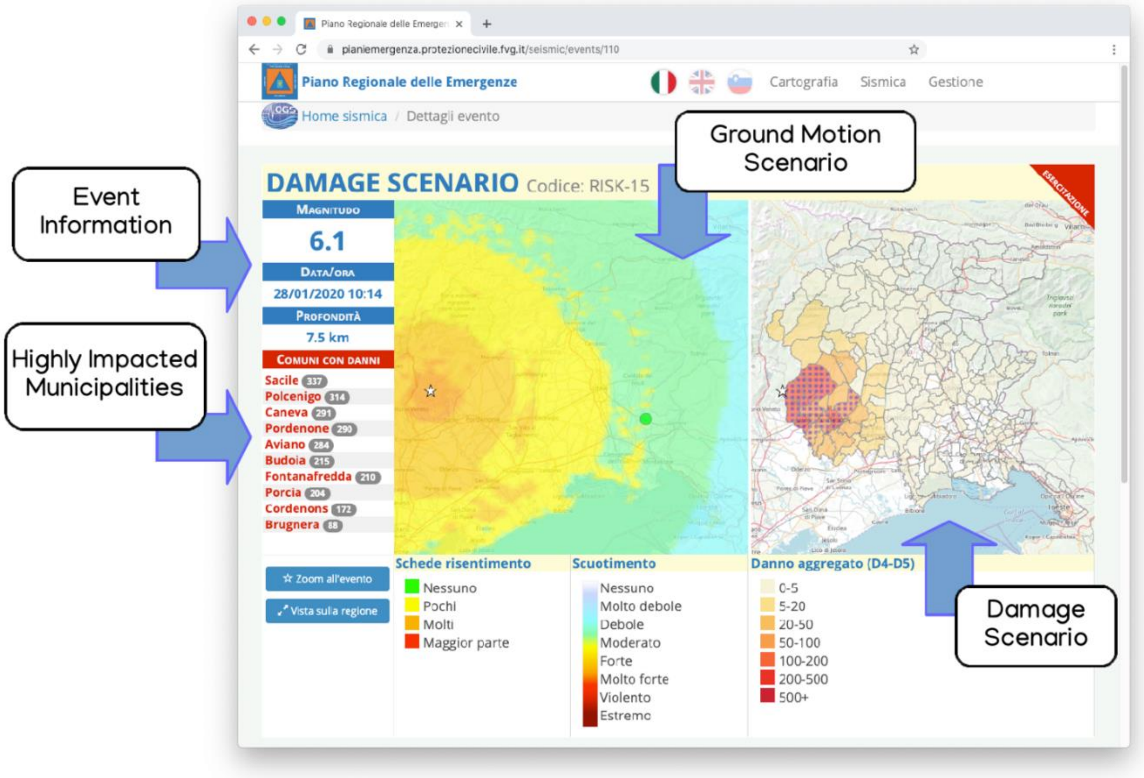
CARAVAN - Earthquake impact forecasting



Processing Infrastructure



Estimated damage

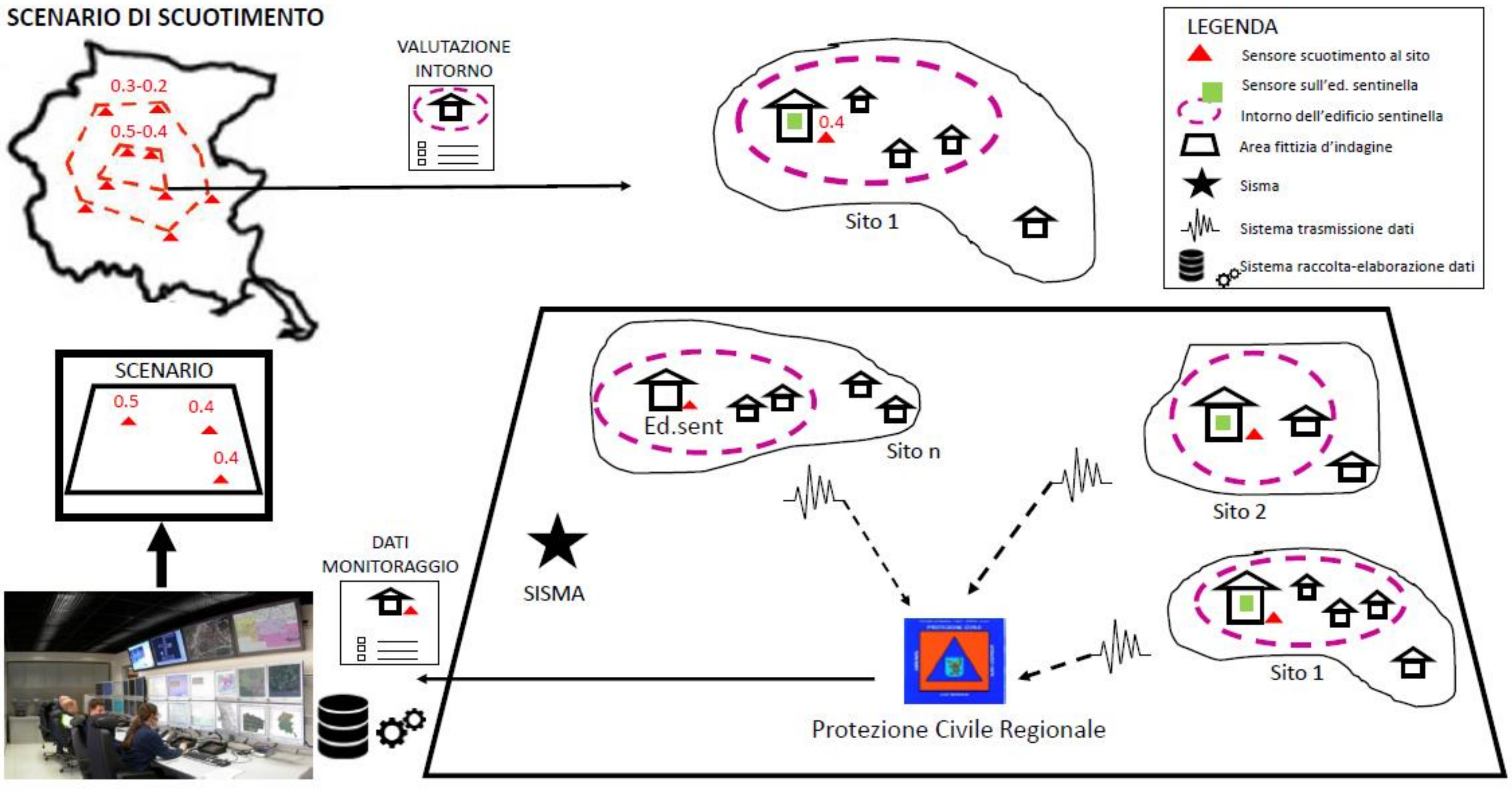


Example of test scenario:

- Number of damaged buildings by aggregating severe damage (level D4) and total collapse (level D5) of the EMS98 scale.
- Option to produce a map of number of people impacted (based on simplified relationships)

from
Poggi et al.,2020

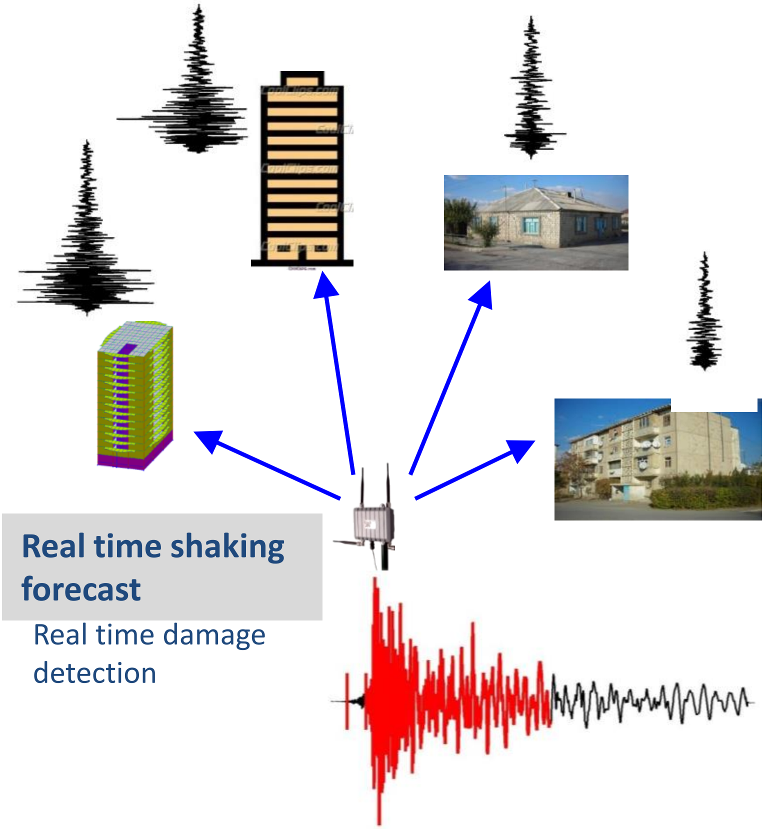
Rapid Damage forecasting in buffer areas



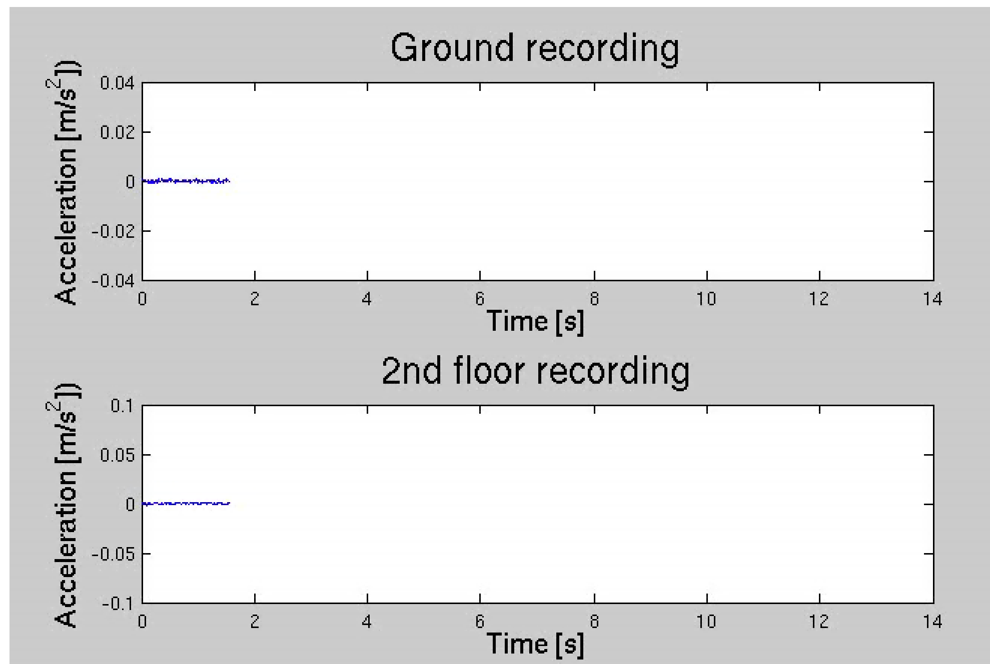
from Grimaz et al.,2017

Method 1

Real time estimation of shaking for different buildings.
Input: base of one of the sentinel building 1) recording at the base of one of the sentinel building (OGS-Uni Trieste)
2) Frequency of oescillation for building type (Uni Udine)



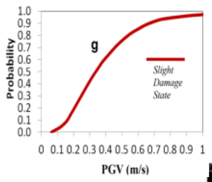
from
Parolai et al.,2015, SRL

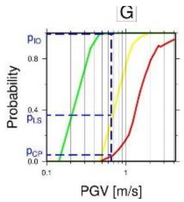


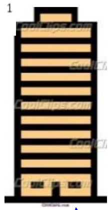
Method 2

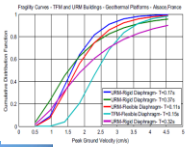
Estimation of the probability of exceedance of acertain limit state for different buildings within an area

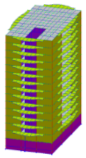
Input: 1) recording at the base of one of the sentinel building (OGS-Uni Trieste)
2)Fragility curves for building type (Uni Udine)





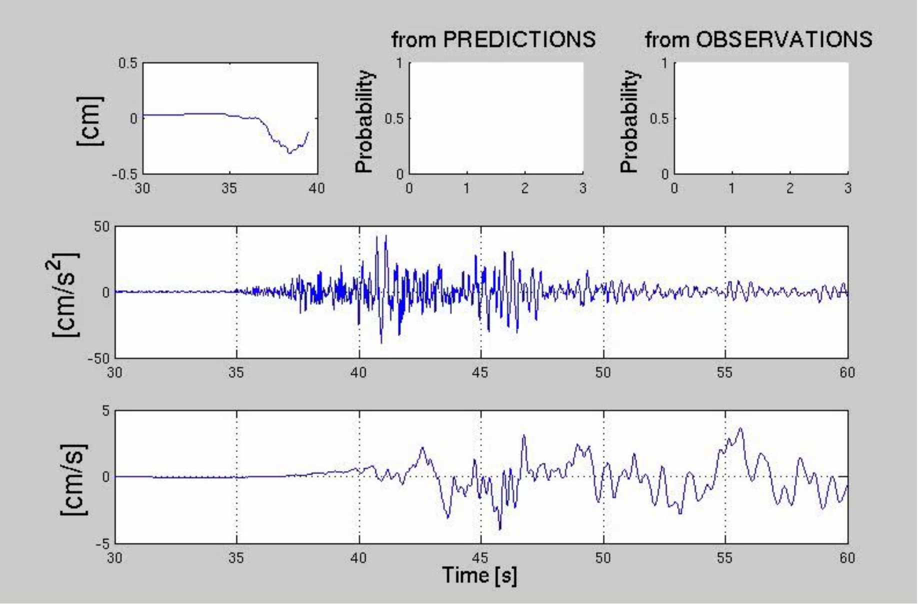






Real time damage forecast

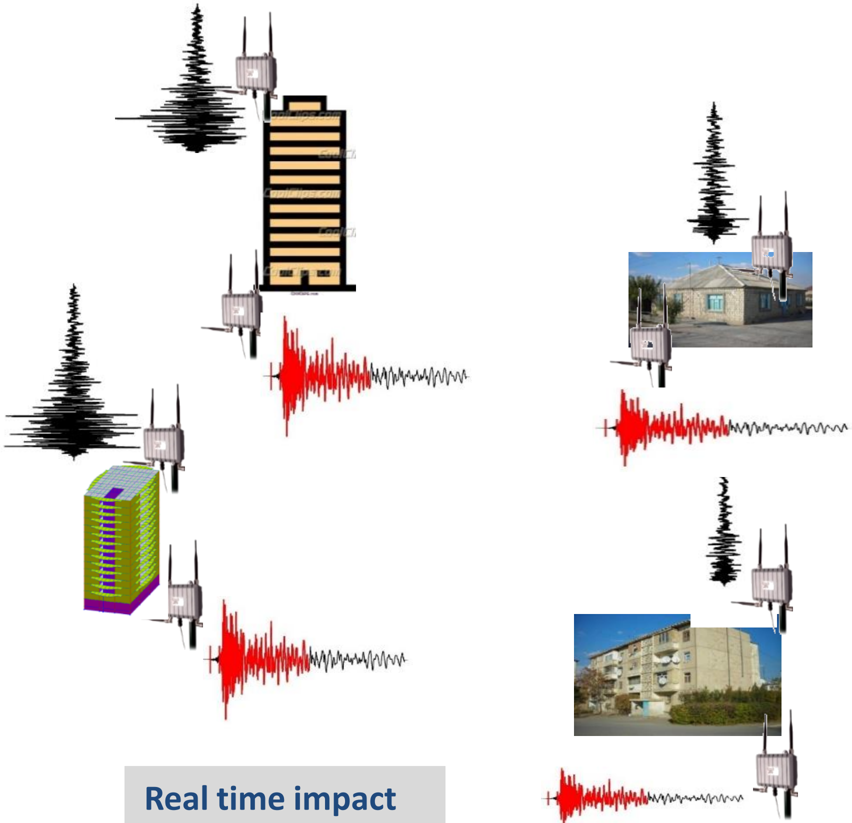
Real time shaking foecasting



from
Parolai et al.,2015, SRL
Megalooikonomou et al. 2018.

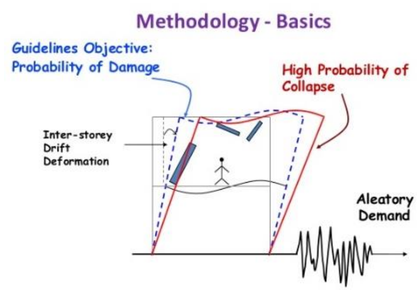
Method 3

First level estimate of possible damage in buildings with sensors at the base and at the top.
Input: 1) recording at the base of one of the sentinel building (OGS-Uni Trieste)
2) Real time measurement of interstorey-drift and/or resonance frequency variation (OGS-Uni Udine)

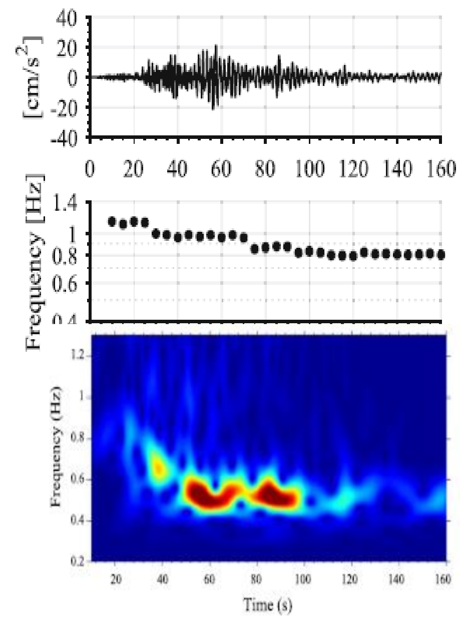


Real time impact forecast

from
Parolai et al.,2015, SRL

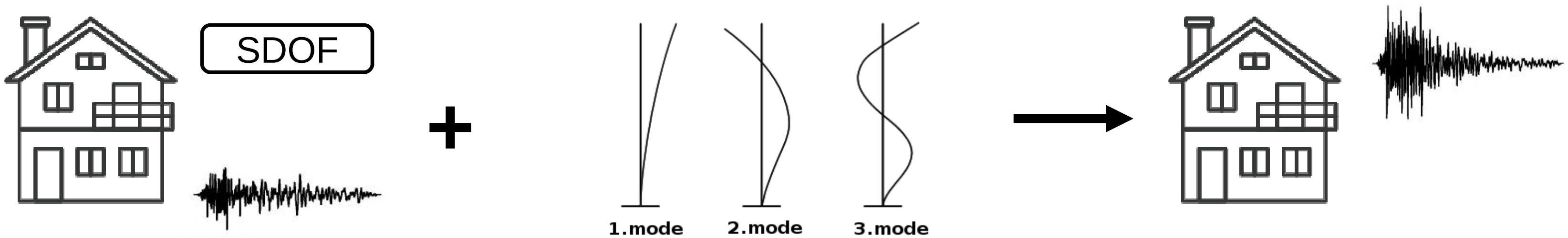


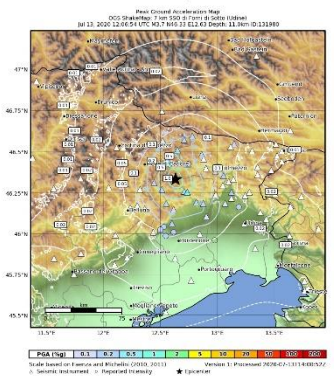
from Pianese et al, 2018



Estimating The Building's Dynamic Behavior

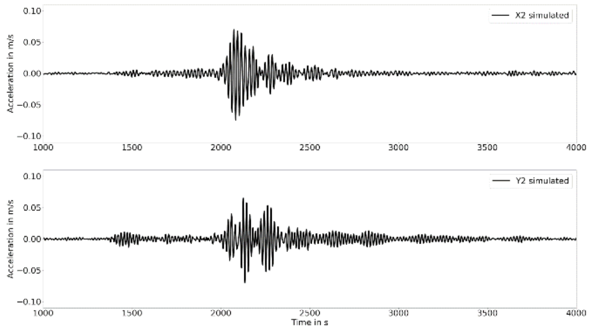
Generally, different buildings react differently to the same input ground motion. This depends on their different structural dynamic behavior, that influences expected damage.





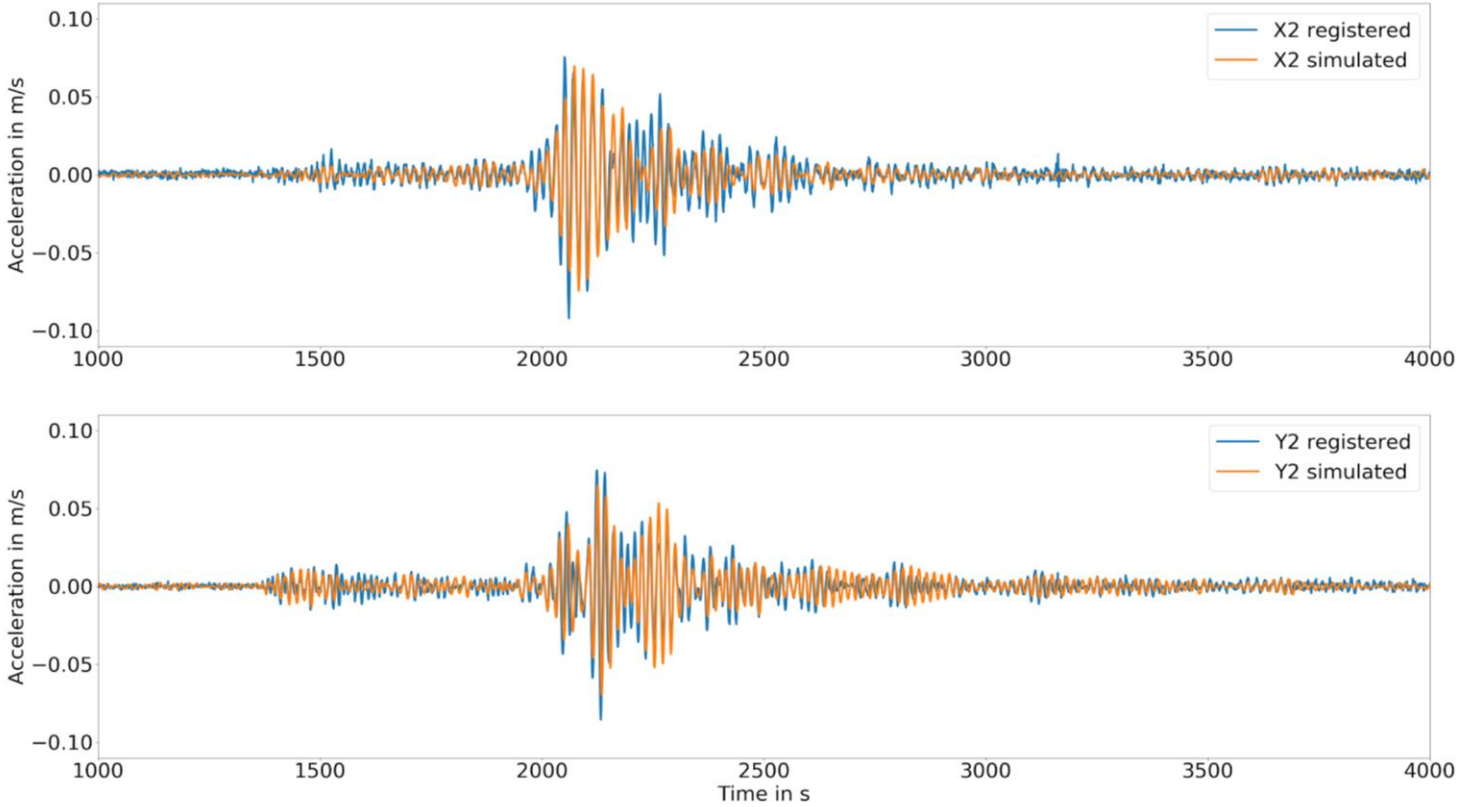
Recordings of the M3.7 event 13.07.2020 (Tramonti di Sopra)

Monitored building in Aviano (UD) characterized by noise measurements (Sentinella/Armonia projects)

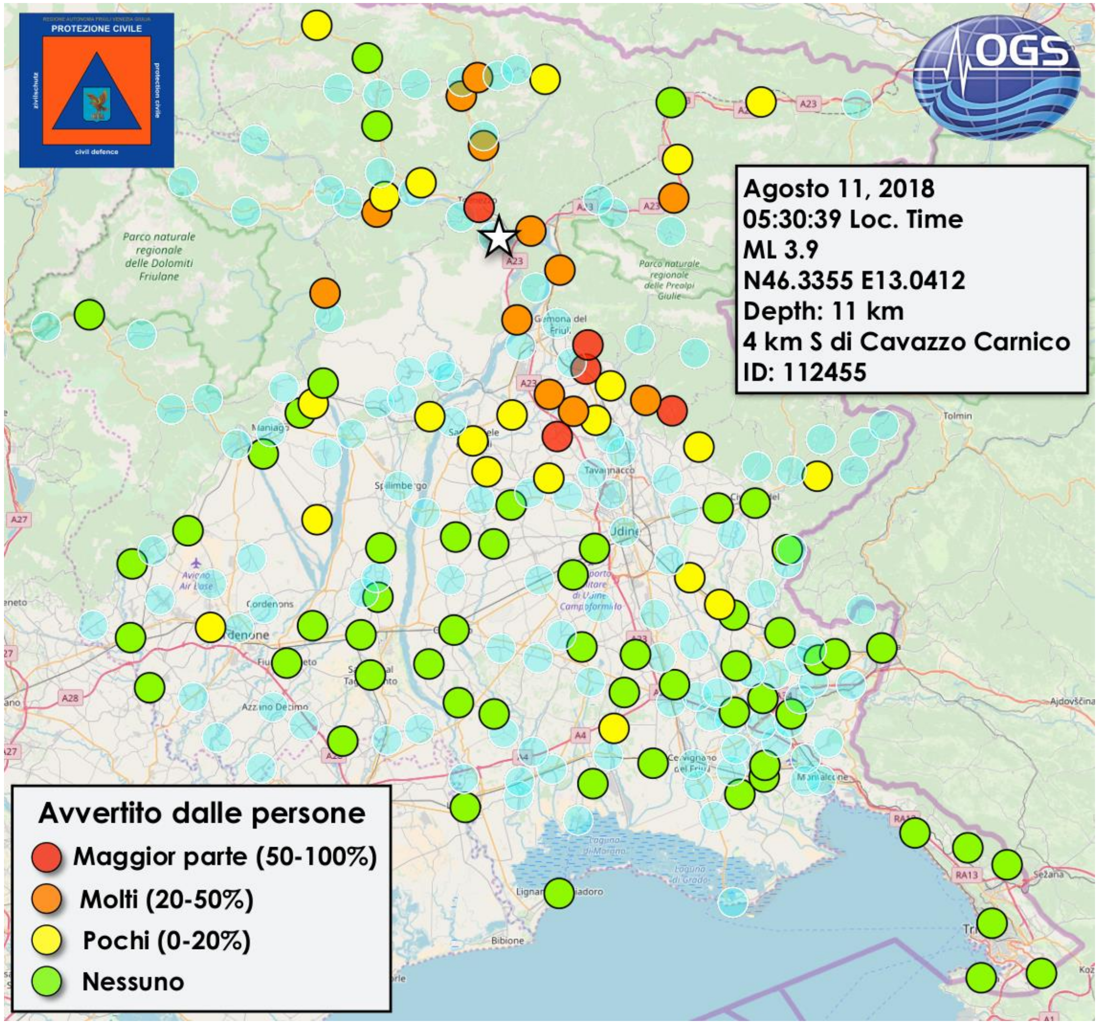


Simulated Acceleration at the top of the building

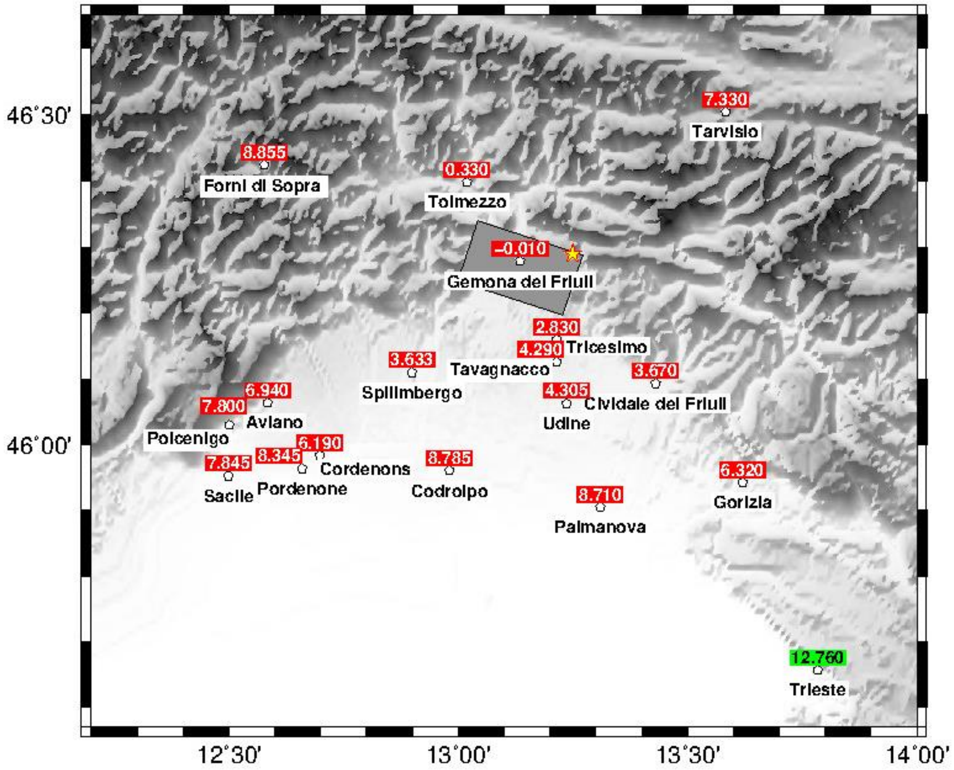
Recorded and simulated acceleration

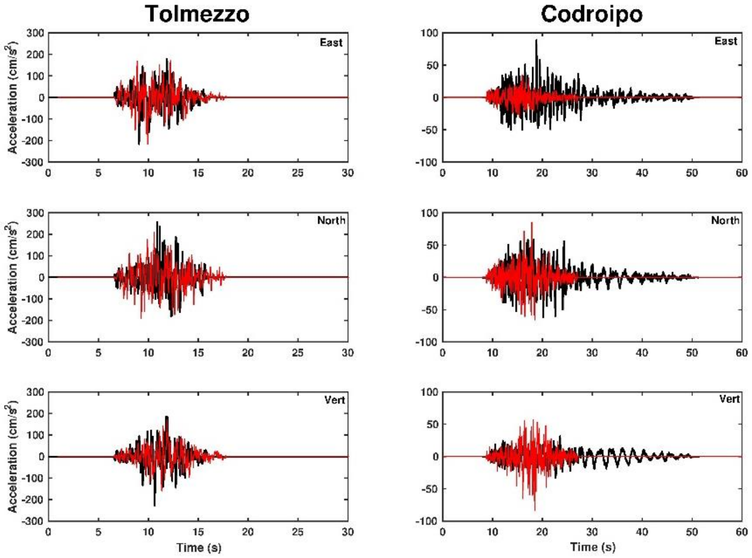


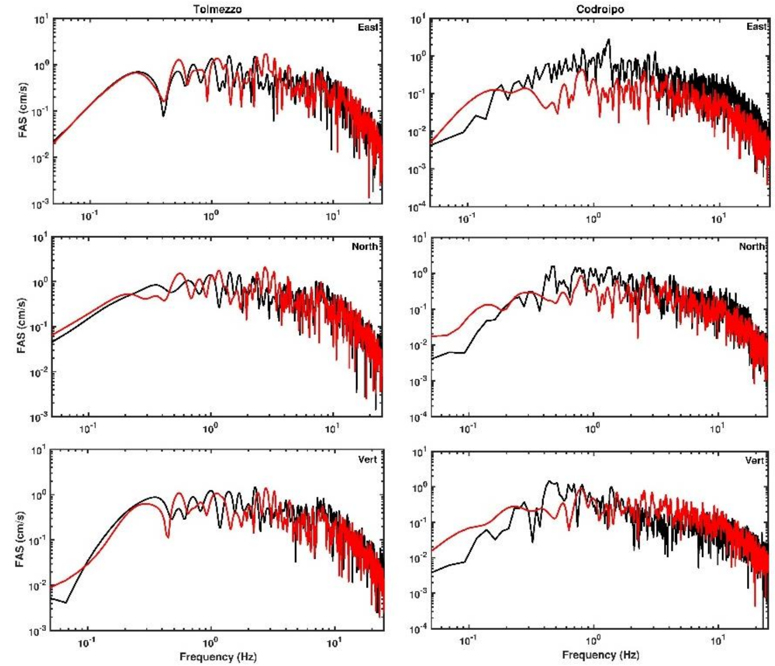
Integration of the information from seismic stations with those provided by the Civil protection volunteers: Sentinel buildings used as verification points



Feasibility for DOSEEW in case of repetition of the 1976 Event

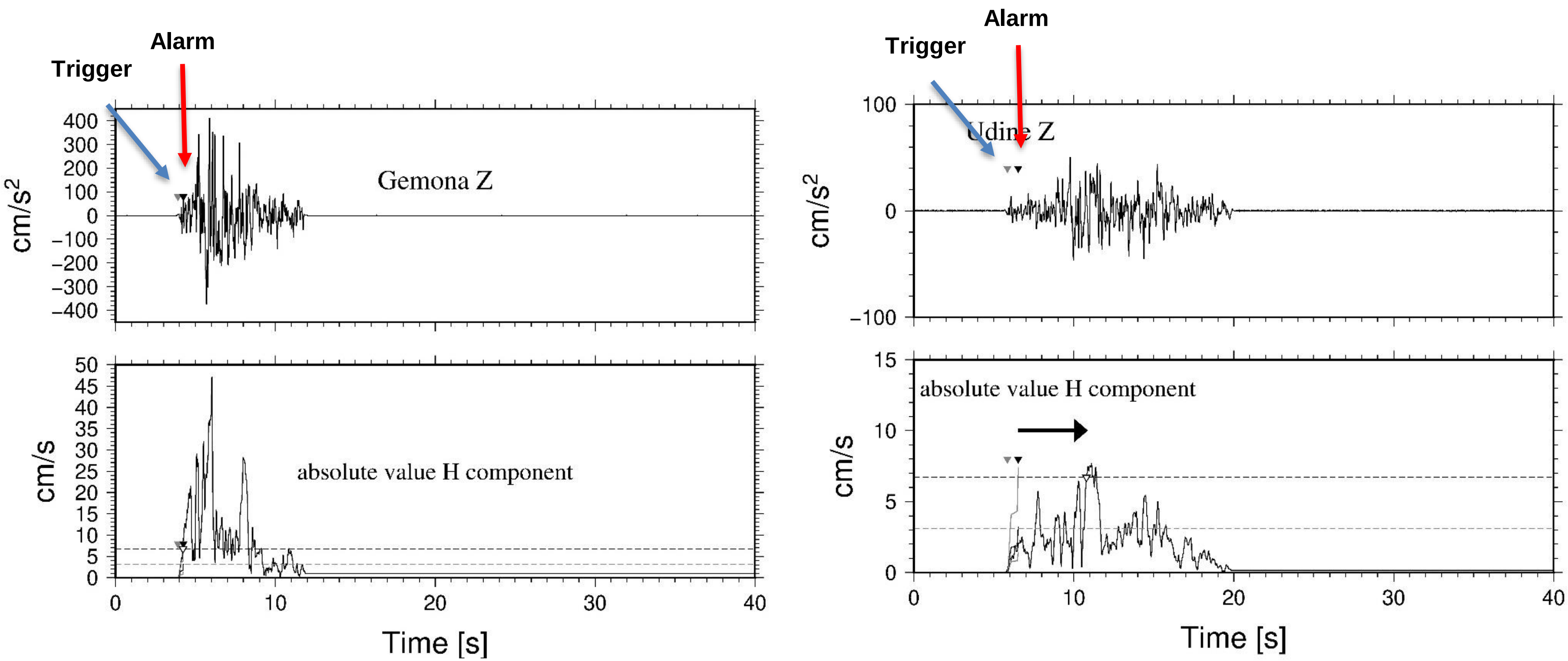






from
Parolai et al.,2020

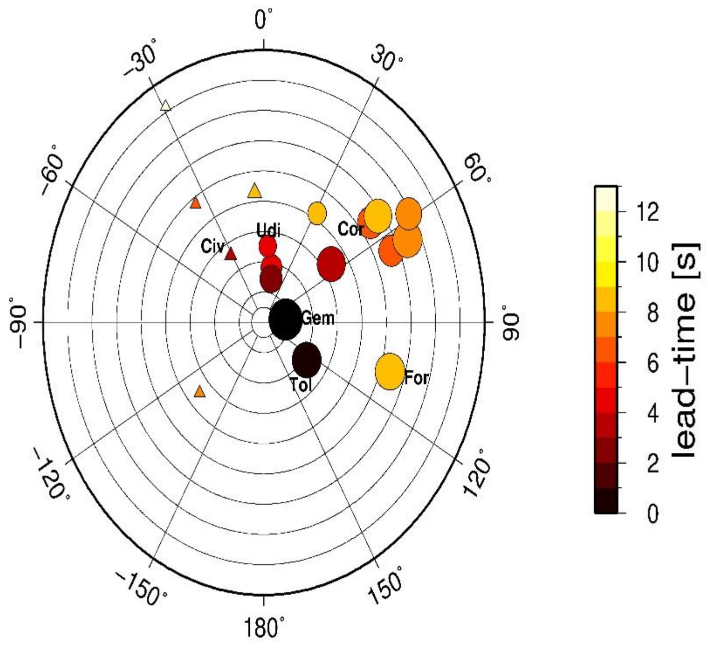
DOSEEW applied to the synthetic data

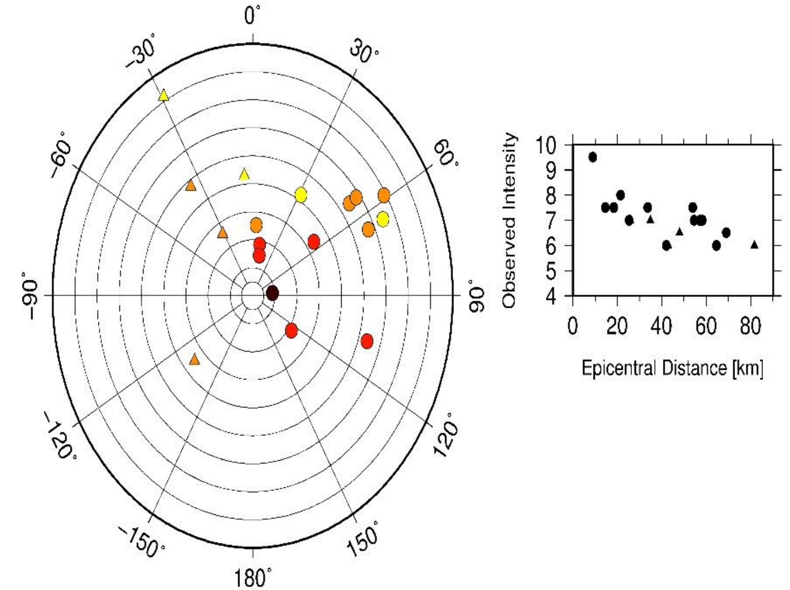


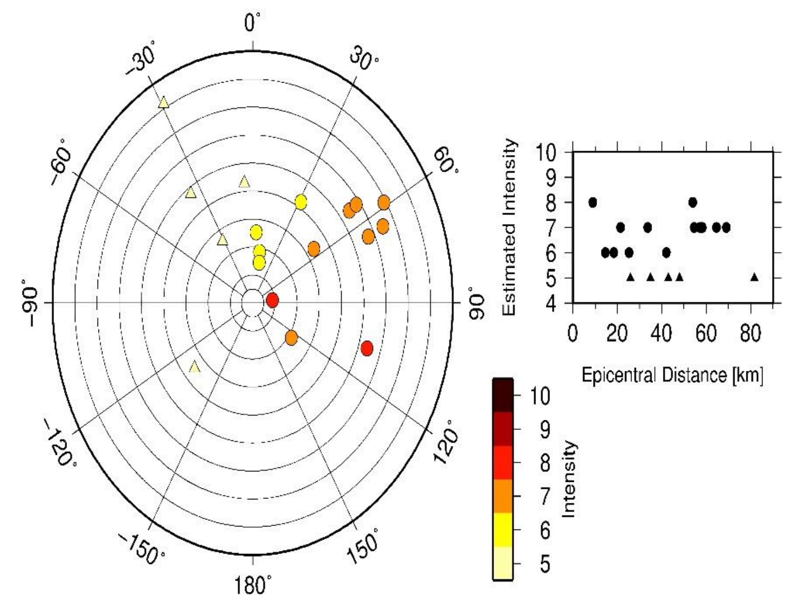
from
Parolai et al.,2020

DOSEEW applied to the synthetic data

Strong dependency of lead-time on slip distribution

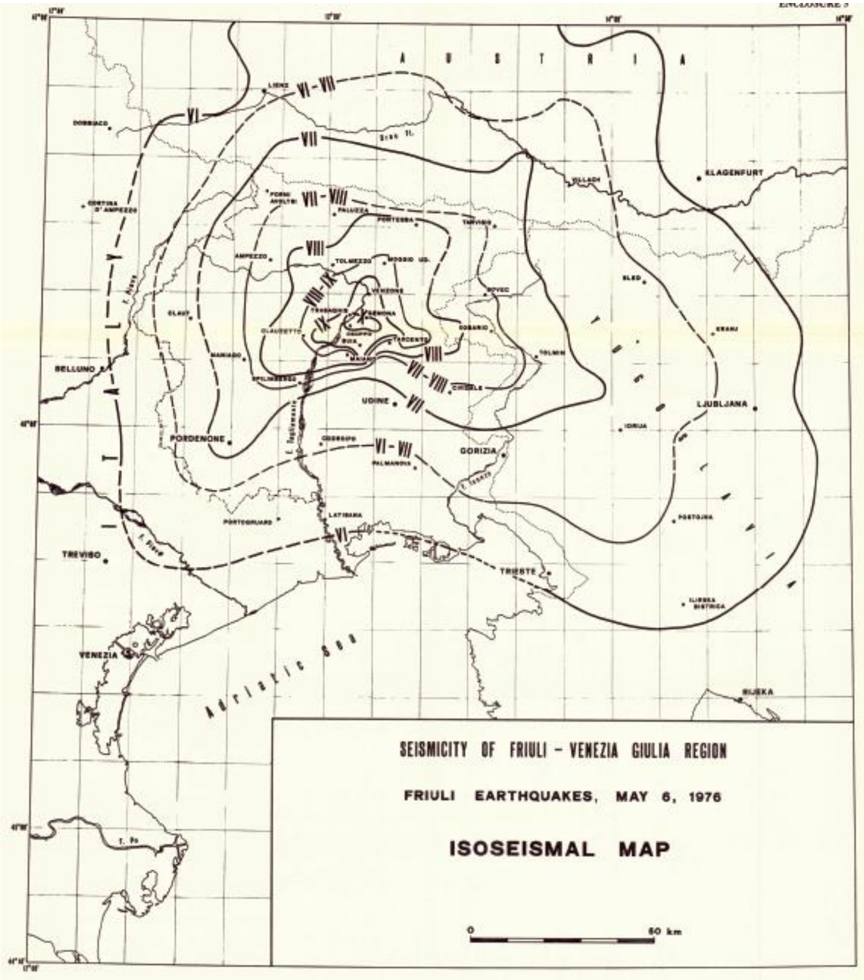






from
Parolai et al.,2020

Possible reduction of 10% of injured persons



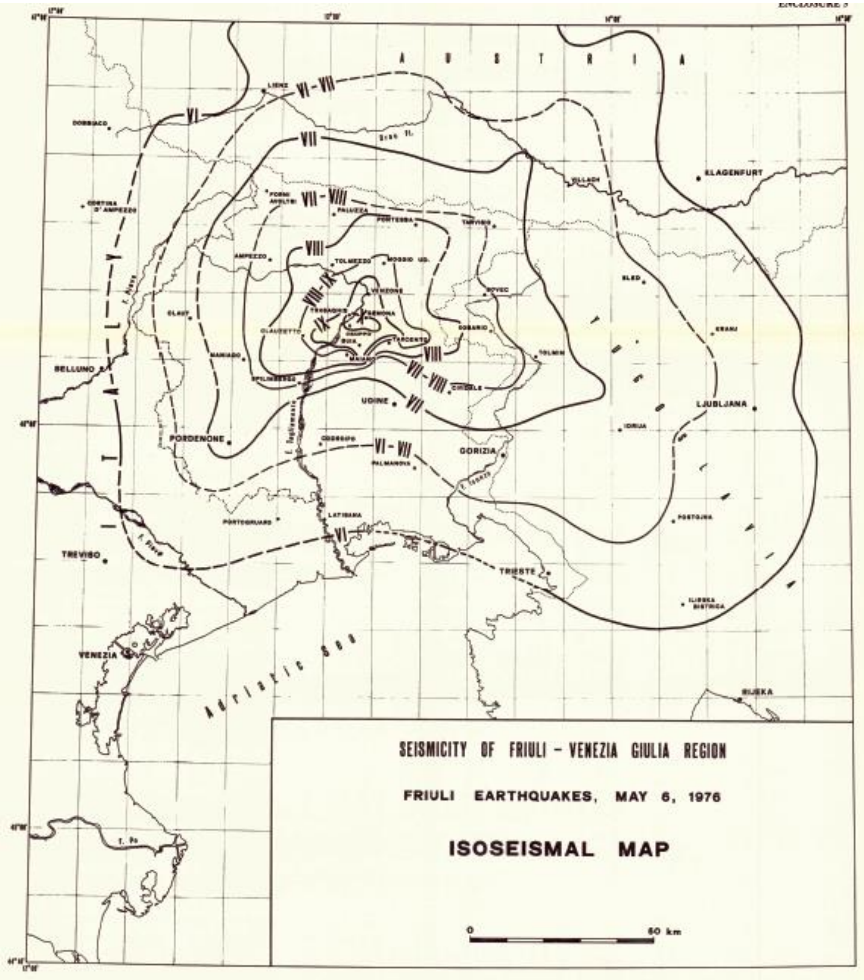
from
Parolai et al.,2020

Table 1 - Summary of the localities and lead times vs injured person during the 1976 Friuli earthquake.

Locality	Lead time (s)	1976 Intensity	1976 Injured
Cividale	3.67	VII	18
Cordenons	6.19	VII	5
Tarvisio	7.33	VII	5
Pordenone	8.34	VII	27
Udine	4.30	VII	53
Forni di Sopra	8.85	VII-VIII	4
Sacile	7.84	VI-VII	6
Tavagnacco	4.29	VII-VIII	24
Spilimbergo	3.63	VII-VIII	10
Tricesimo	2.83	VII-VIII	10

Possible several seconds to stop the plant of TAL

No action was possible for this scenario for the Magnetic Marelli being in the blind zone



from
Parolai et al.,2020

Magneti Marelli Automotive Lighting, Tolmezzo (UD)

- production of electronic
- components for LED lights
- 5.000 m^2
- > 1100 employees

TAL – Transalpine Pipeline

- Italy, Austria and Germany
- 40% of the energy needs of Germany and the Czech Republic, and 90% of Austria
- 753 km
- 7500 m^3/h
- 750 employees involved
- 1.2 x 10^9 €

Damage Assessment for Rapid Response (DARR)

$$x_j = b_1 x_{j-1} + b_2 x_{j-2} - S_0(\Delta t)^2 a_{j-1},$$

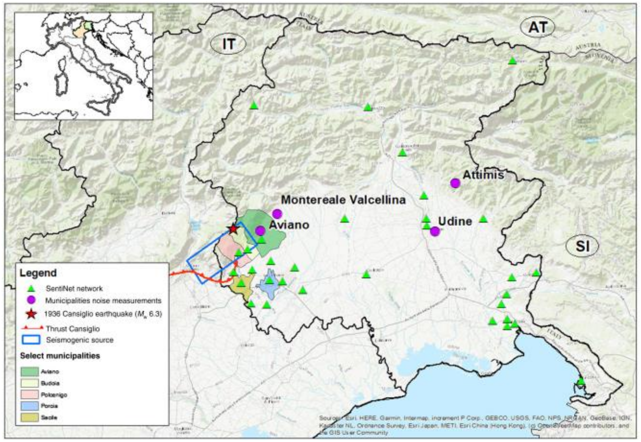
with the coefficients b_1, b_2, and S_0 defined as

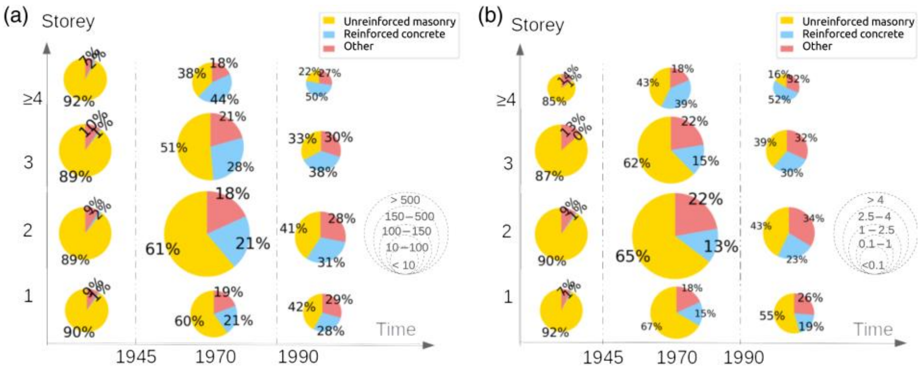
$$b_1 = 2e^{-\zeta\omega_0\Delta t}\cos(\omega_d\Delta t),$$

$$b_2 = -e^{-2\zeta\omega_0\Delta t},$$

$$S_0 = e^{-\zeta\omega_0\Delta t}\sin\frac{(\omega_d\Delta t)}{(\omega_d\Delta t)},$$

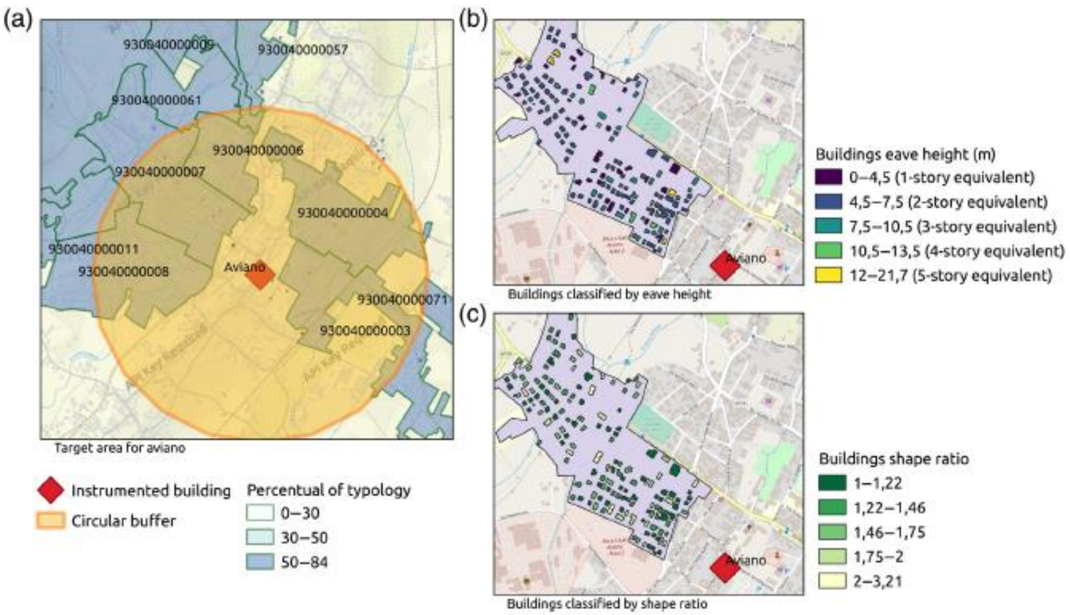
$$\omega_d = \omega_0(1-\zeta^2)^{\frac{1}{2}}.$$





from
Scaini et al.,2021

Damage Assessment for Rapid Response (DARR)



from
Scaini et al.,2021

$$x_j = b_1 x_{j-1} + b_2 x_{j-2} - S_0(\Delta t)^2 a_{j-1}, \quad (1)$$

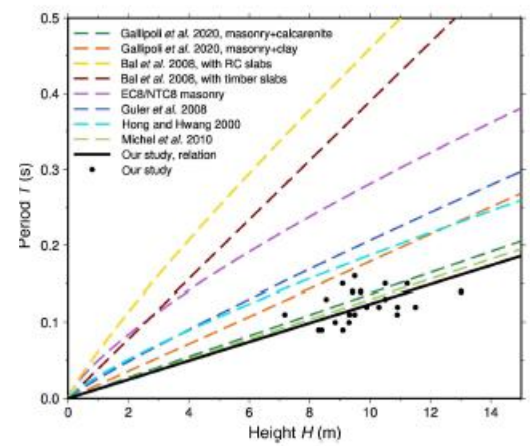
with the coefficients b_1, b_2, and S_0 defined as

$$b_1 = 2e^{-\zeta\omega_0\Delta t}\cos(\omega_d \Delta t), \quad (2)$$

$$b_2 = -e^{-2\zeta\omega_0\Delta t},$$

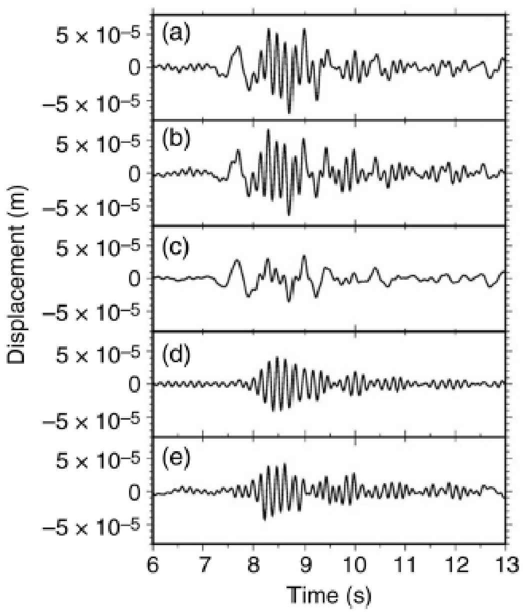
$$S_0 = e^{-\zeta\omega_0\Delta t}\sin\frac{(\omega_d\Delta t)}{(\omega_d\Delta t)},$$

$$\omega_d = \omega_0(1-\zeta^2)^{\frac{1}{2}}.$$

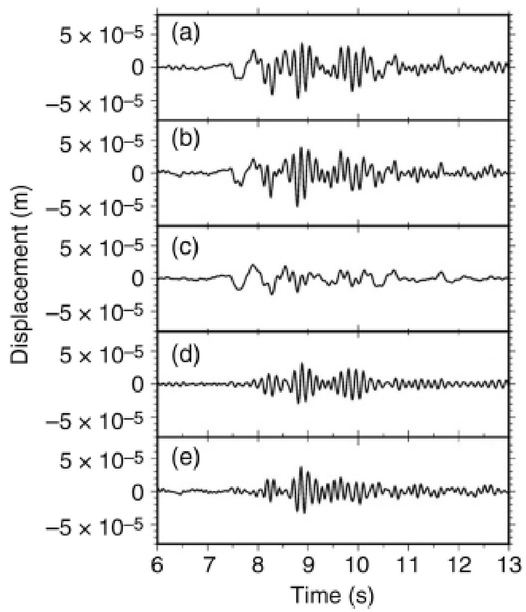


Damage Assessment for Rapid Response (DARR)

X



Y



$$x_j = b_1 x_{j-1} + b_2 x_{j-2} - S_0 (\Delta t)^2 a_{j-1},$$

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$$S_0 = e^{-\zeta\omega_0\Delta t}\sin\frac{(\omega_d\Delta t)}{(\omega_d\Delta t)},$$

$$\omega_d = \omega_0(1-\zeta^2)^{\frac{1}{2}}.$$

from Scaini et al.,2021

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Damage Assessment for Rapid Response (DARR)

Application to different areas

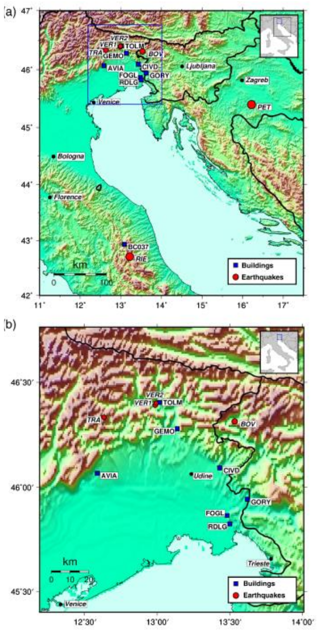

TABLE 1
Relative Displacement (in Centimeters) and Interstory Drift Limits (in Percentage) for Extensive and Complete Structural Damage for Selected Building Typologies (Simple Stone or Regular Unreinforced Masonry [URM], and Reinforced Concrete [RC] Frames and Shear Walls)

Building Typology	Relative Displacement (cm)		Interstory Drift Ratio (%)	
Damage Level	Extensive	Complete	Extensive	Complete
Simple stone URM, low-rise (1–2 stories)	0.85	1.40		
Simple stone URM, mid-rise (3–5 stories)	1.35	2.10		0.61
Simple stone URM, high-rise (>5 stories)	1.61	2.41	0.34	
Regular URM, RC floors, low-rise (1–2 stories)	1.38	2.36		
Regular URM, RC floors, mid-rise (3–5 stories)	2.19	3.50		0.45–0.72*
Regular URM, RC floors, high-rise (>5 stories)	2.47	3.87		
RC frame, low-rise (1–3 stories)	3.01	4.51	0.13	0.30
RC frame, mid-rise (4–7 stories)	4.49	6.74	0.12	0.27
RC frame, high-rise (>7 stories)	6.10	9.15	0.16	0.38
RC shear walls, low-rise (1–3 stories)	3.90	5.94	0.03	0.06
RC shear walls, mid-rise (4–7 stories)	6.12	9.59	0.12	0.28
RC shear walls, high-rise (>7 stories)	8.21	12.86	0.23	0.56

Relative displacement (displacement between top and bottom) limits are provided by Lagomarsino and Giovinazzi (2006). Interstory drift limits are provided by Borzi *et al.* (2008) for URM and by the deliverables of the Risk-UE project (Mouroux and Brun, 2006) for RC. Limits were calculated based on finite-element modeling of different building typologies and represent the threshold for occurrence of extensive and complete damage, corresponding to D3 and both D4 and D5 damage level of European Macroseismic Scale 1998 (EMS-98) (Grünthal, 1998). The same Interstory Drift Ratio limit is provided for all masonry buildings for extensive damage, whereas for complete damage one value is provided for stone and one for regular URM.
*Depending on percentage of voids.

from Petrovic et al.,2023

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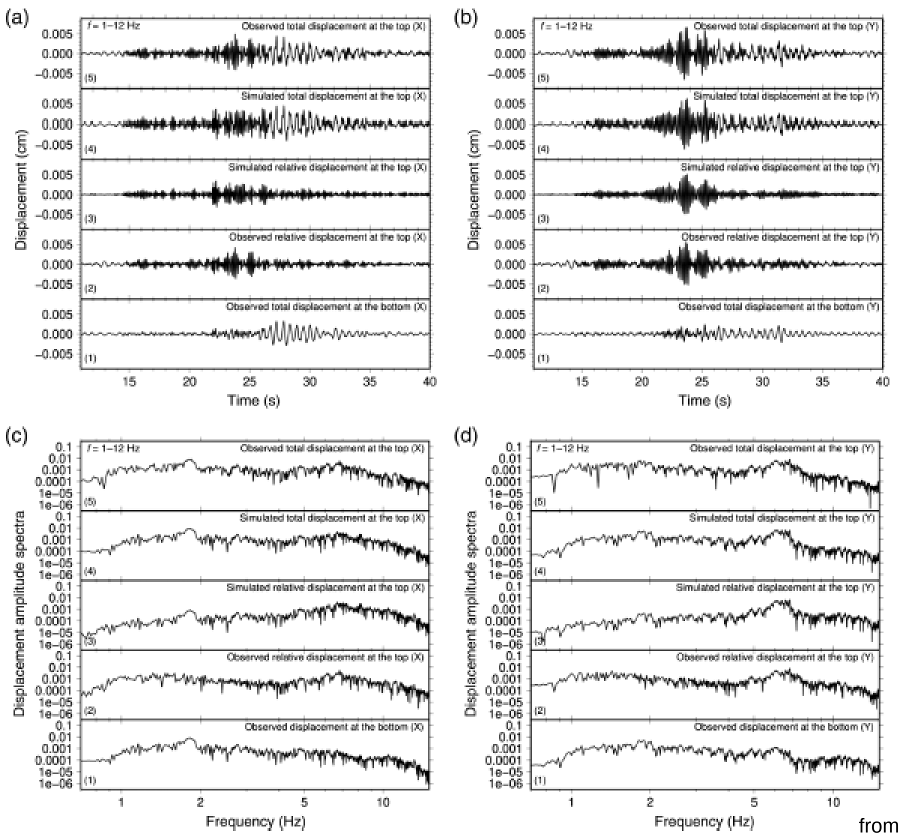
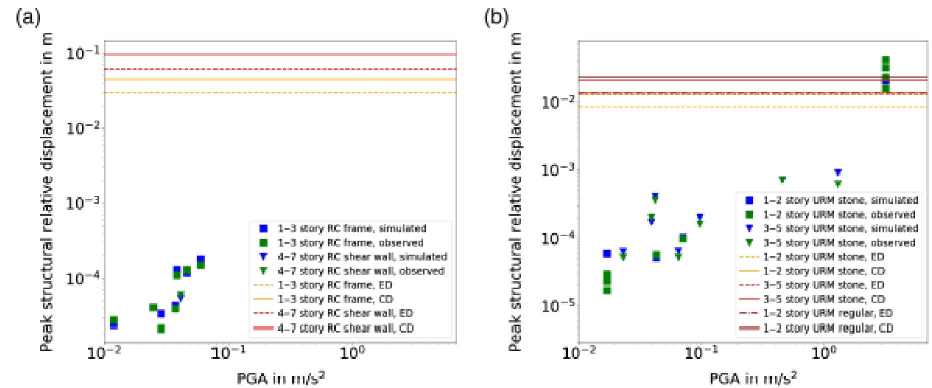
Damage Assessment for Rapid Response (DARR)





from Petrovic et al.,2023

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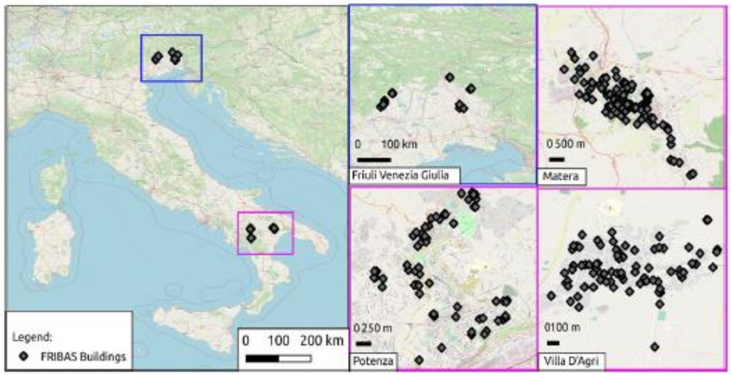
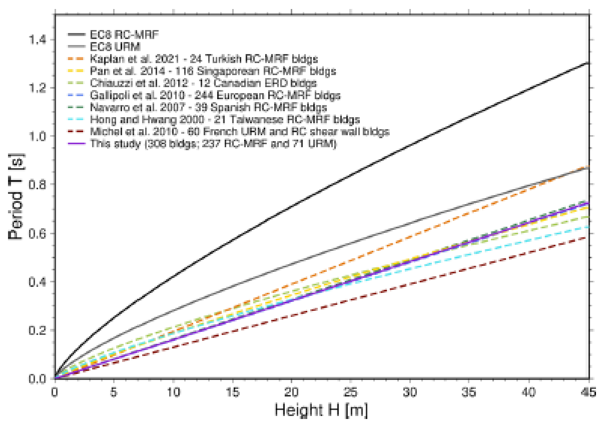
Some recent developments

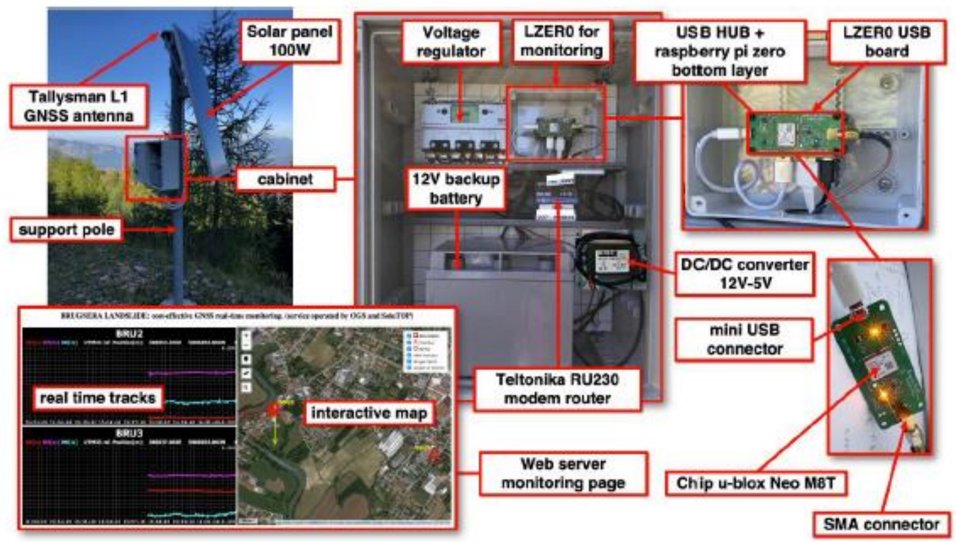
Fribas data base





from Gallipoli et al.,2023

Integration of Strong motion and GNSS data
Cost effective GNSS



from Zuliani et al.,2022

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