The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2142-16

Advanced Conference on Seismic Risk Mitigation and Sustainable Development

10 - 14 May 2010

Some remarks on the earthquakes in L`Aquila, Haiti and Chile. Seismology and damages

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Advanced Conference on Seismic Risk Mitigation and Sustainable Development
Trieste, May 13 2010

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FOREWORD

Between April 2009 and February 2010 3 significant earthquakes occurred.

The study of these earthquakes provided a great increase of knowledge on causes and effects.

Herein some remarks on aspects concerning seismology and damage are presented and discussed. These two features are strongly correlated and therefore they must be studied together.

- **L'Aquila earthquake (Italy). April, 6 2009 Mw = 6.3**
- **Haiti earthquake. January, 12 2010 Mw = 7.0**
- **Maule earthquake (Chile). February, 27 2010 Mw = 8.8**

Within the same period of time others earthquakes occurred, among which:

- Baja California (Mexico). April, 4 2010 Mw = 7.2
- Southern Qinghai (China). April, 13 2010 Mw = 6.9

SOME INTRODUCTORY REMARKS

- The combination of seismology and seismic engineering is necessary to get robust assessment of scenario earthquakes.

- Without seismological information the interpretation of the buildings' behaviour during an earthquake is more difficult and sometimes more uncertain.

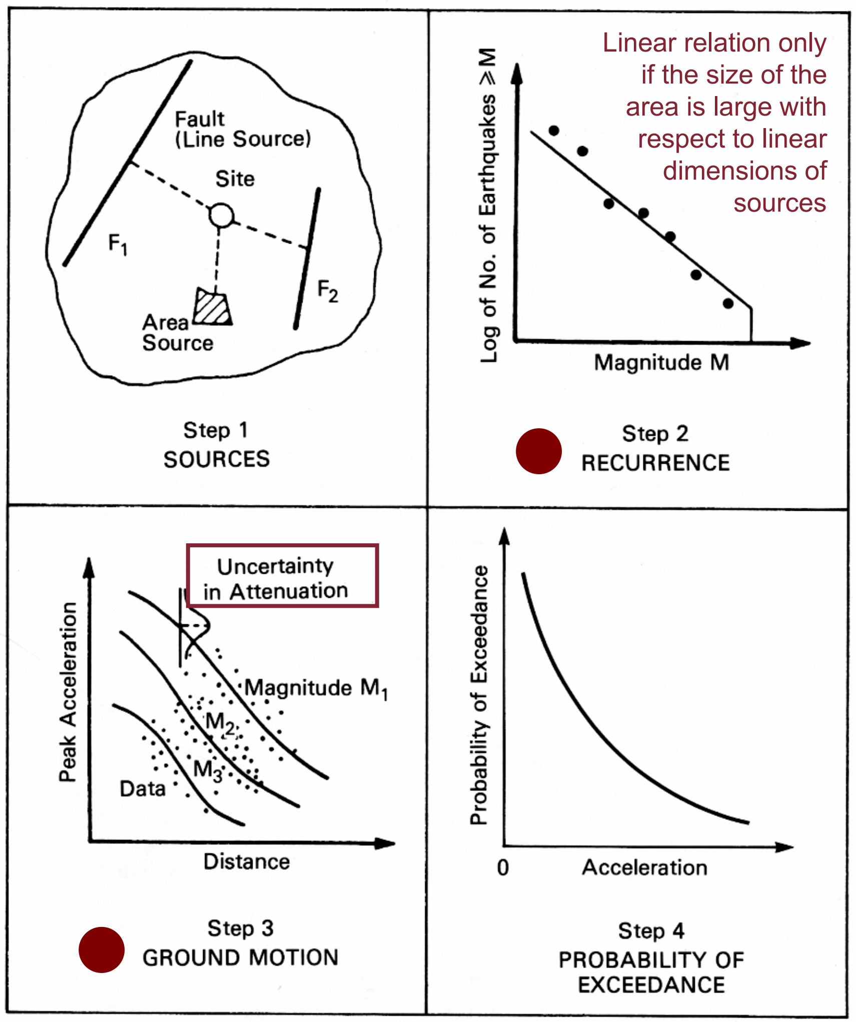


FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

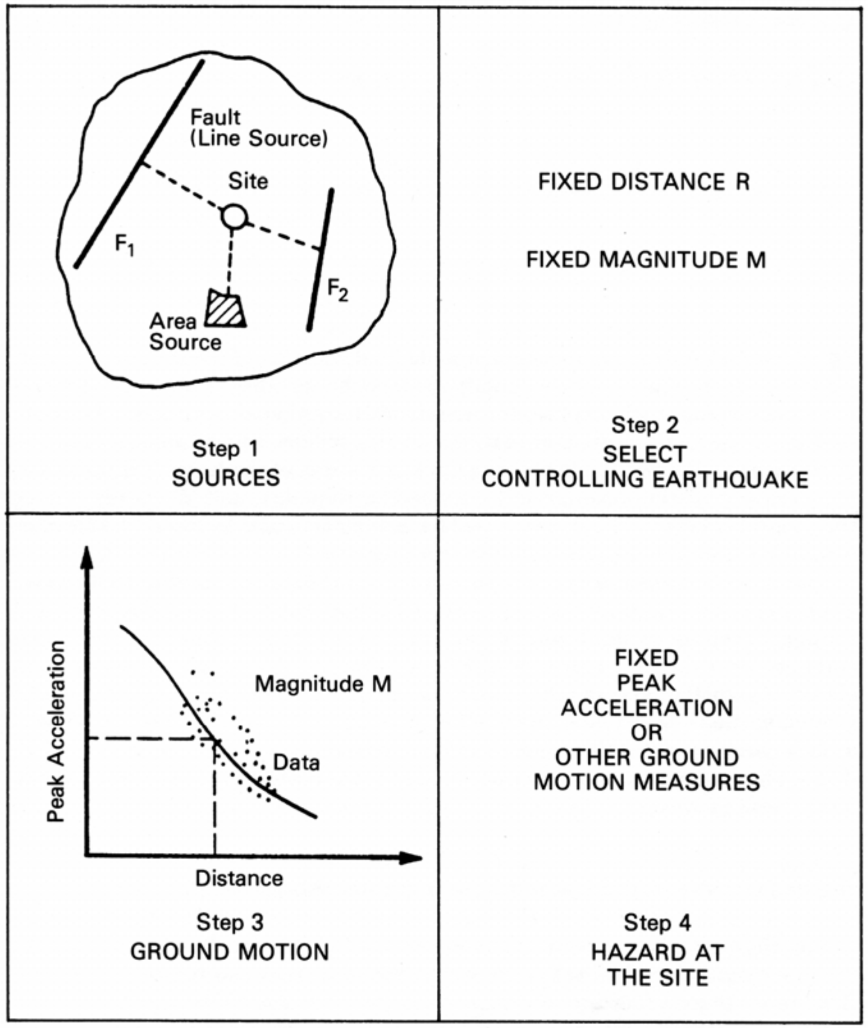


FIGURE 4.1 Basic steps of deterministic seismic hazard analysis (after TERA Corporation 1978).

PSHA Probabilistic and DSHA Deterministic

procedures after Reiter (1990)

SOME INTRODUCTORY REMARKS 2

➢ Deterministic, or scenario, seismic hazard assessment can estimate several scenario earthquakes, even the largest possible, based on geophysical, geological, and geotechnical data and using appropriate numerical simulations of the rupture process and of wave propagation. This way it is even possible to assess reasonable ground motion signals.

➢ In order to appraise earthquake damages both a robust seismic hazard assessment and a realistic buildings' vulnerability estimation are necessary.

PROBABILISTICS vs. OBSERVED VALUES

Kobe (17.1.1995), Gujarat (26.1.2001), Boumerdes (21.5.2003) Bam (26.12.2003), E-Sichuan (12.5.2008) and Haiti (12.1.2010) earthquakes

PGA(g)

	Expected with a probability of exceedence of 10% in 50 years (return period 475 years)	Observed
• Kobe	0.40-0.48	0.7-0.8
• Gujarat	0.16-0.24	0.5-0.6
• Boumerdes	0.08-0.16	0.3-0.4*
• Bam	0.16-0.24	0.7-0.8
• E-Sichuan	0.16-0.24	0.6->0.8
• Haiti	0.08-0.16	0.3-0.6*

- Global Seismic Hazard Assessment Program (GSHAP)
- Why are observed values higher than expected ones??

*from I, if non linear effects (e.g. liquefaction) is considered the value may be smaller

Courtesy Prof. G. Panza

SOME INTRODUCTORY REMARKS

- Past probabilistic hazard assessments have not always been confirmed by strong ground motion recordings and by damage observations.

- Probabilistic hazard assessment improves with higher quality historical data. Nonetheless, often historical data is available for too short time windows. Moreover, several uncertainties are still present in the available models. i.e. Attenuation relations assume the same propagation model for all the events, but such hypothesis is not very realistic.

SOME INTRODUCTORY REMARKS 4

ATTENUATION

Empirical relations are not capable to capture relevant aspects of the phenomenon of space attenuation of peak values.

SOME INTRODUCTORY REMARKS

Stability tests increased in the last 500 years with respect to that of the period 1000-1500.

This suggests that the available data from past events **may well not be representative of future earthquakes and that the use of independent indicators of the seismogenic potential of a given area is needed**.

SOME INTRODUCTORY REMARKS

ACCELERATION PARAMETERS:
- PGA (PSHA) - EPA - DGA

PGA (used in PSHA) is the horizontal peak ground acceleration with 10% probability of exceedance in 50 years. This quantity is obtained treating probabilistically both the available data about the seismicity observed within each Seismogenic Zone and the propagation of seismic waves (attenuation relations).
NOTE: PGA is not an instrumental value, in fact it derives from probabilistic analyses.

EPA (Effective Peak Acceleration) is defined as the average of the maximum ordinates of elastic acceleration response spectra (5% damped) within the period range from 0.1 to 0.5 seconds, divided by a standard factor of 2.5.

L'Aquila EQ - Seismic demand
Comparison EPA and instrumental PGA

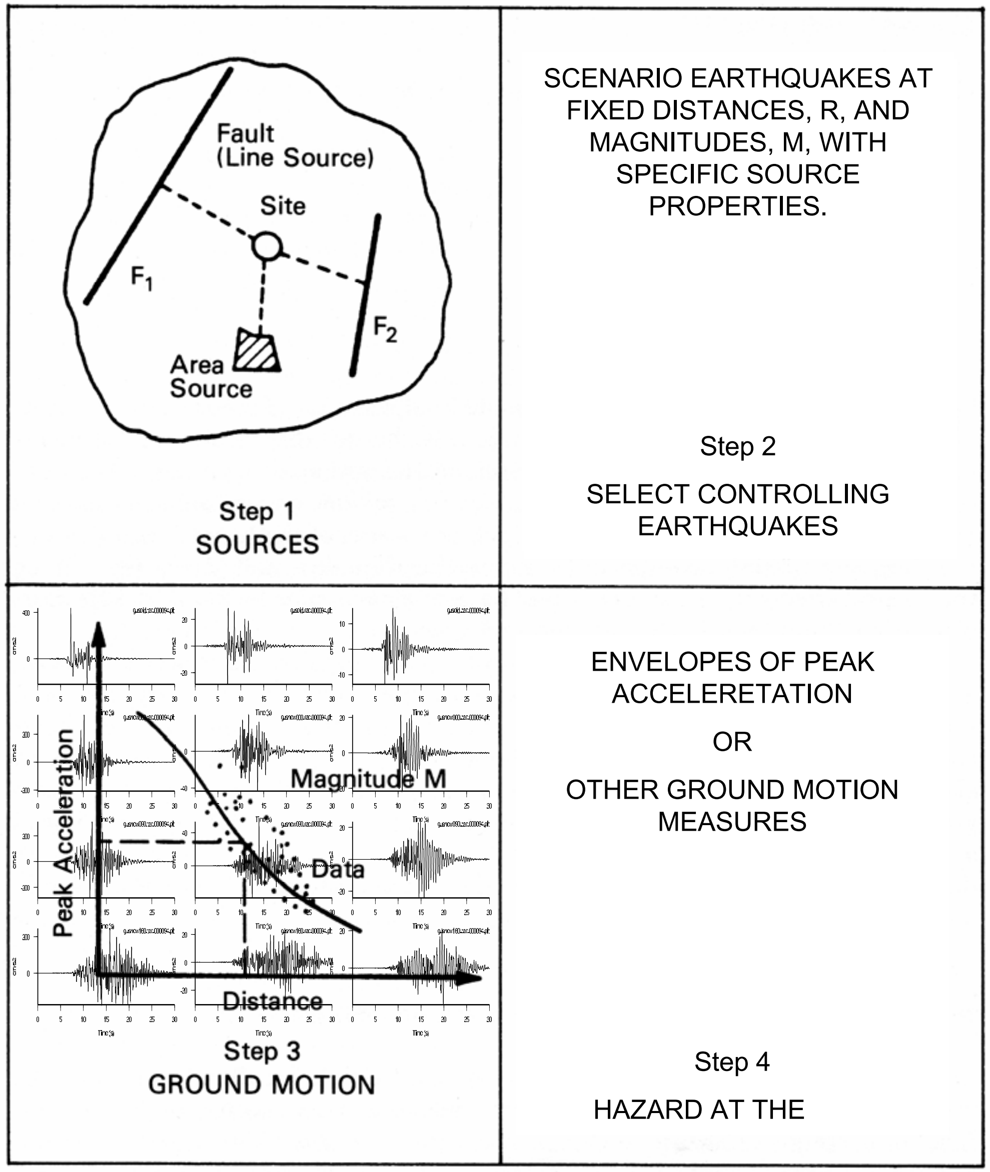
Record - main shock	PGA (g)	PGV (cm/s)	$EPA_{(0.1\text{-}0.5)}$ (g)	$S_{d,max}$ (cm)
AQV_EW	0.626	36.7	0.471	12.2
AQV_NS	0.598	40.5	0.502	8.0
AQG_EW	0.416	33.6	0.316	13.1
AQG_NS	0.434	35.9	0.309	12.0
AQA_EW	0.394	30.5	0.254	10.1
AQA_NS	0.451	24.5	0.384	7.2
AQK_EW	0.342	30.3	0.220	24.2
AQK_NS	0.340	38.6	0.245	22.6
AQU_EW	0.263	20.6	0.209	9.5
AQU_NS	0.316	30.7	0.157	12.4

- PGA and PGV are instrumental peak
- EPA gives a measure of the ground motion intensity in terms of acceleration and at the same time is related to the structural response. **The observed damage is consistent with EPA**
- $S_{d,max}$ is the maximum spectral displacement.

SOME INTRODUCTORY REMARKS

DGA (DSHA) is the horizontal acceleration anchoring the elastic response spectrum at the period T=0 s, computed from the response spectrum obtained through the modelling of the ground motion caused by the strongest earthquakes observed in each cell falling in the Seismogenic Zones. Introduced by Prof. G. Panza.

DGA is practically equivalent to EPA.
The comparison between DGA and PGA (return period 475 years) is possible only in Italy thanks to the uniqueness of the length of its earthquake catalogue.



NEO-DETERMINISTIC Proposed by prof. G. Panza

NDSHA analyses

New approach based on synthetic signals computation

No need of attenuation relations

SOME INTRODUCTORY REMARKS

Prof. Panza stated:

The comparison of the seismic hazard maps produced for Italy by the PSHA and NDSHA approaches shows that, as a rule, NDSHA provides values larger than those given by the PSHA in high-seismicity areas and in areas identified as prone to large earthquakes, but where no strong earthquake has been recorded in the last 1000 years.

L'Aquila – Haiti – Chile

Earthquakes

Trieste, May 13, 2010

Frequency of Occurrence of Worldwide Earthquakes Based on Observations Since 1900

Category	Magnitude	Number of earthquakes/year
Great	≥8	1
Major	7 - 7.9	18
Strong	6 - 6.9	120
Moderate	5 - 5.9	800
Light	4 - 4.9	6200

Source: National Earthquake Information Center, U.S. Geological Survey

- Chile: Great (M_W 8.8)
- Haiti: Major (M_W 7.0)
- L'Aquila: Strong (M_W 6.3)

Damage highlights in L'Aquila

Soil crack

Hole in the ground

Soft storey

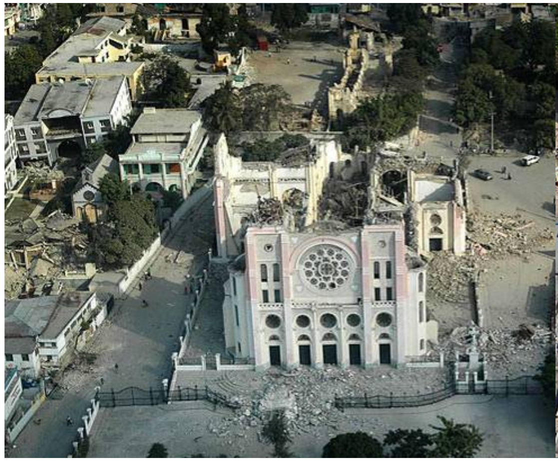
Masonry collapse

Damaged church

Failure of a bridge

Damage highlights in Haiti

Collapse of the cathedral



Building failure

Extensive damage to poor edifices

Reinforced concrete floor

Coastal lateral spreading

Damage highlights in Chile

Historic masonry bridge

Reinforced concrete bridge

RC Building collapse

Damage to monument

Façade overtunring

Adobe houses

L’Aquila earthquake April 6th, 2010

- On April 6, 2009 (1:32 UTC) an earthquake of magnitude M_w 6.3, originated by a normal fault rupture, shook the Abruzzo Region of Central Italy causing 309 death, hundreds of injured and thousand of homeless. It is the strongest earthquake recorded in Italy since 1980 (Irpinia earthquake).
- L’Aquila city was located in near-fault position.
- The focal mechanism exhibits the same direction as many of the major tectonic structures visible on the surface.
- Affected population > 70 000 – 80 000
  Casualties ~ 309
  Homeless ~ 50 000 - 20 000 (depending on the date)
  Preliminary loss estimation ~ € 16-18 Bi

L'Aquila earthquake April 6th, 2010 – Main features

Time: GMT 01:32 – Local 03:32

Epicentre: Lat. 42.32 N Long. 13.32 E (MedNet INGVBO)
Epicentre: Lat. 42.33 N Long. 13.32 E (Global CMT Catalog)
Epicentre: Lat. 42.32 N Long. 13.32 E (USGS)
Focal depth: 9 km
The epicentre is located approximately 6 km South-West of L'Aquila.

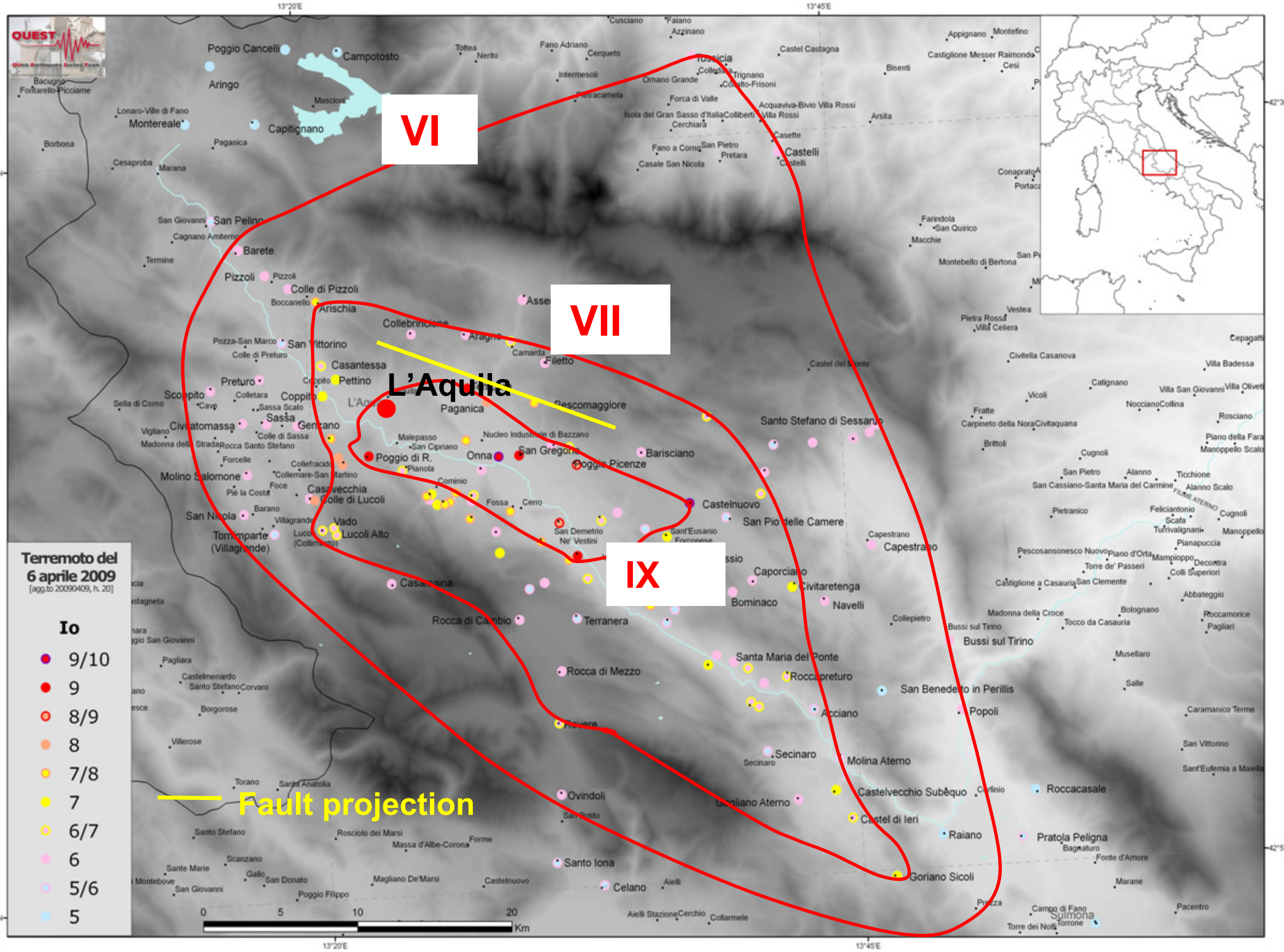
M_w = 6.3 (Moment Magnitude; INGV, USGS, CMT)
M_0 = 3.4 x 10^{18} N m (Seismic Moment; CMT, USGS)
M_0 = 3.7 x 10^{18} N m (Seismic Moment; INGV)

Rupture surface: 20 km x 10 km = 200 km^2 (first estimate)
Rupture surface: 17 km x 14 km = 238 km^2 (actual estimate)

Slip distribution inversion predicted maximum slip at depth of about 1.1-1.4 m and very small slip at the surface (about 15 cm)

L’Aquila earthquake - Seismology

Macroseismic felt intensities. Isoseismal lines (MCS)



L. Decanini

(May 2009)

Haiti EQ January 12th, 2010

Time: GMT 21:53 – Local 4:53

Epicentre: Lat. 18.46 N Long. 72.53 W (USGS)
Focal depth: 10 km
The epicentre is located approximately 25 km West of Port-Au-Prince.

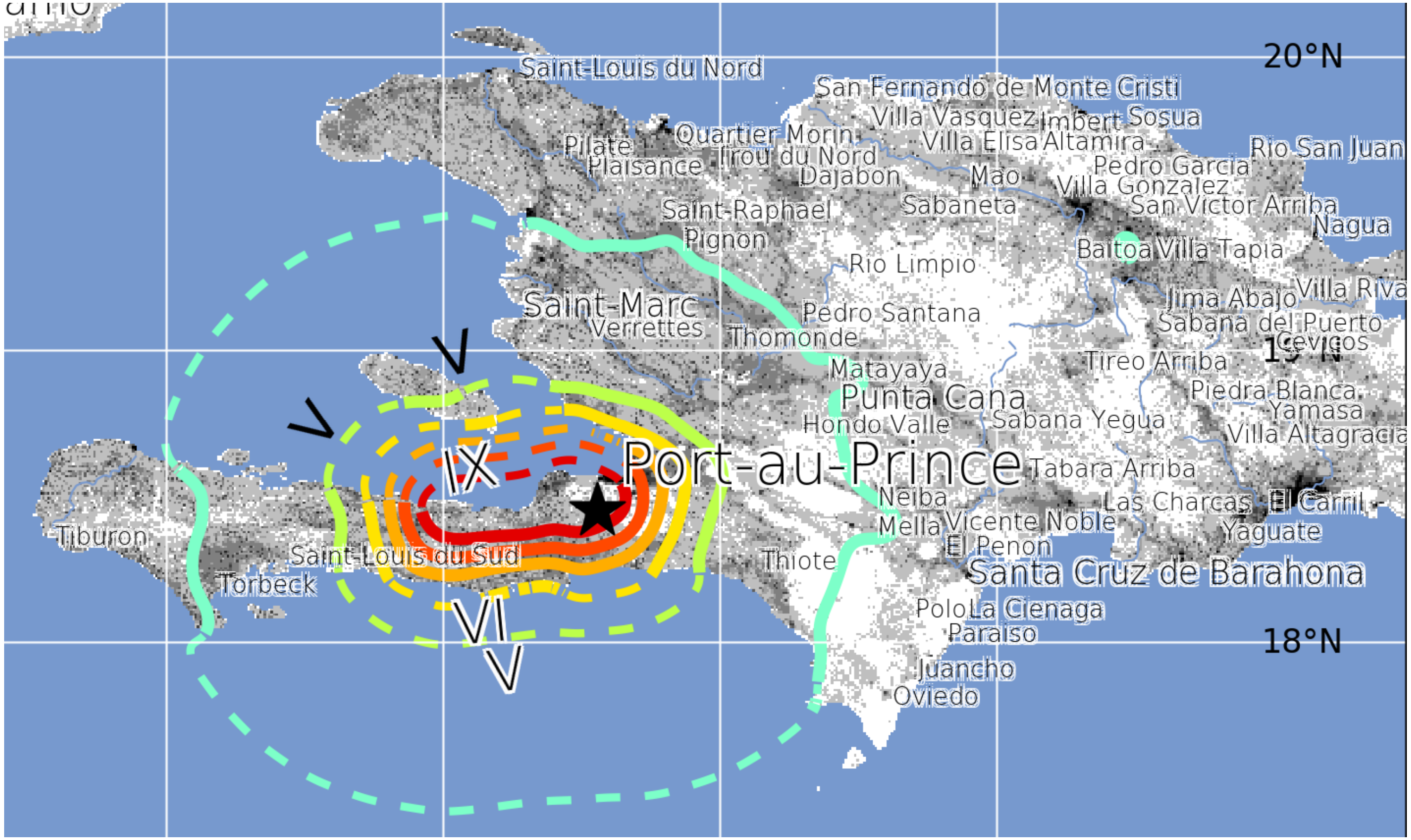
M_w = 7.0 (Moment Magnitude; USGS)
M_0 =4.5 x 10^{19} N m (Seismic Moment; USGS)

Rupture surface: ~ 30 km x 20 km
Maximum slip: ~ 5 m; Average slip: ~ 2 m

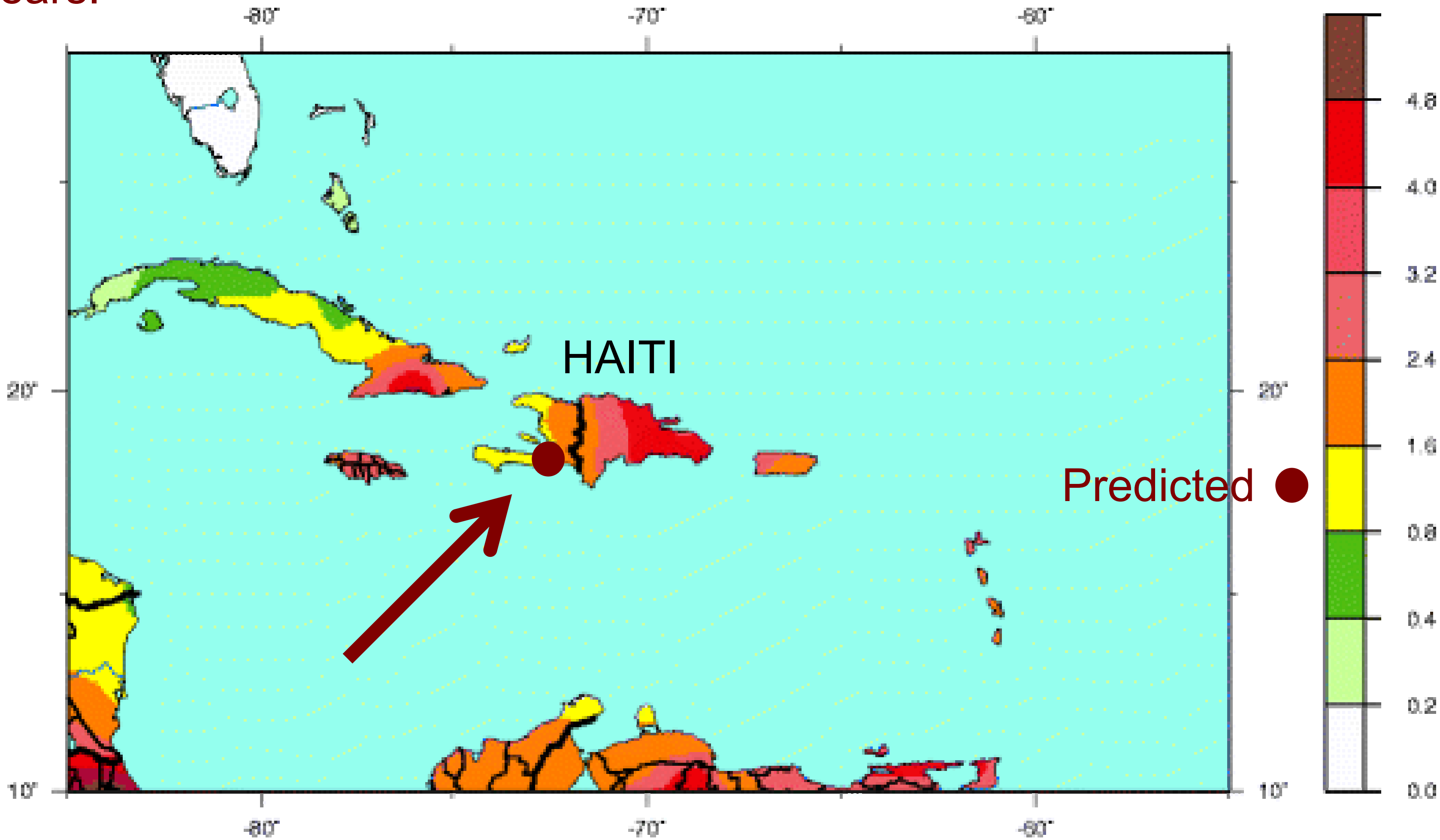
Affected population > 2 Mi
Casualties ~ 200 000
Homeless ~ 1 000 000
Preliminary loss estimation ~ € 40 Bi ?

Seismology of Haiti EQ

Macroseismic felt intensities. Isoseismal lines (MM)



Carribbean hazard. P.G.A. with 10% Probability of Exceedance in 50 years.



Estimated EPA $\geq$ 0,4 g (from damage, Decanini 2010)

Chile EQ February 27th, 2010

Time: GMT 06:34 – Local 03:34

Offshore Maule Earthquake
Epicentre: Lat. 35.85 S Long. 72.72 W (USGS)
Epicentre: Lat. 35.95 S Long. 73.15 W (Global CMT)
Focal depth: 35 km
The epicentre is located approximately 325 km South-West of Santiago.

M_w = 8.8 (Moment Magnitude; USGS, CMT)
M_0 =1.8 - 2 x 10^{22} N m (Seismic Moment; CMT, USGS)

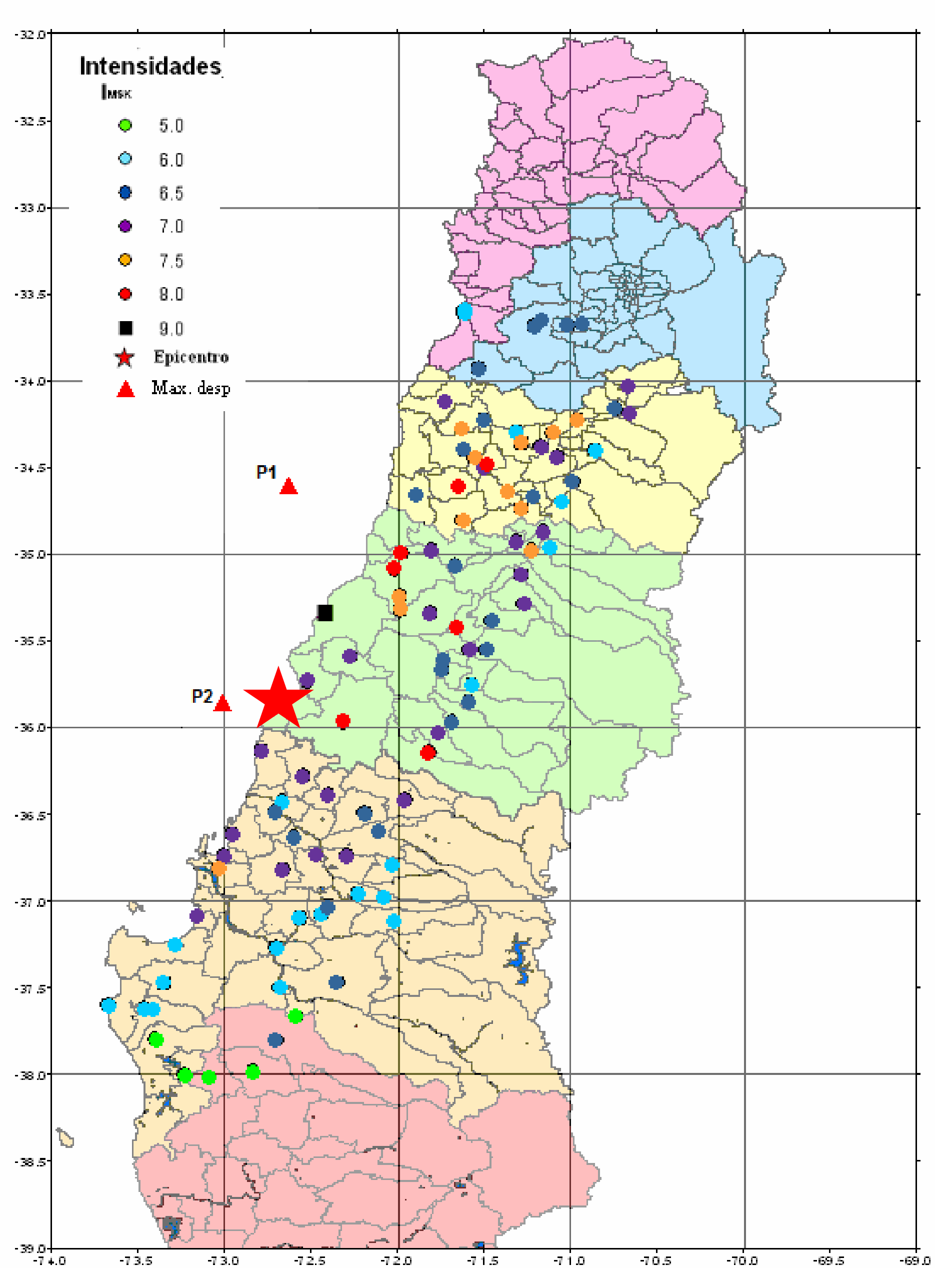
Rupture surface: 500 km x 150 km ?
Maximum slip: ~ 12 m; Average slip: ~ 7 m (USGS)

Affected population > 2 Mi
Homeless ~ 800 000

Casualties ~ 500
Preliminary loss estimation ~ € 25-30 Bi

Seismology of Chile EQ

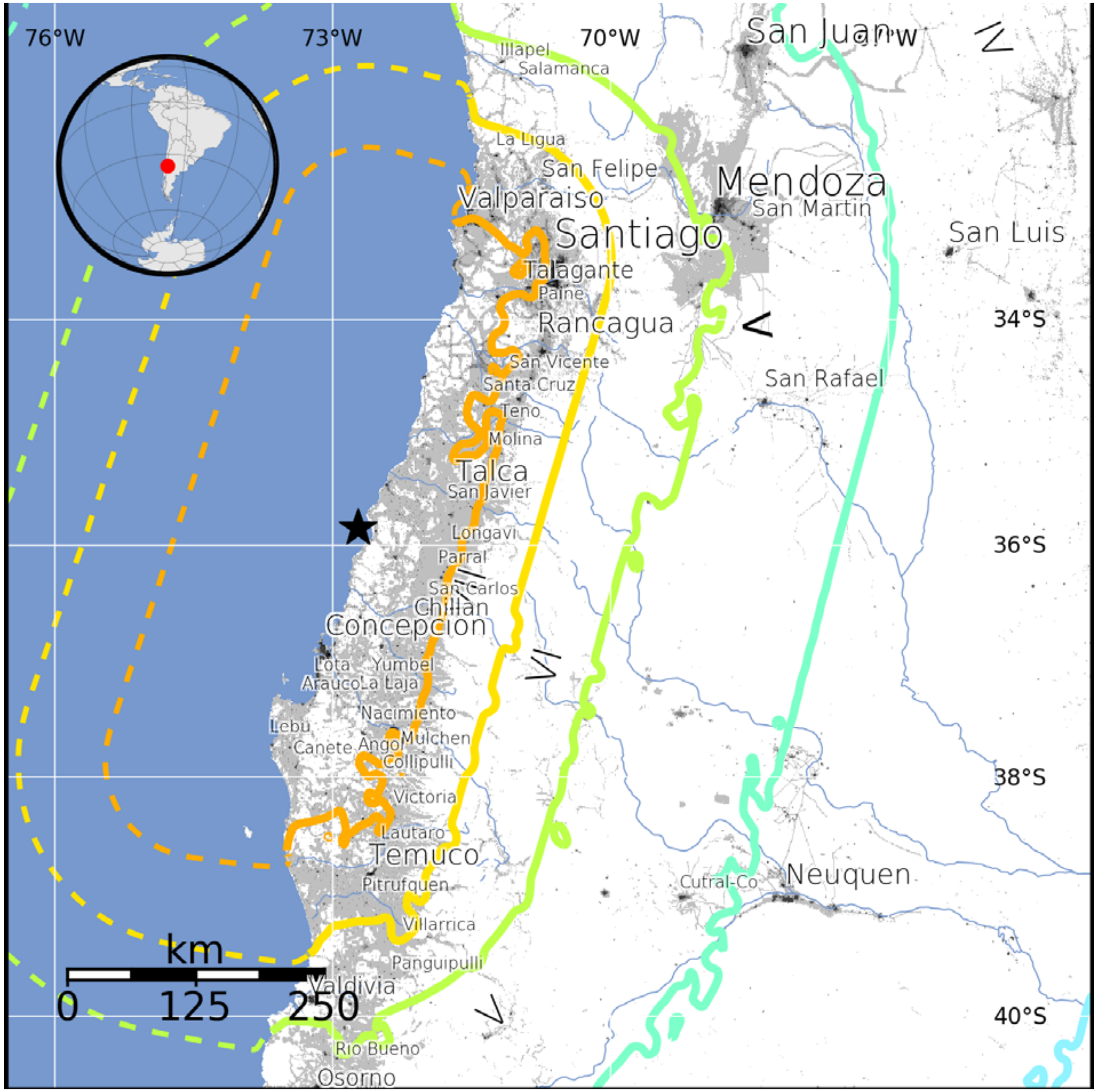
Macroseismic felt intensities (MSK)



(Astroza et al 2010)

Seismology of Chile EQ

Macroseismic felt intensities.
Isoseismal lines (MM).

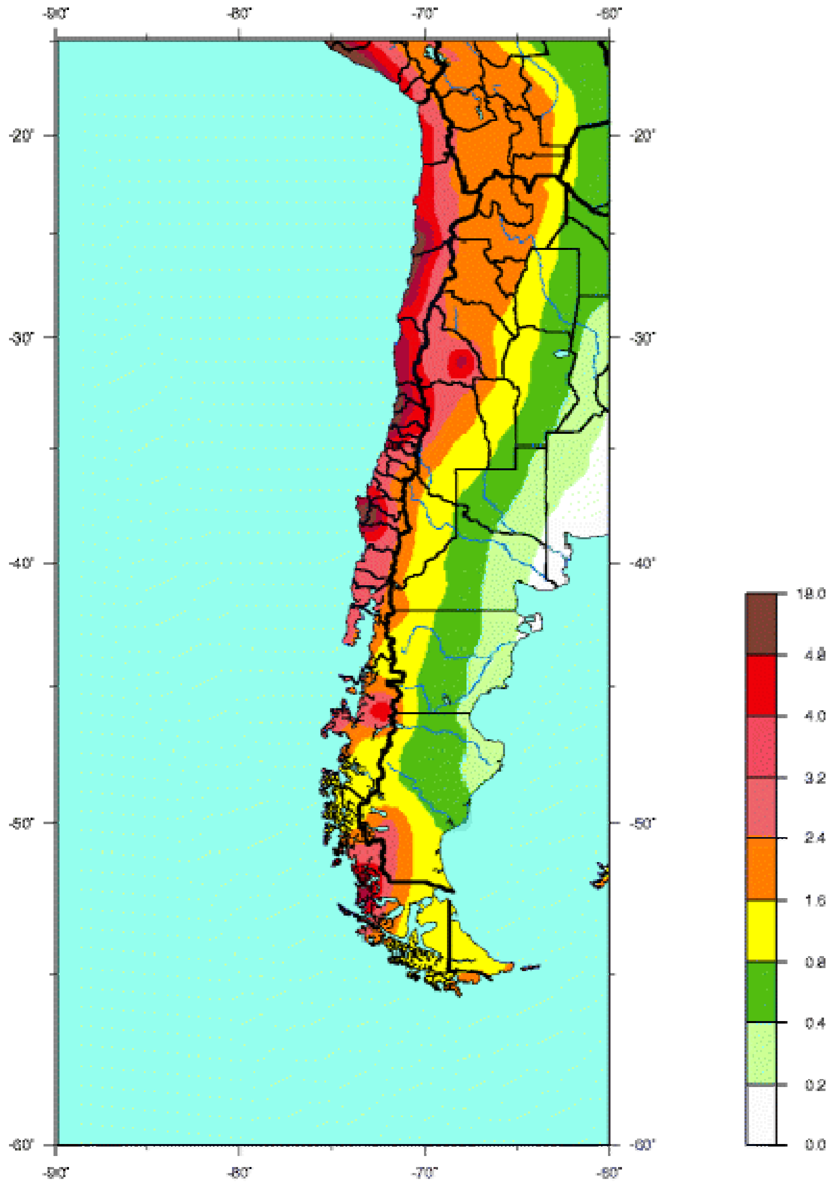


Peak Ground Accelaration with 10% Probability of Exceedance in 50 years (PSHA).

The PGA is not well correlated with the damage potential

Different indicators of the Damage potential have been proposed, i.e.

- **I_A - Arias Intensity**
- **P_D - Destructiveness potential factor by Araya and Saragoni**



COMPARISON OF SEISMOLOGICAL PARAMETERS

Issue	L'Aquila	Haiti	Chile
Magnitude M_W	6.3	7.0	8.8
Seismic Moment (N m)	3.4×10^{18}	4.5×10^{19}	2×10^{22}
Normalised energy release	1	13	5900
Maximum Estimated Intensity (MM)	~ VIII	~ IX	~ VIII
Fault Size Area (km^2)	230	600	75 000
Maximum slip (m)	1.2	5	12
Average slip (m)	0.5	2	7
Area x Average slip (km^2 x m)	115	1200	525 000
Normalised energy release	1	10	4600

- **THE ENERGY RELEASE OF CHILE EQ IS ABOUT 5000 TIMES THAT OF L'AQUILA EQ.**

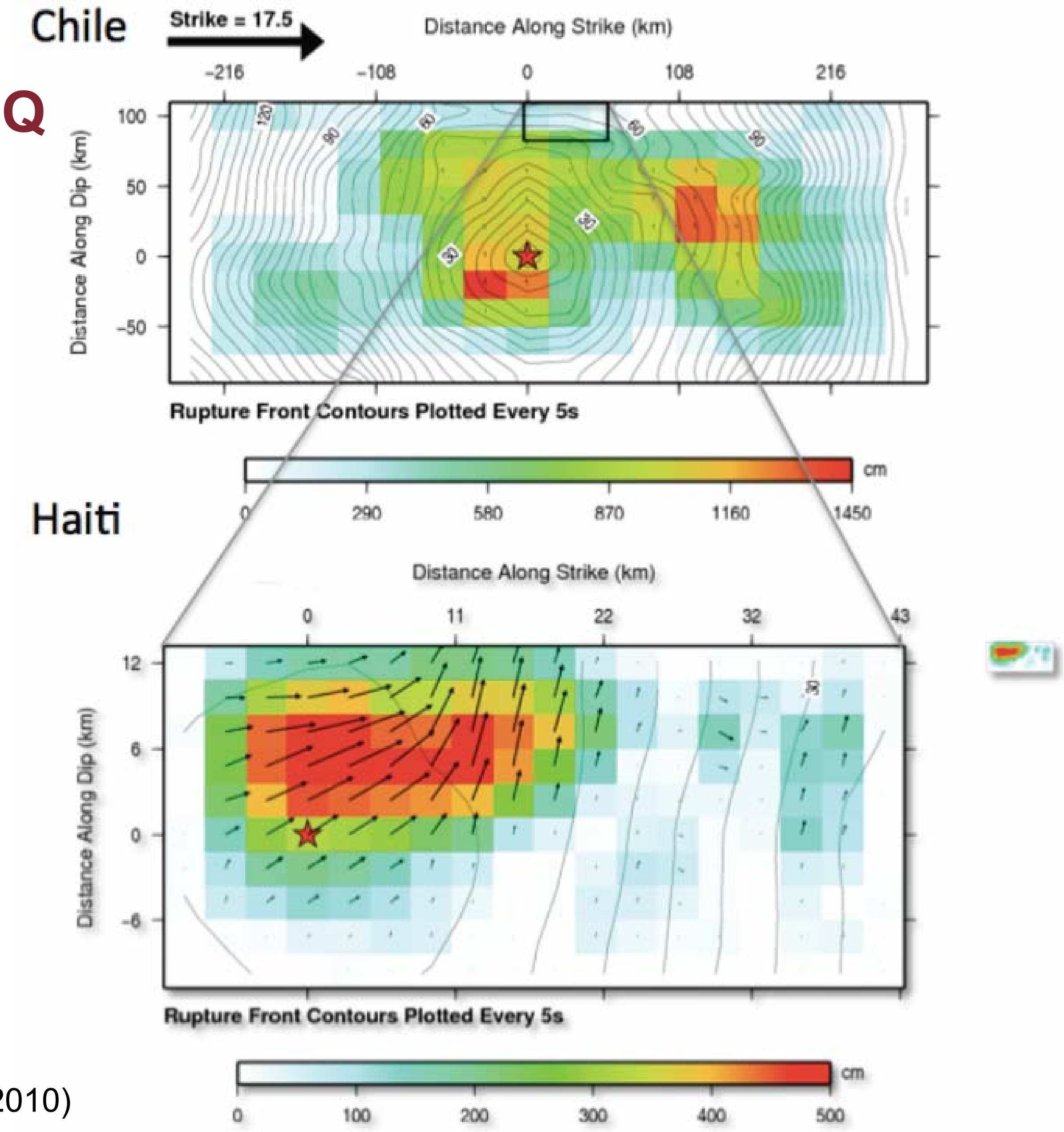
- **THE ENERGY RELEASE OF HAITI EQ IS ABOUT 12 TIMES THAT OF L'AQUILA EQ.**

Seismology of Chile EQ and Haiti EQ

Rupture process Comparison

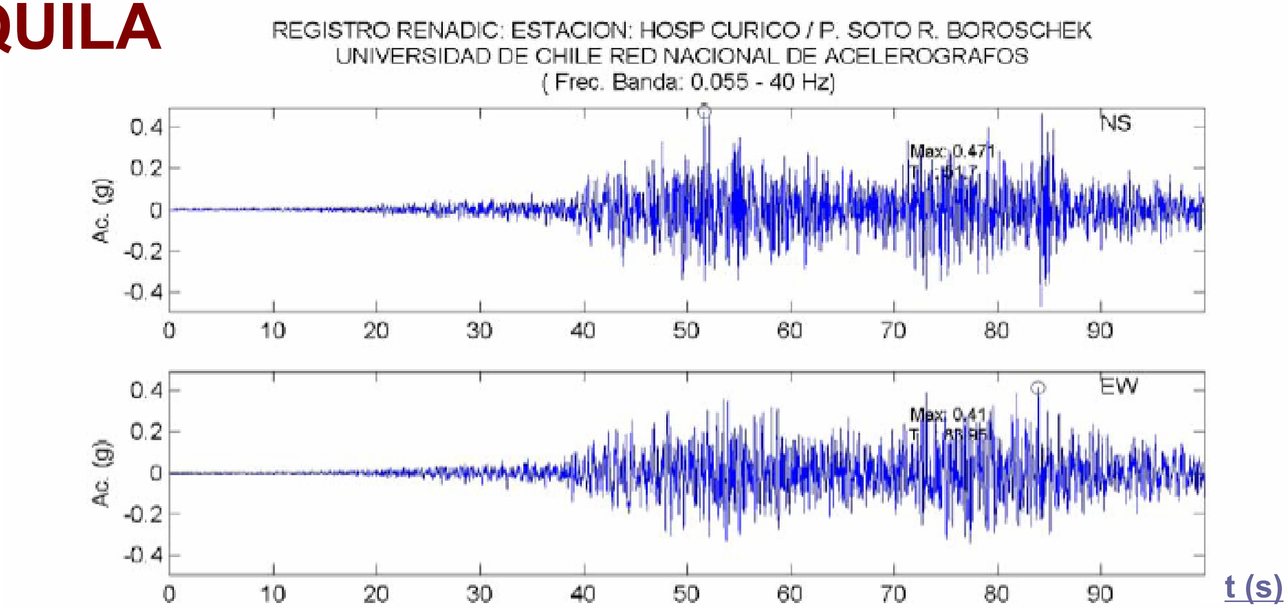
Maximum slip:

- Haiti ~ 5 m
- Chile ~ 12 m
- L'Aquila ~ 1.2 m



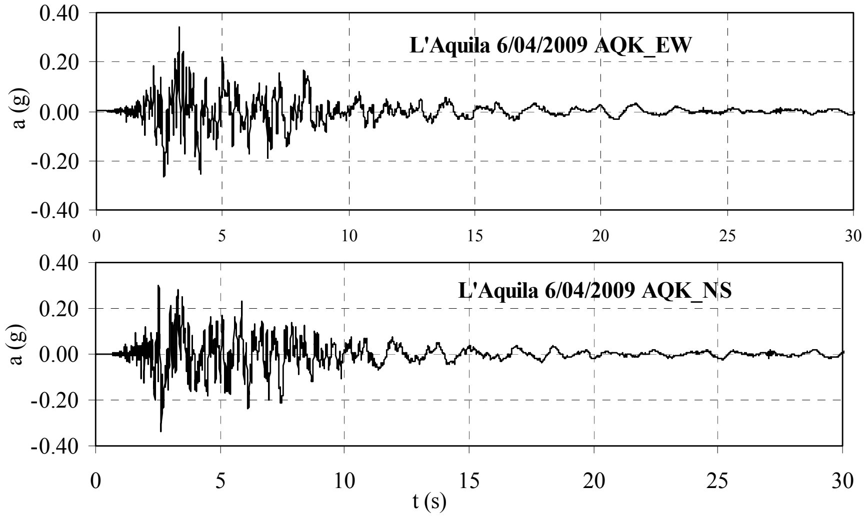
(Hayes 2010)

COMPARISON OF STRONG MOTION RECORDS CHILE – L'AQUILA



M_w = 8.8

Renadic



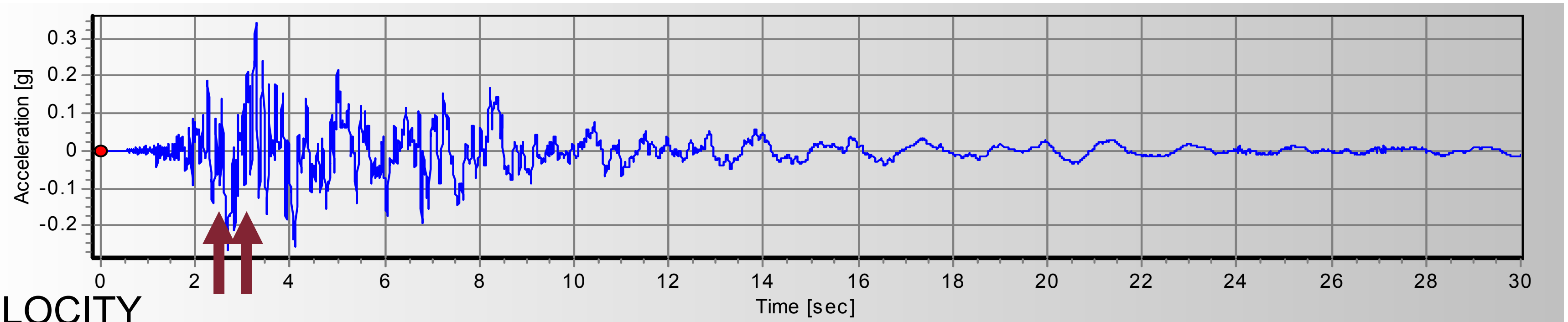
M_w = 6.3

RAN

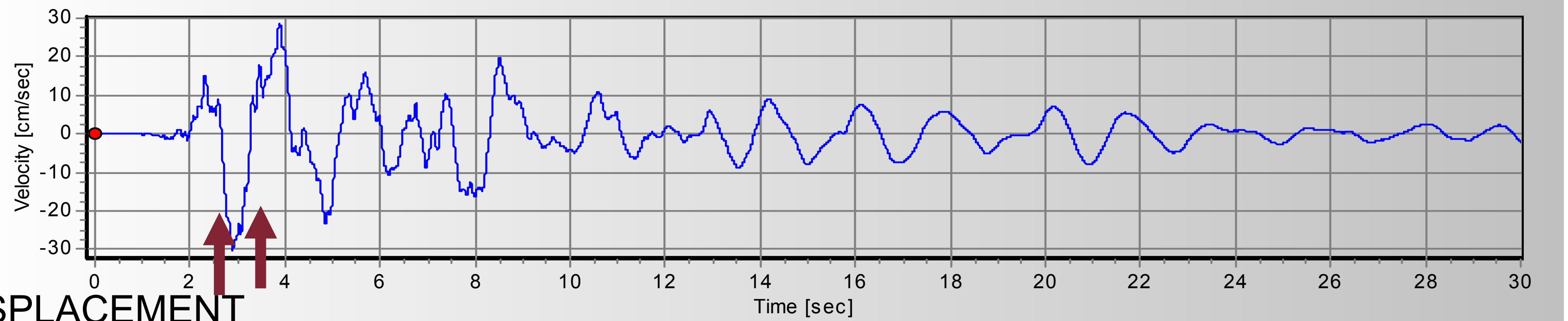
Very different strong motion duration.

L'AQUILA EQ - RECORD AQK STATIONS

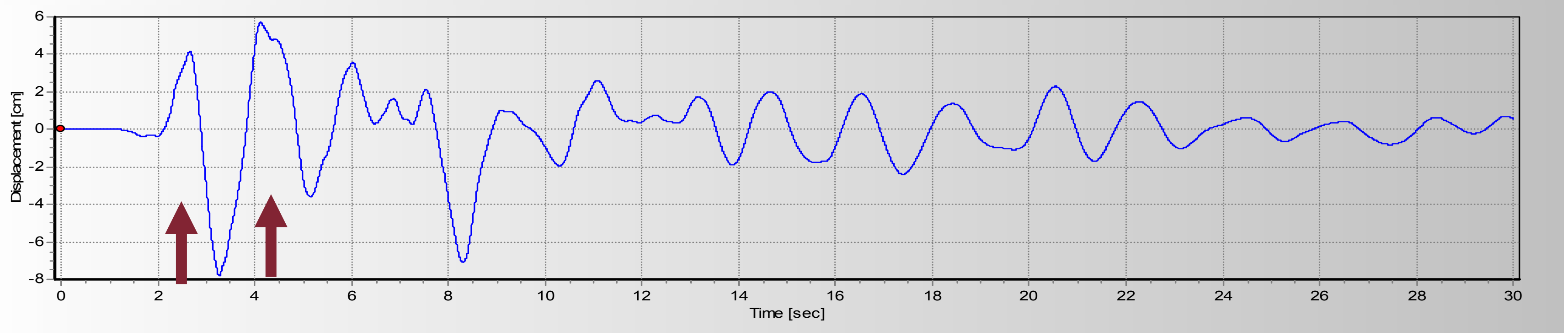
ACCELERATION



VELOCITY



DISPLACEMENT



For records AQK and AQU (two station closer to downtown L'Aquila). Intense double sided velocity pulses are quite distint on both records.

This pulses occuring in the beginning of strong shaking are typical of near-fault motions and they impart significant input energy to structures.

The duration of strong shaking is short (between 3-10 seconds).

The extent of damage was limited by the short duration. The number of Yielding Reversals NYR is low.

L’AQUILA EARTHQUAKE

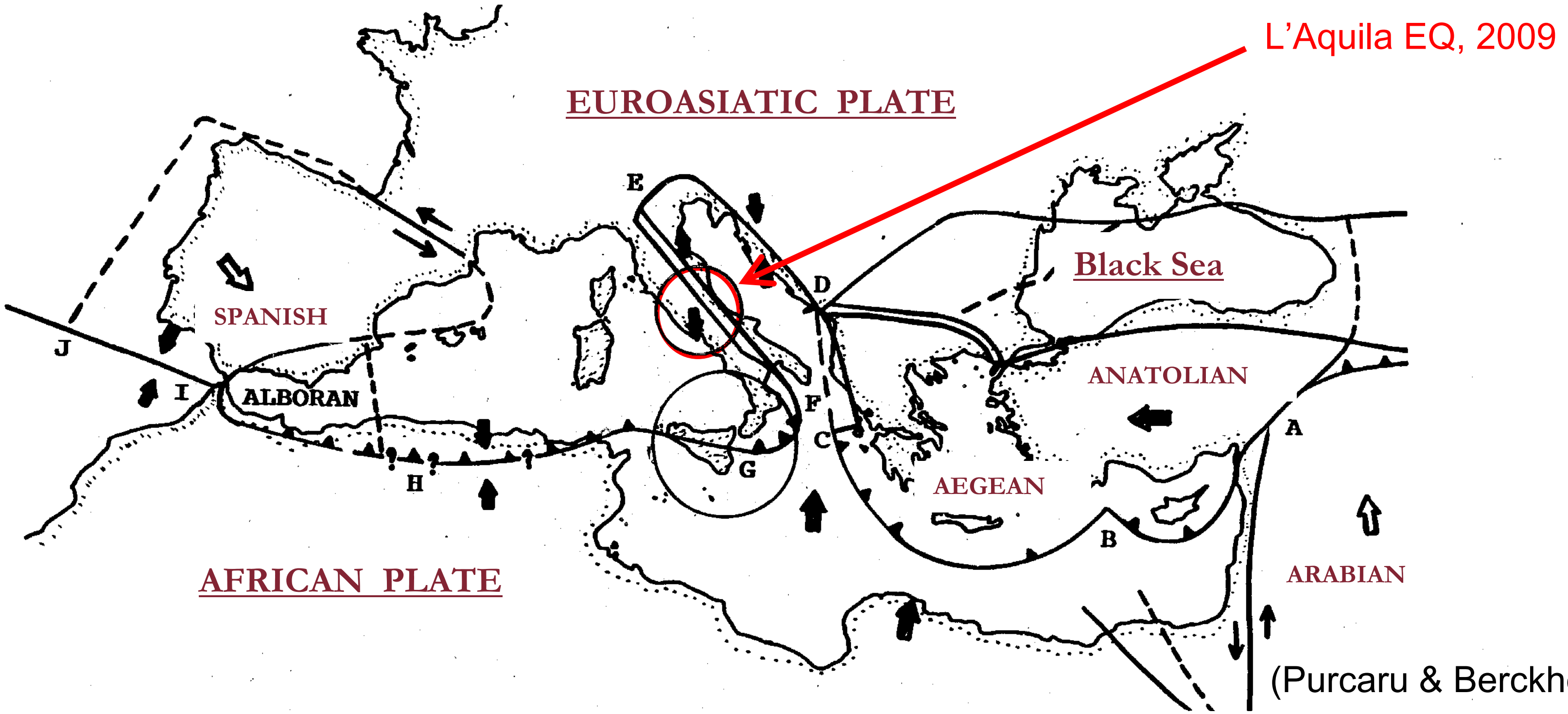
APRIL 6, 2009

SPECIFIC ASPECTS

Trieste, May 13, 2010

L'Aquila earthquake - Seismology

Plate tectonics. European region. Simplified scheme



(Purcaru & Berckhemer 1985)

Large earthquakes originate mainly on a narrow belt along the central Appennines, accommodating a NE-trending extension, with a rate of about 3mm/yr.
The geological model of plate tectonics provides the most coherent global explanation of the occurrence of the majority of earthquakes.

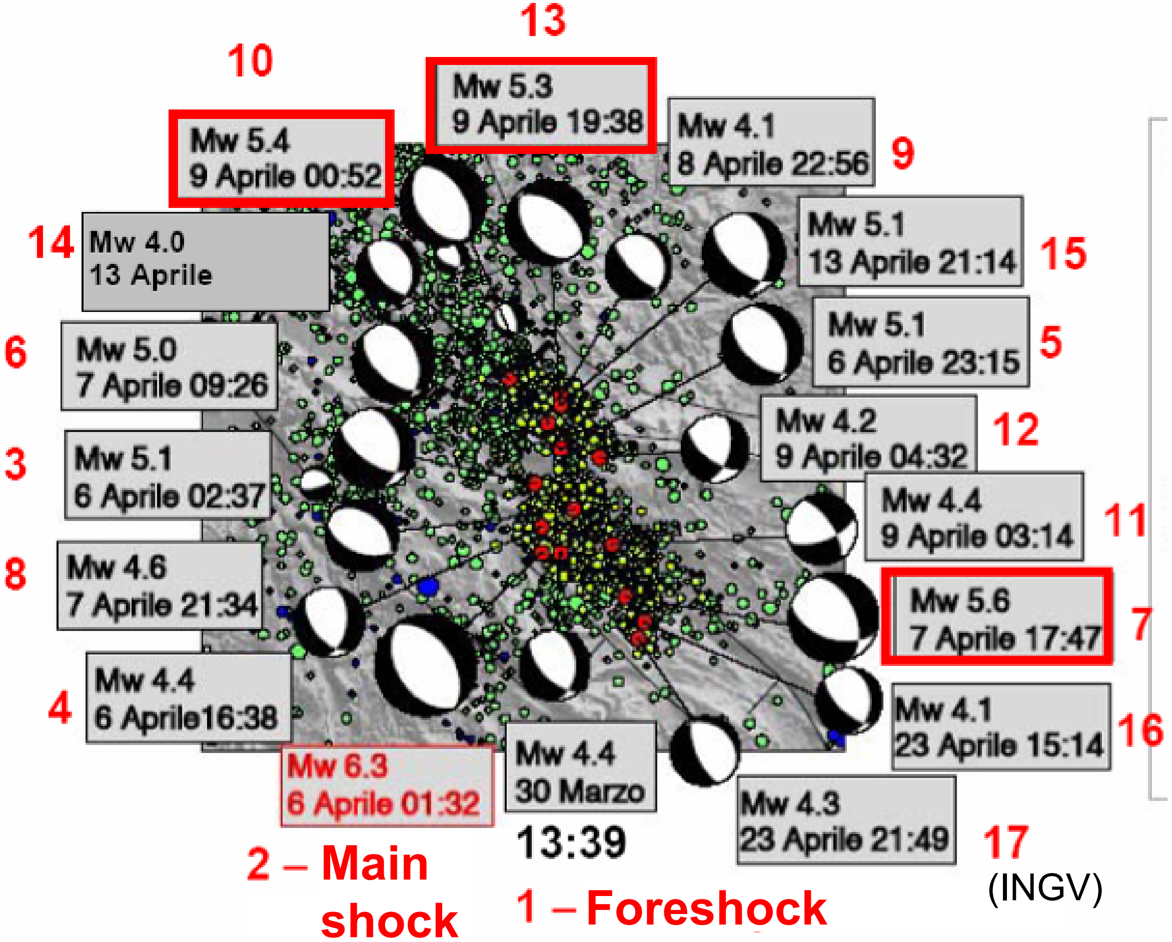
L'Aquila earthquake - Seismology

Focal mechanisms, seismic sequence

The main shock was preceded by a sequence of foreshocks, which started several months before, with a significant shock of magnitude M_w 4.4 on 30th March and culminating with a M_L 3.9 and a M_L 3.5 shock about 5 and 3 hours before the main event, respectively.

Subsequent to the main shock, many aftershocks were recorded, including seven aftershocks of moment magnitude larger than or equal to 5.0. Initially, the aftershock activity occurred near L'Aquila and towards S-SE of the town, whereas a couple of days later it migrated towards the north. In particular, a M_W 5.6 event occurred on April 7 at 17:48 UTC in the Aterno Valley, about 4 km SW from the village of Fossa, whereas on 9 April at 00:53 UTC an event of MW 5.4 took place near Campotosto about 16 km northwards L'Aquila

Focal mechanisms (March/April 2009) $M_W \geq 4$ (INGV – CNT)



(INGV)

L’Aquila earthquake - Seismology

Focal mechanism, main shock

Date 04/06/09   Region CENTRAL ITALY   Ml 6.2   Mw 6.3
Centroid Location:
Or. Time 1:32:47.2 Lat. 42.32 N Long. 13.32 E Dep 12. fixed

Best Double Couple   M0: 3.7*10**25
P1 str: 147 dip: 43 slip: -88
P2 324 47 -92

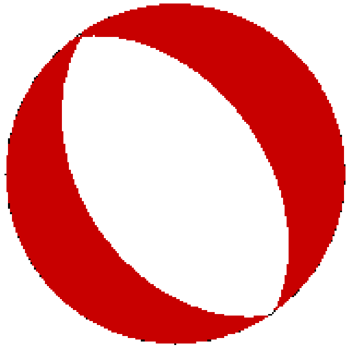
040609A

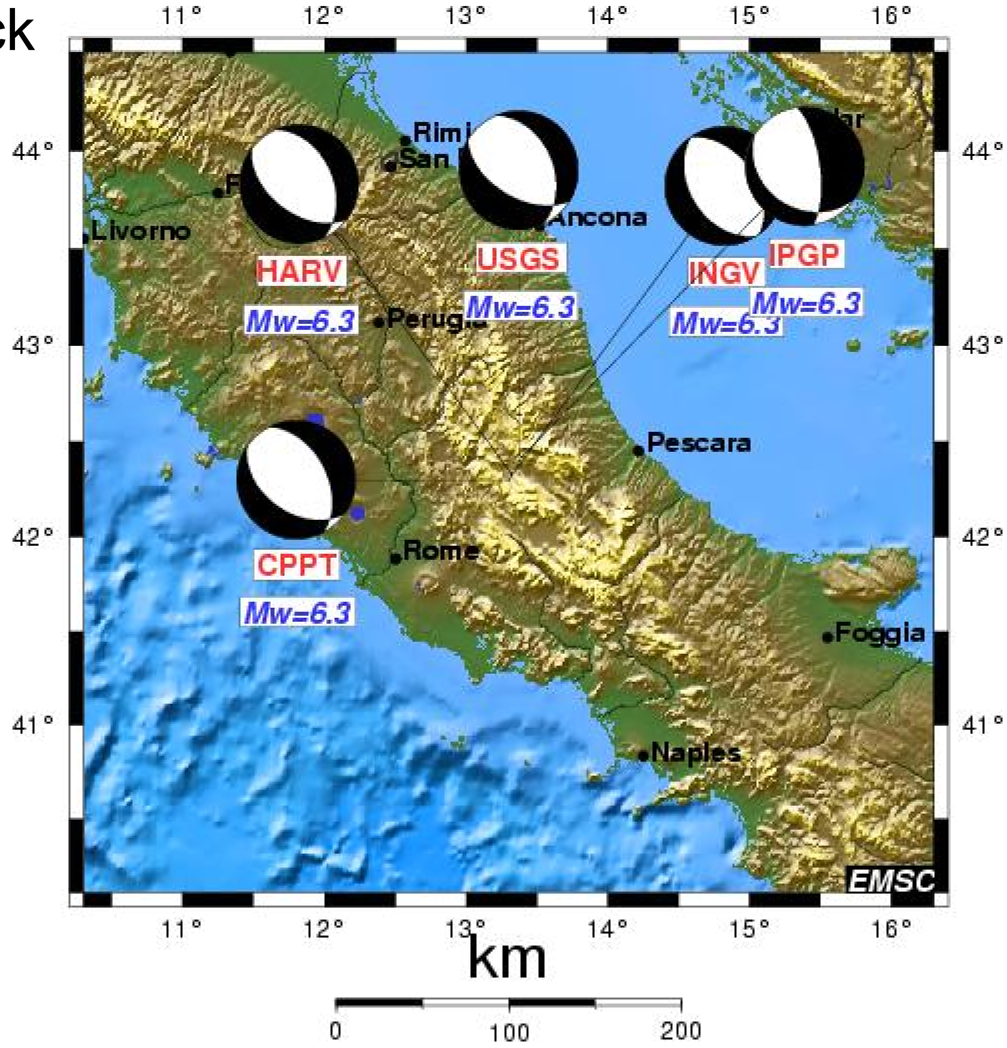
Moment Tensor   (10**25 dyn-cm)
mrr: -3.75 mtt: 1.22 mff: 2.53
mrt: 0.23 mrf: -0.16 mtf: -1.71

Principal Axes

	val:	plg:	az:
T	3.72	2	55
N	0.05	1	325
P	-3.76	88	200

DATA USED: MEDNET
AUTHOR: INGVBO





L’Aquila event was a normal faulting earthquake. The city is located very close to the epicenter in hanging wall position.

L'Aquila earthquake – Seismology

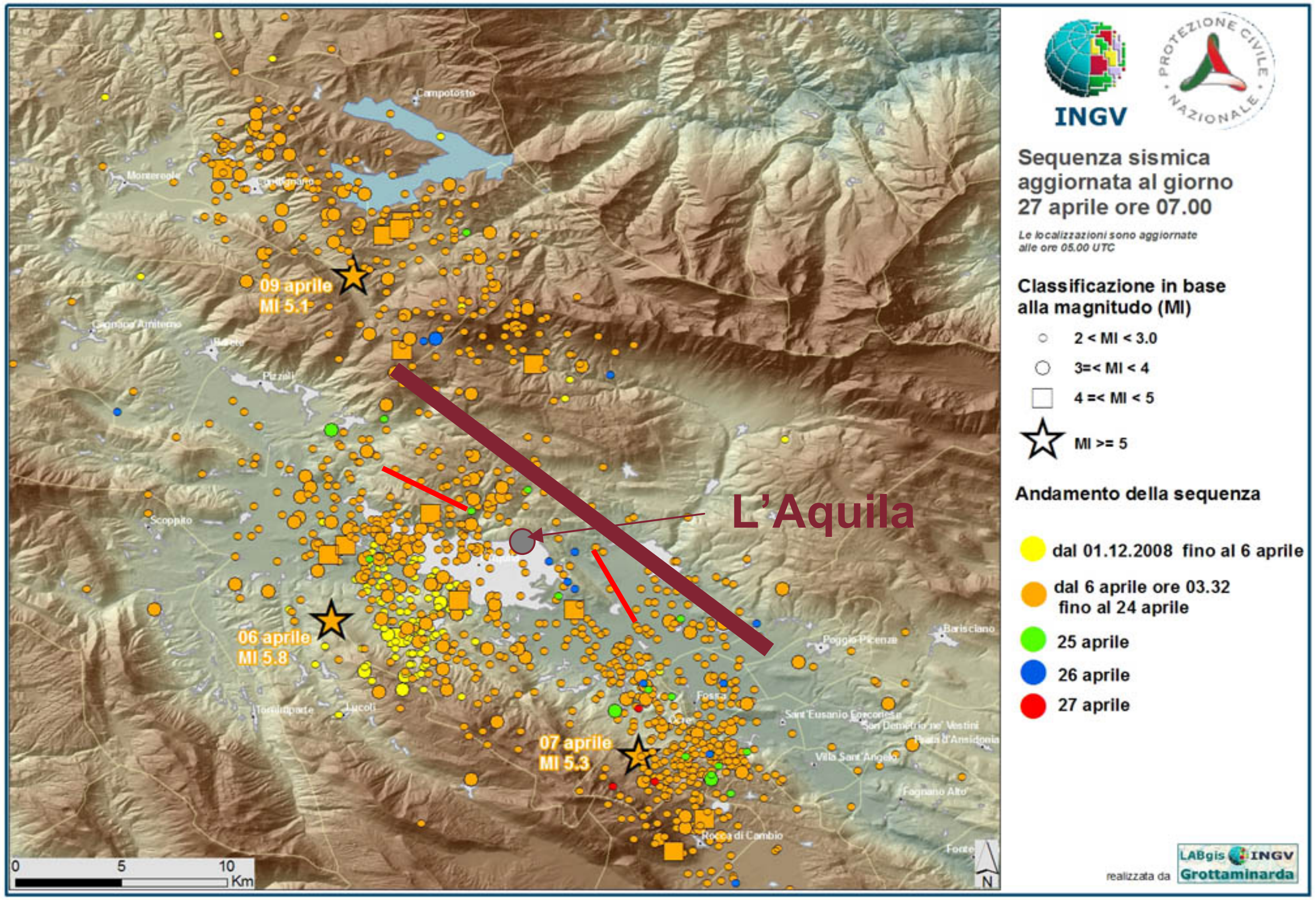
Directivity and Macroseismic intensity

- **The main shock nucleated at a shallow depth of 9 km , with the hypocenter located close to the north-western border of the surface projection of the fault, with a possible directivity-induced amplification effects due to both up-dip and along-strike rupture propagation that could have contributed to the increase of the damage pattern in L'Aquila and in the villages located to the southeast.**

- **L'Aquila city, which was severely damaged by the event, is located about 6 km from the epicentre in hanging wall position. Macroseismic intensity, according to the MCS scale (Mercalli Cancani Sieberg) was X in the little village of Onna (located to about 10 km from L'Aquila) and IX in L'Aquila city.**

L'Aquila earthquake - Seismology

Epicentres, aftershocks
Fault surface projection first estimate



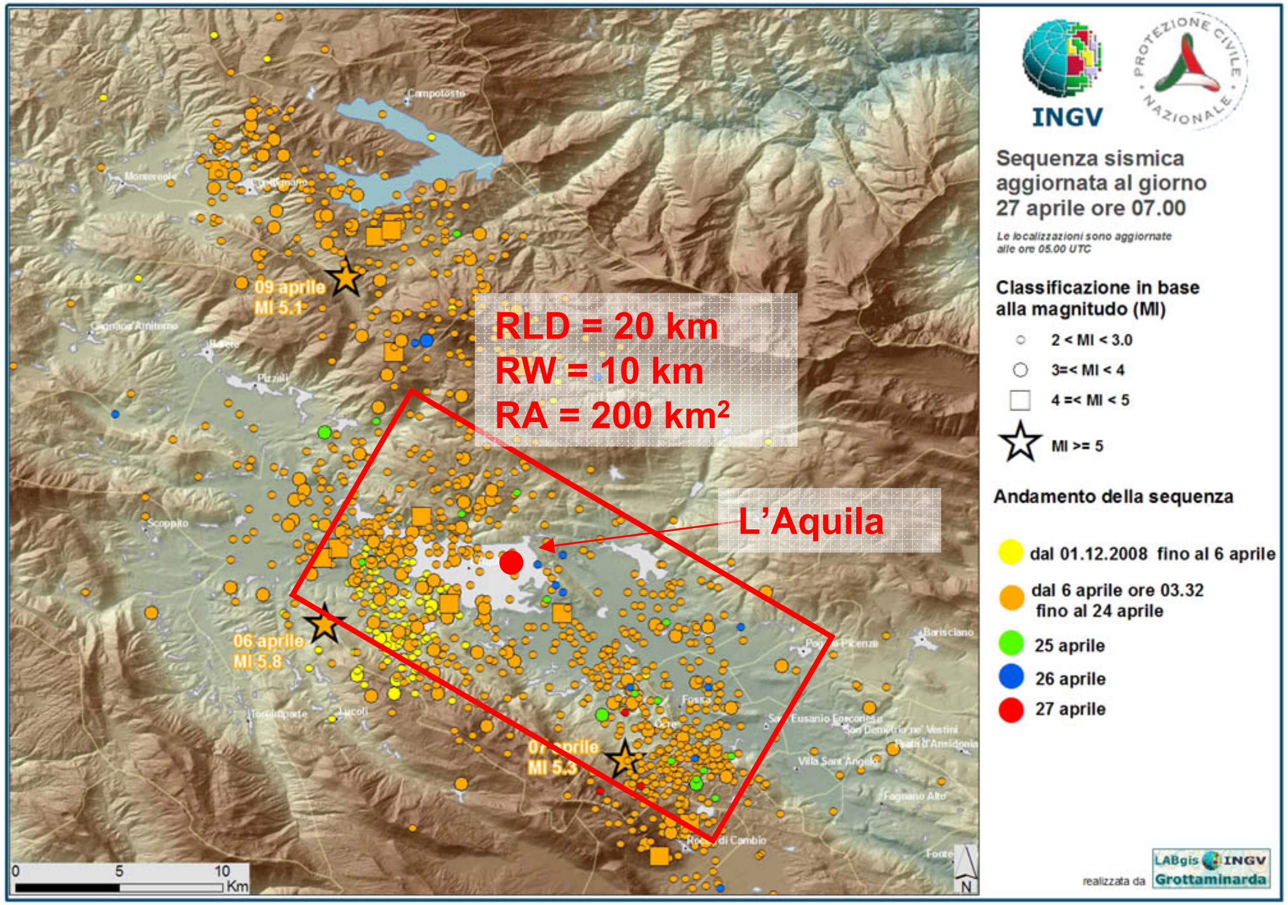
Strike ≅ 130°

Dip ≅ 50

(L. Decanini with A. Lorè, 29-04-2009)

L'Aquila earthquake - Seismology

Epicentres, aftershocks and rupture surface projection



According

Wells & Coppersmith (1994)

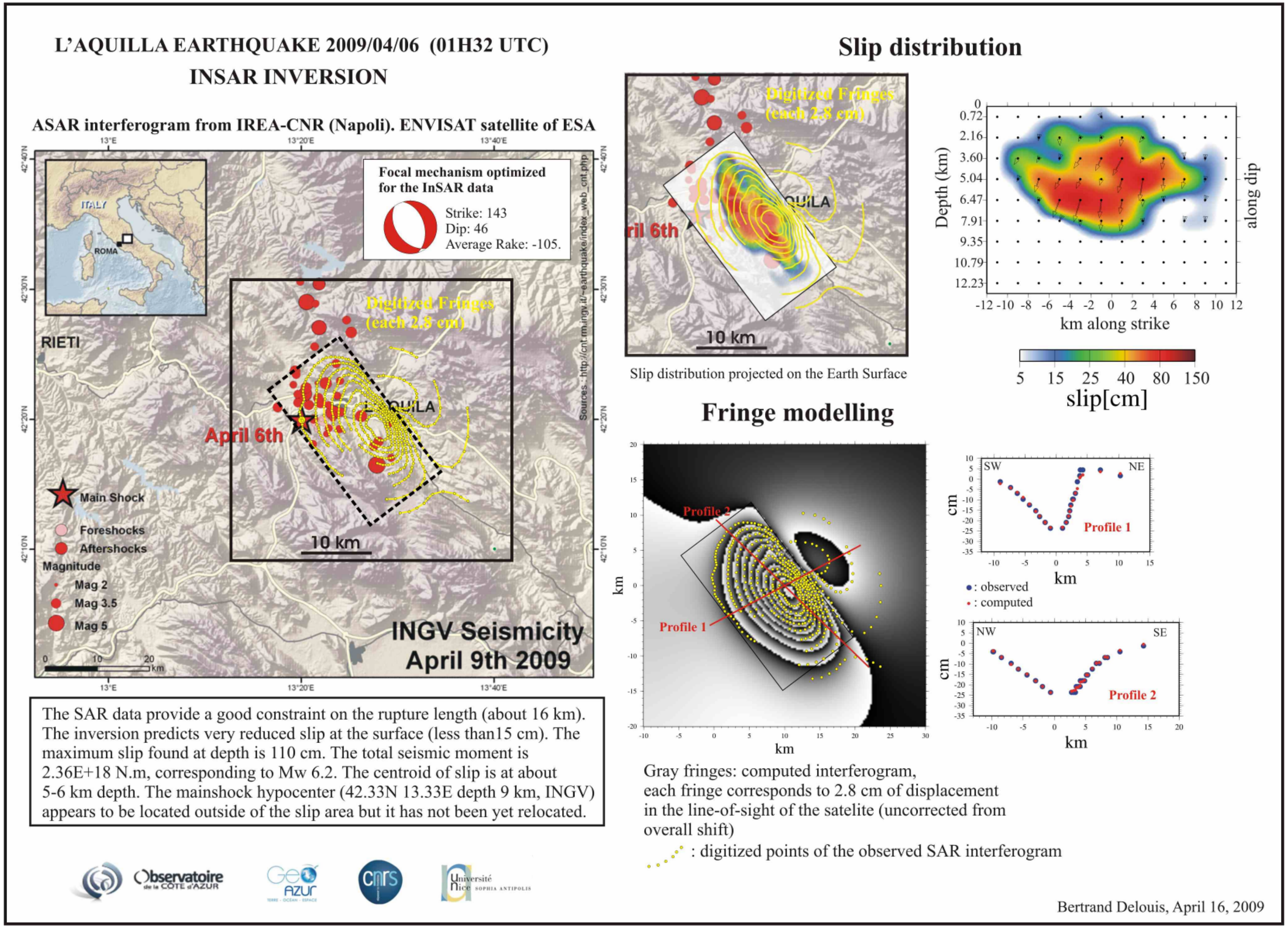
On the basis of:

- position of aftershocks
- field observation
- isoseismal lines

(L. Decanini, 30-04-2009)

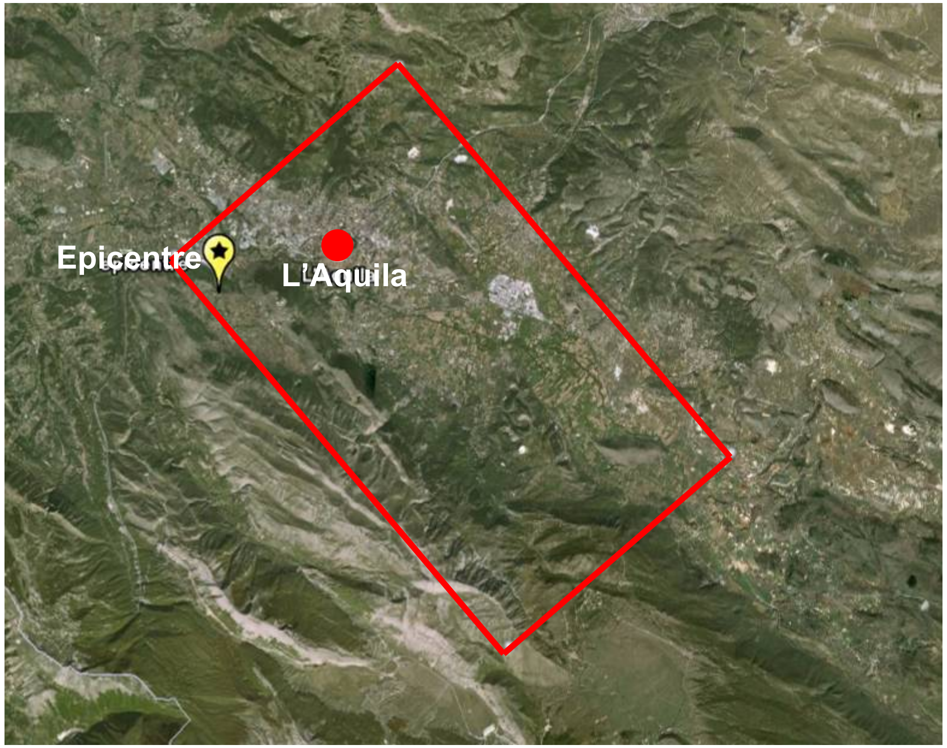
L'Aquila earthquake - Seismology

Rupture Process



L'Aquila earthquake - Seismology

Epicentre and rupture surface projection (recent study)



Base map from Google Earth

The rupture plan has a strike of 142°, a dip of 50° and a rake of 90°.

The rectangular rupture plane of about 238 km^2 (17x14 km^2) and lacated at a depth between 0.6 km and 11.8 km from the surface.

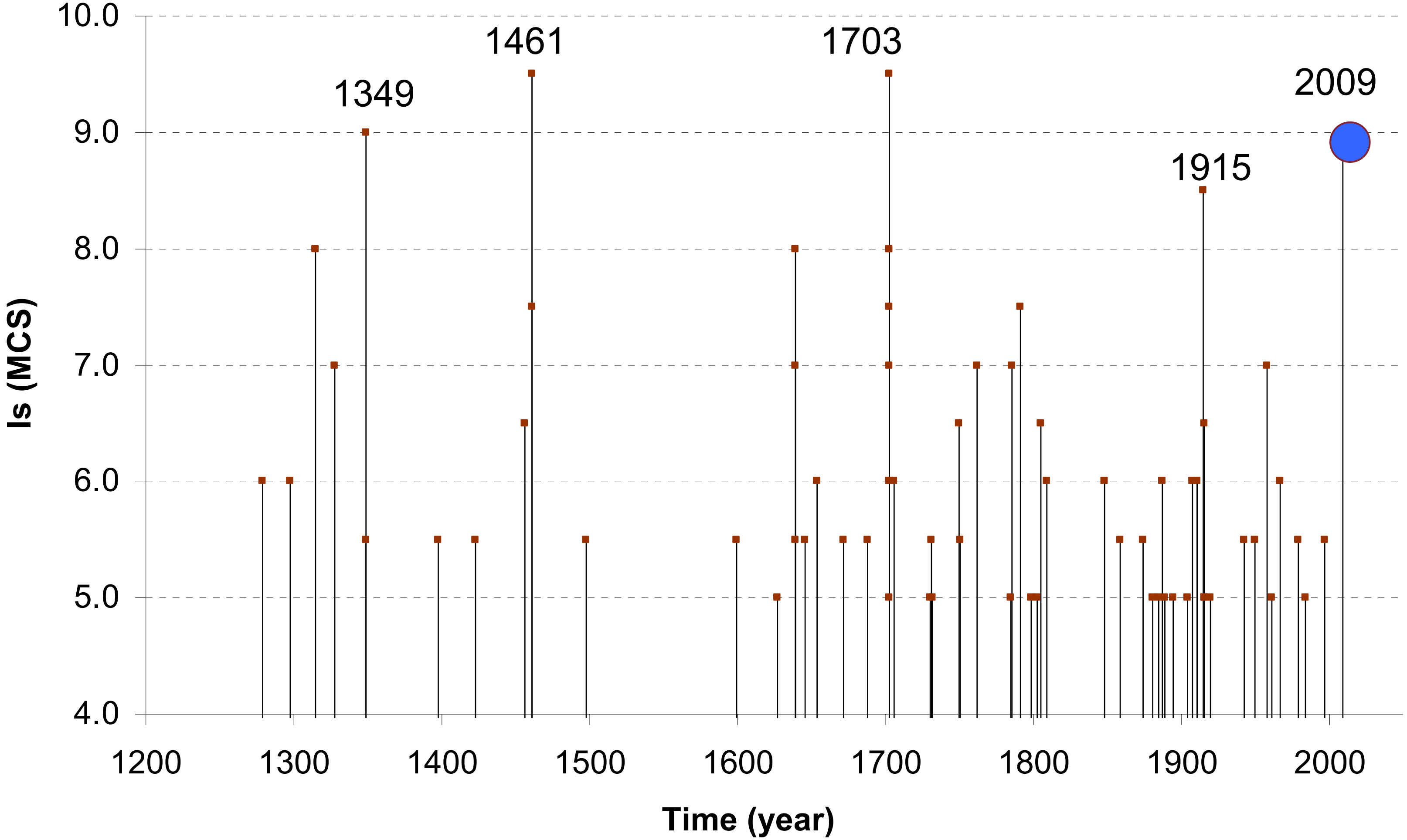
Chioccarelli & Iervolino (2010)

Cheloni (INGV)

The data on the rupture surface are not uniquely identified by seismologists but the various estimates are not very different each other.

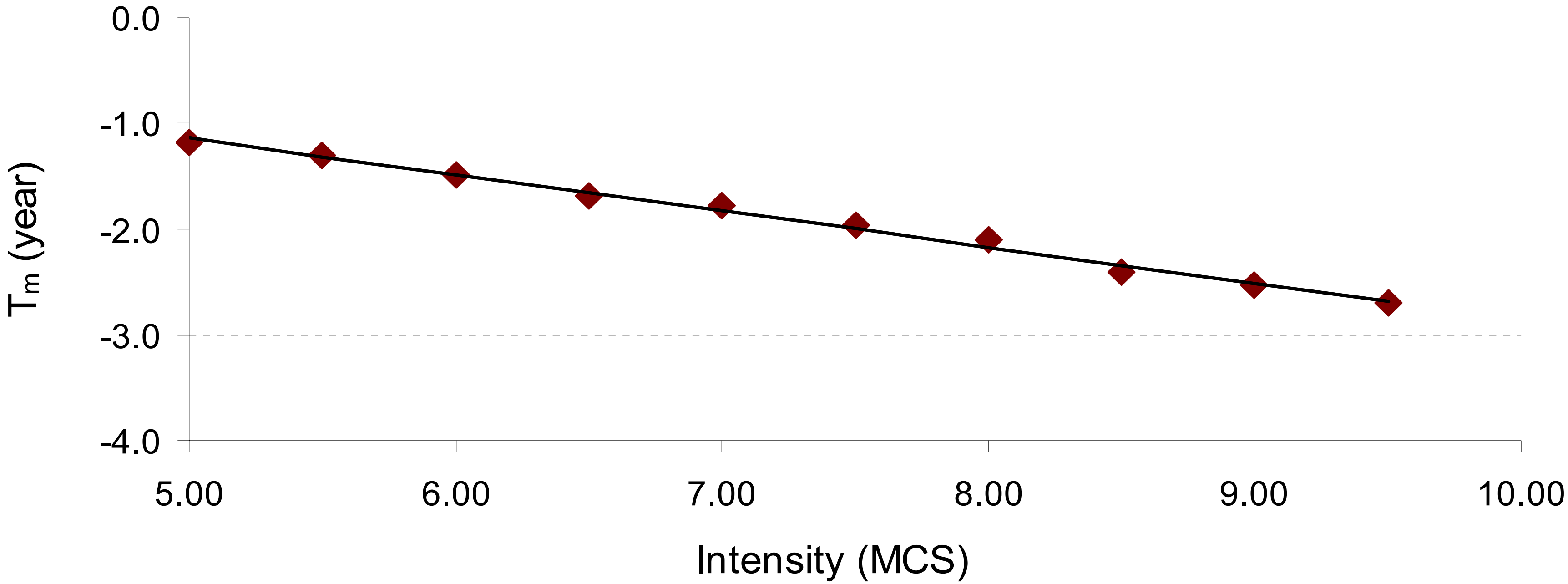
L'Aquila earthquake - historical sismicity

Local macroseismic (MCS) catalogue



L'Aquila earthquake - historical sismicity

Occurence Frequency of Macroseismic Intensity



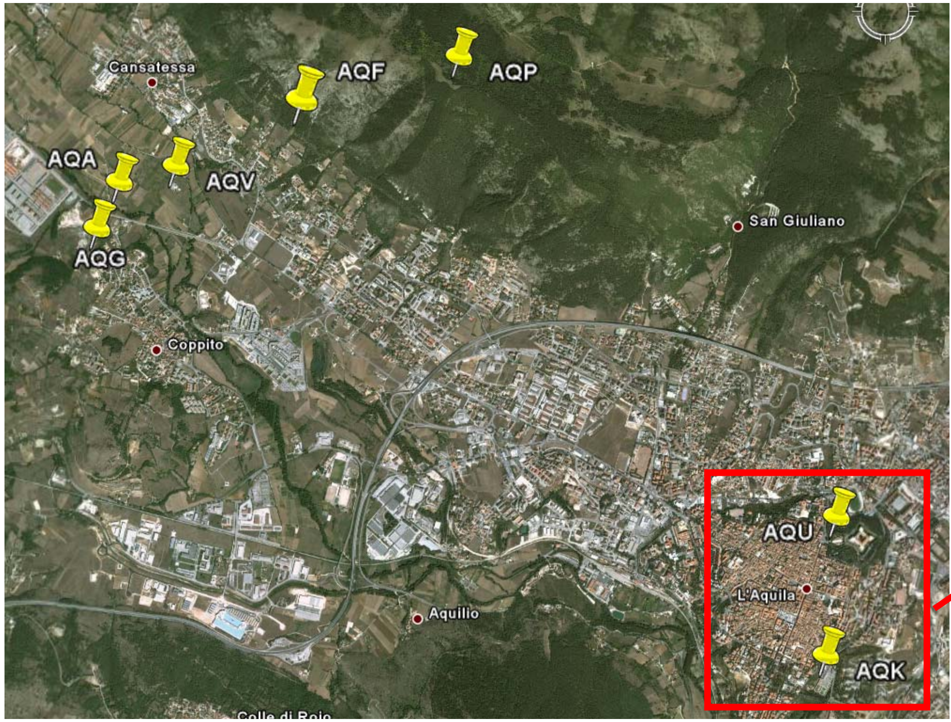
For a mean return period of 475 years, usually adopted for design of new construction, an expected intensity of 9.5 MCS results. **Events with intensity of 9, like the L'Aquila one, have a mean return period of 325 years. Therefore the L'Aquila EQ is not an exceptional event.**

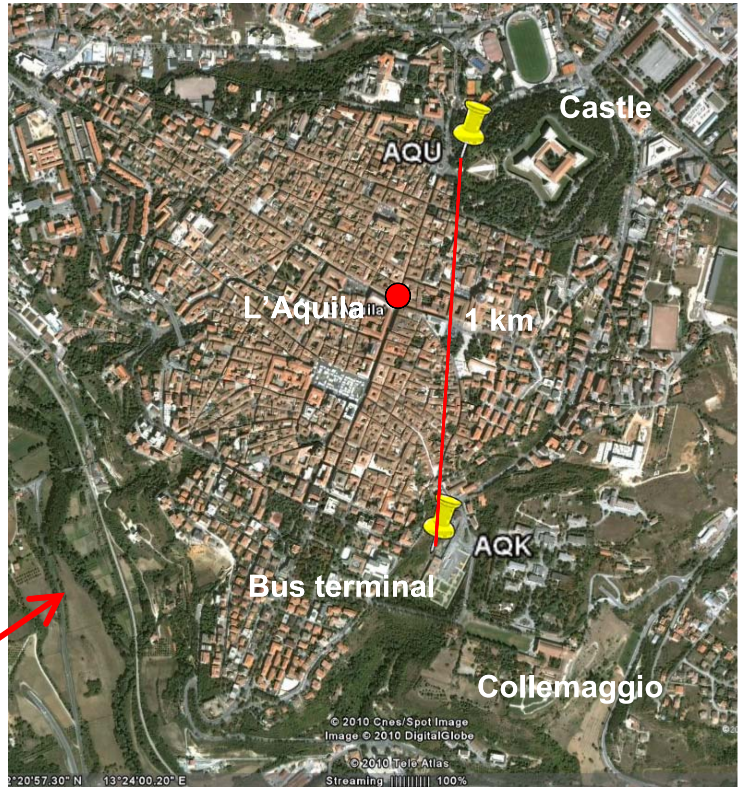
2009 L'Aquila Earthquake

Seismic Demand

L'Aquila EQ - Seismic demand

Strong ground motion records





The geographical position of the considered stations is shown in Figures. Two stations are located near downtown L'Aquila (**AQK, AQU**) and near to heavily damaged areas, three in the Aterno Valley (AQA, AQG, AQV) and two at NE of the Aterno Valley (AQF, AQP).

L’Aquila EQ – Displacement Demand

The analysis of the displacement demand is of fundamental importance both for the application of the displacement-based design and for the design of base isolated structures. Moreover, it is a good indicator of the earthquake damage potential.

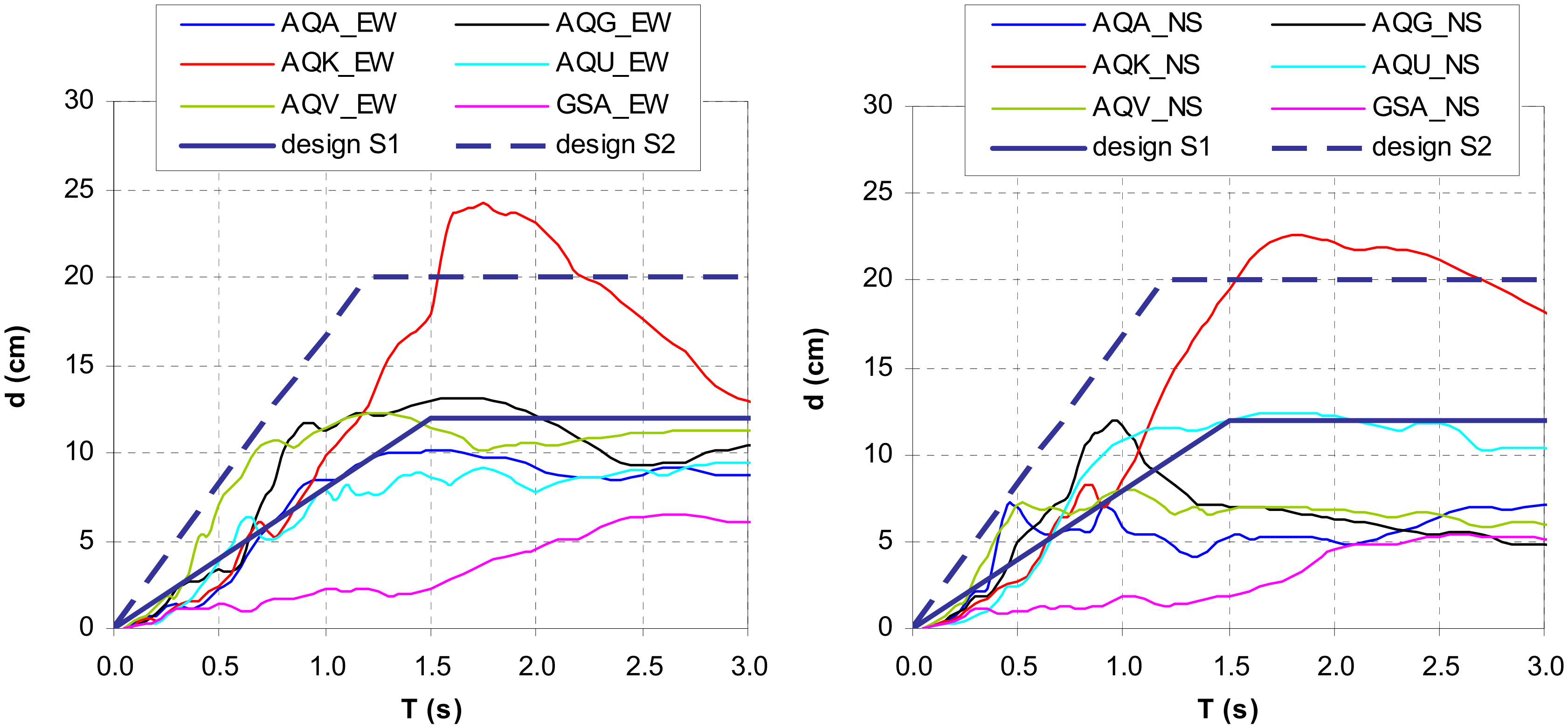
On the whole, the displacement demand is moderate, indicating a non-extraordinary event. The displacement demand does not exceed 13 cm with the exception of AQK records, which show maximum values of 24 cm and 22 cm for the component EW and NS, respectively.

The displacement demand increases in the range of period from 0 to about 1-1.5 s and then remains constant or decreases. This trend is consistent with that gathered from the study of a large number of accelerograms.

Displacement spectra of the near-fault records compared to the spectra proposed for design (Decanini et al. 2003) for soil S1 (rock or stiff soil) and S2 (intermediate soil).

L’Aquila earthquake - Seismic demand

Displacement demand – main shock



Decanini et al. (2010)

Displacement spectra of the near-fault records compared to the spectra proposed for design (Decanini et al. 2003) for soil S1 (rock or stiff soil) and S2 (intermediate soil).

L'Aquila EQ - Seismic demand

Strong ground motion records – main shock parameters

	PGA (g)	PGV (cm/s)	$EPA_{(0.1\text{-}0.5)}$ (g)	$S_{d,max}$ (cm)	IV (cm)	I_A (cm/s)	I_H (cm)
AQV_EW	0.626	36.7	0.471	12.2	69.5	280.7	128.0
AQV_NS	0.598	40.5	0.502	8.0	63.8	198.3	94.5
AQG_EW	0.416	33.6	0.316	13.1	37.8	128.5	115.6
AQG_NS	0.434	35.9	0.309	12.0	47.8	128.9	91.8
AQA_EW	0.394	30.5	0.254	10.1	21.6	156.0	87.3
AQA_NS	0.451	24.5	0.384	7.2	44.8	170.2	75.3
AQK_EW	0.342	30.3	0.220	24.2	34.4	99.5	138.5
AQK_NS	0.340	38.6	0.245	22.6	41.5	118.5	142.1
AQU_EW	0.263	20.6	0.209	9.5	26.5	70.5	82.6
AQU_NS	0.316	30.7	0.157	12.4	52.9	62.1	103.1

PGA and PGV are instrumental peak

A useful parameter, which can give an indication of both the spectral values and the spectral shapes, is the effective peak acceleration (EPA), which is given by the average pseudo-acceleration in the period range 0.1-0.5 s divided by 2.5. The EPA gives a measure of the ground motion intensity in terms of acceleration and at the same time is related to the structural response.

$S_{d,max}$ is the maximum spectral displacement

IV is the maximum incremental velocity, given by the area enclosed by the largest acceleration pulse

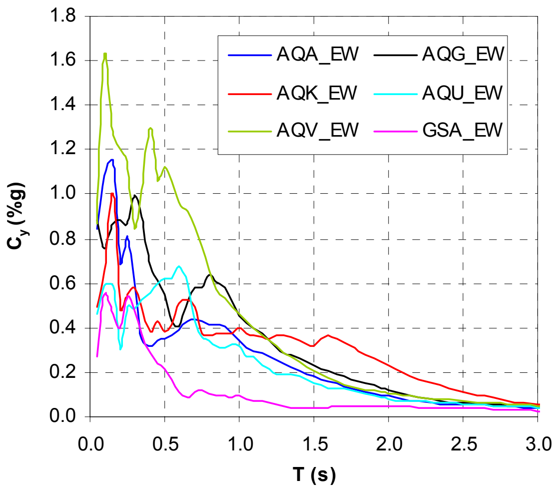
I_A is the Arias intensity

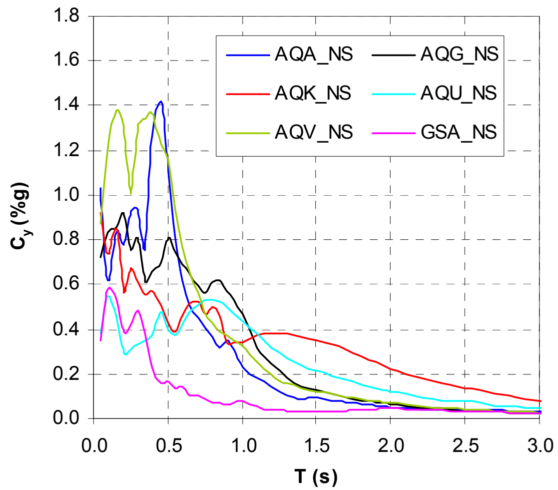
I_H is the Housner intensity

L'Aquila earthquake - Force Demand

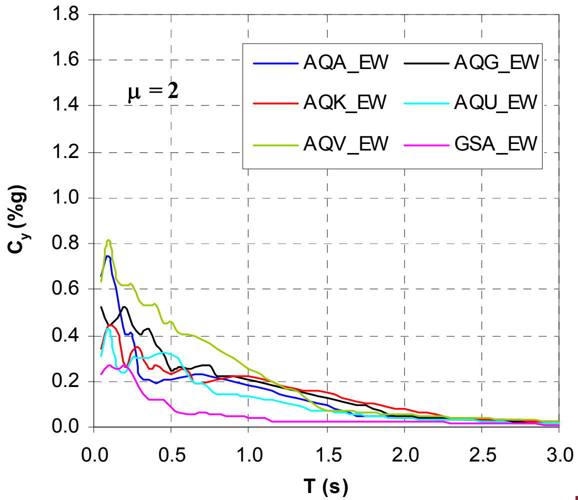
The reduction of the force demand due to the ductility is remarkable. In mean, the reduction of the peak values with increasing ductility is equal to 35%, 45% and 60% for ductility equal to 1.5, 2 and 4, respectively.
The elastic acceleration spectrum is not always a good indicator of the destructiveness potential of a ground motion. In fact, the observed damage, especially in reinforced concrete buildings, seems not consistent with the high elastic strength demands depicted in the spectra.

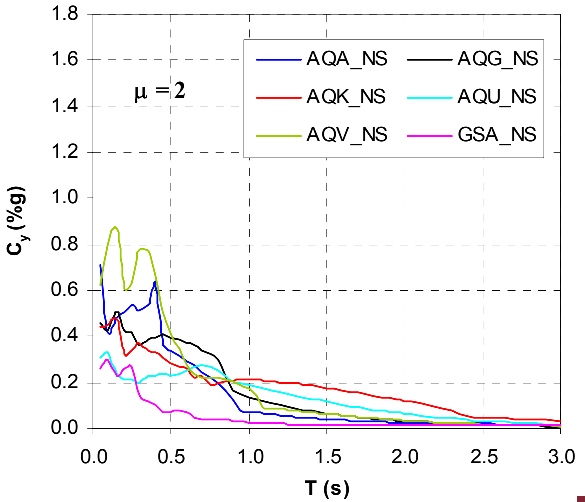
Decanini et al. (2010)





Elastic system



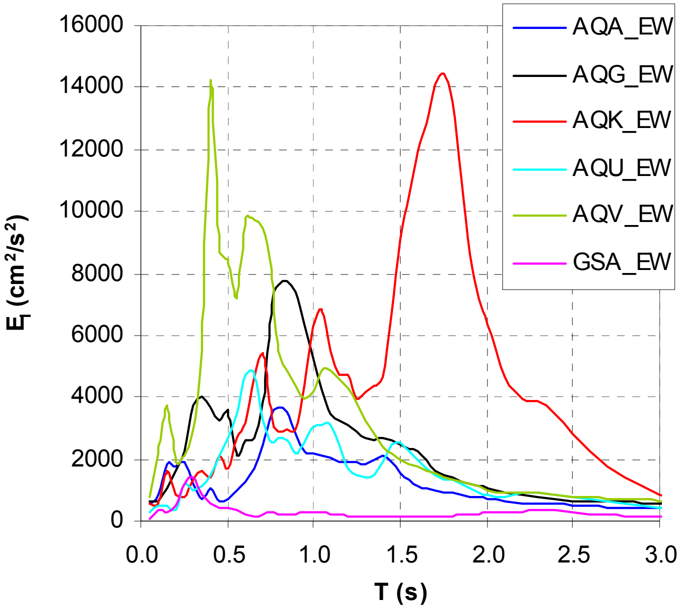


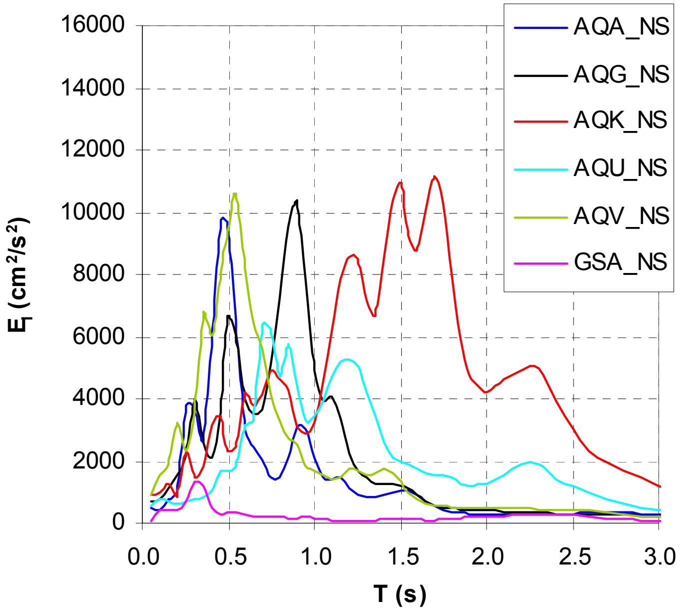
$C_y = F / W$

Inelastic system with constant displacement ductility μ=2

L'Aquila EQ – Input Energy demand

Decanini et al. (2010)





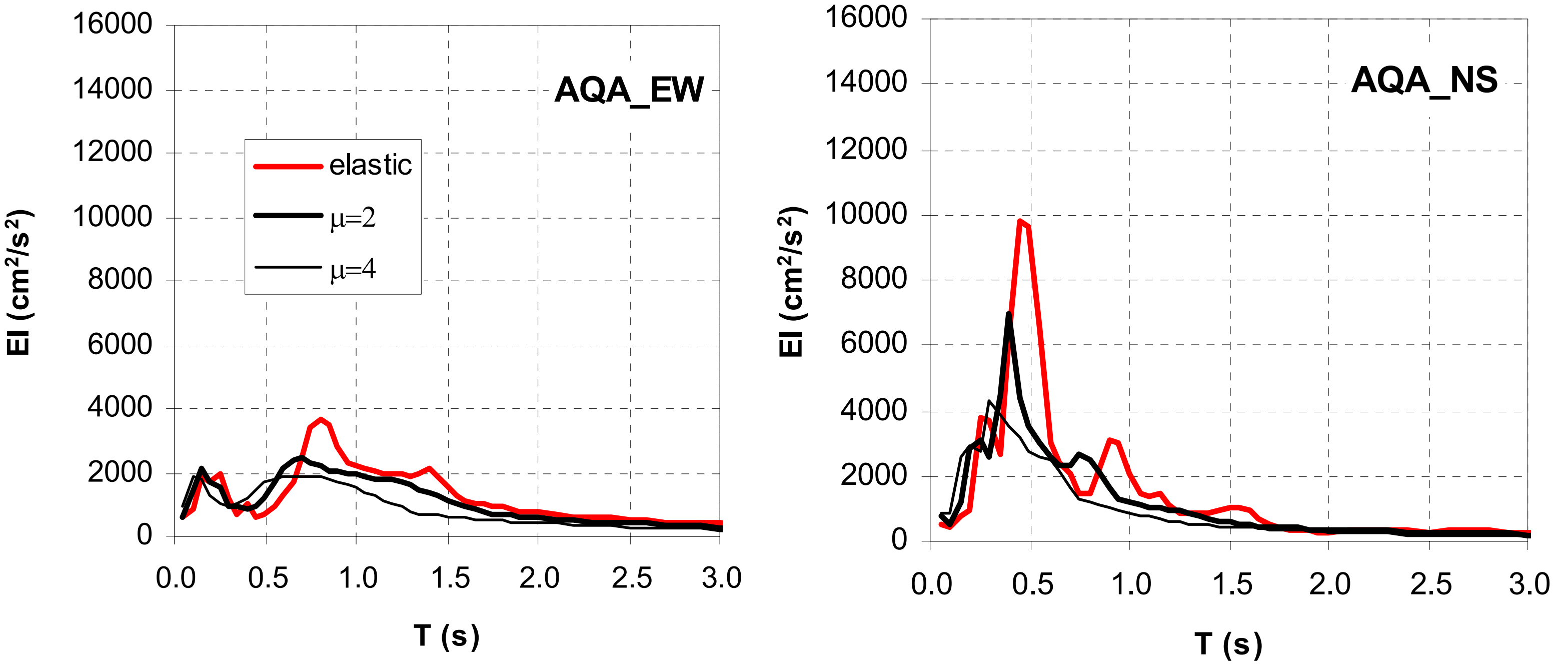
Absolute elastic input energy spectra for unit mass are plotted in figures

The maximum demand in terms of energy occurs at periods greater than those related to the maximum values of the pseudo-accelerations.

The AQK spectral shapes differ noticeably from the others, in fact the peak values occur at about 1.7 s, the same period value was found for the maximum displacement demand. The AQK records could have been affected by local effect.

L'Aquila EQ – Input Energy Demand (elastic and inelastic)

Decanini et al. (2009)



➢ The input energy constant ductility spectra show a shift of the peak values towards higher frequencies. The effect of ductility on the maximum spectral values is less marked than in the pseudo acceleration spectra.

➢ The energy demand related to the aftershocks is low, the comparison with the main shock highlights a remarkable decrease

L'Aquila EQ – Input Energy Demand

To measure the global demand in terms of energy, the parameters $AEI_{(0\text{-}2)}$ and $AEI_{(0\text{-}4)}$, given by the integral of the absolute elastic input energy per unit mass (5% damped) in the range of periods 0-2 s and 0-4 s (Decanini & Mollaioli 1998) were estimated. The energy demand varies significantly among the different accelerograms reaching the maximum values for AQK and AQV records. These energy parameters are not well correlated to the instrumental PGAs, better correlations are obtained with the PGVs and the maximum spectral displacements S_{dmax}.

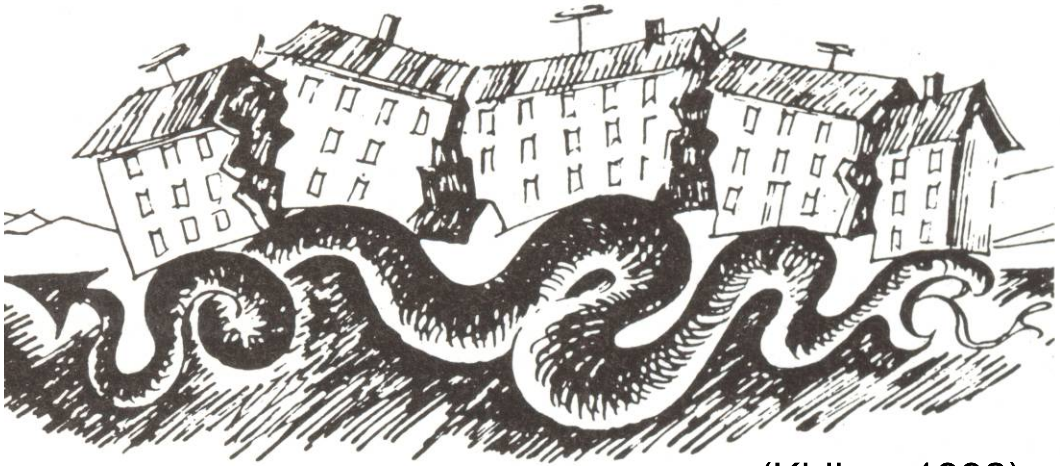
For L'Aquila event, a general agreement between observed damage and displacement, energy and inelastic force demands has been observed.

It seems that displacement and energy demand together could give a good estimate of the earthquake damage potential.

2009 L'Aquila Earthquake

Damage

L'Aquila earthquake - Earthquake losses



(Kirikov 1992)

Losses (estimated by Decanini 2009)

TANGIBLE LOSSES   **€ 16-18 billions**

(buildings and infrastructures damage, interruption and e reinstatement of productive activities, ecc.)

INTANGIBLE LOSSES non measurable in financial terms

(deaths, injured, psychological shock, social disruption, etc.)

Usability - Damage Survey in private and public buildings

L'Aquila, updated up to march 2010

A Safe to occupy

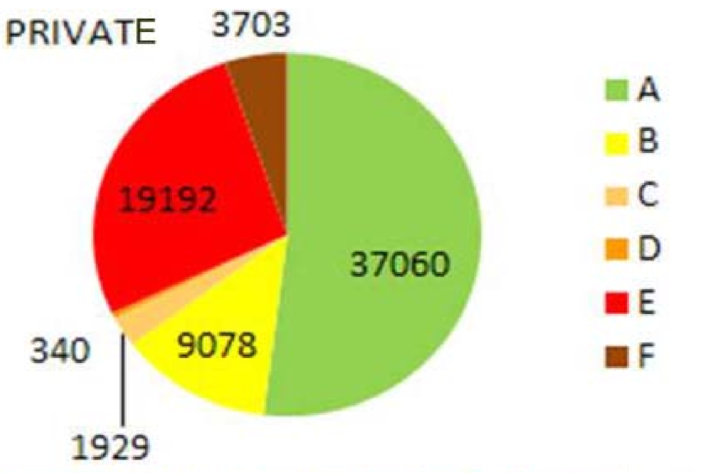
B Safe to occupy after very limited interventions

C Only limited use allowed (*yellow-tagged*)

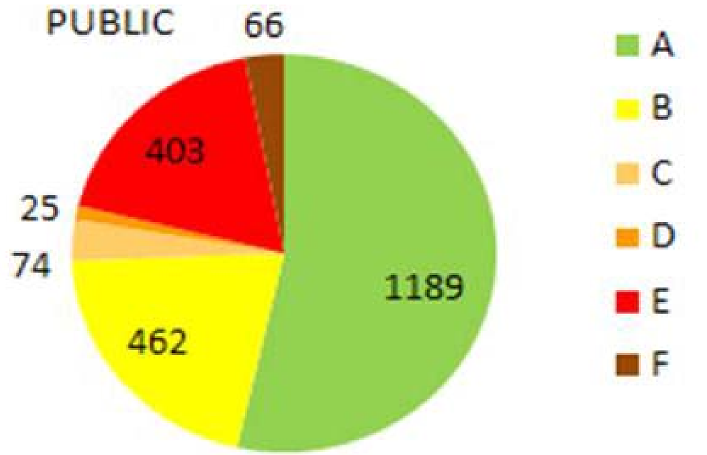
D Unsafe to occupy,
further investigations necessary

E Unsafe to occupy (*red-tagged*)

F Unsafe to occupy due to external threat



A	B	C	D	E	F	Tot
37060	9078	1929	340	19192	3703	71302
52,0%	12,7%	2,7%	0,5%	26,9%	5,2%	



A	B	C	D	E	F	Tot
1189	462	74	25	403	66	2219
53,6%	20,8%	3,3%	1,1%	18,2%	3,0%	

Masonry and reinforced concrete buildings

Courtesy of Giacomo Di Pasquale

Office of Seismic Risk Reduction

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Introduction

Most of the RC buildings existing in this area are designed with elderly seismic codes. Moreover, they may present deficiency both in the structural configuration and in detailing design and construction due to lacking of appropriate application of the code or to incorrect application of their rules.

Reinforced concrete buildings in L'Aquila, constructed in different eras probably starting from the thirties, possess very diverse characteristics in terms of both strength and ductility. From the last ISTAT (Istituto Nazionale di Statistica) building census, the RC buildings in L'Aquila amount to 4113, which is about the 29% of the total building stock.

Despite some noticeable cases of collapse, the majority of RC frame buildings in L'Aquila town centre were not structurally damaged but sustained extensive non-structural damage. It is worth mentioning the total amount of **RC buildings with total collapse is less than 1% of those existing in L'Aquila city showing high individual vulnerability**. This small percentage is maybe due to the short duration of the ground motion and to the presence of infills, which in many cases prevented the development of structural damage.

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Structural layout

The observation of damages highlighted how **structural irregularities**, like:

- presence of moment resisting frames only in one direction of the building
- weak column/strong beam (bad hinges pattern)
- inadequate column cross sections
- abrupt change of vertical resisting systems in elevation
- abrupt change of strength and stiffness in elevation
- interruption of vertical loads resisting elements
- not compact configurations in plan
- large eccentricity in plan
- etc.

seriously compromised the stability of buildings.

In fact, these factors can cause important shaking variation that may include **soft storeys, short columns, significant torsion, pounding**, etc.

L’Aquila EQ - Damage suffered by reinforced concrete buildings

Infill masonry

The role of infills masonry was found to be substantial. In fact, the field survey showed the positive contribution of uniformly distributed infills and the high vulnerability of buildings when discontinuities of infills in elevation are present (open storey configurations).

The damage type most commonly observed in L’Aquila and the surrounding towns to RC frames was non-structural damage to exterior infill walls and interior partitions, varying from small cracks to collapse. Several buildings displayed complete loss of the masonry infill walls at lower storeys. There were also occurrences of out-of-plane failure of a single layer of the infills. **Anyway, in many cases the energy dissipation in the infills walls allowed structures to survive the earthquake with minor or even without structural damage.**

L’Aquila EQ - Damage suffered by reinforced concrete buildings

Structural deficiency

Structural deficiency can be caused by design or **construction** process and/or age.

They include:

- inadequate stirrup in columns and transverse reinforcement not adequately anchored around the longitudinal bars or shear reinforcements (stirrups) absent or having large spacing
- lack of stirrups in columns and beam-column joints, deficient detailing
- lack of adequate anchorage in smooth reinforcement
- eccentric beam-column joint
- poor quality of concrete
- lack of adequate anchorage length
- inadequate upper rebars in beam
- inadequate lap splices

Concerning the **quality of concrete**, in general it varies from **bad to medium**, with a **great variability** from one point of a building to another point, perhaps due to the fact that the concrete was usually made in situ. Local defects in concrete were also observed, like segregation, cold joints, etc.

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Pounding

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Typical damage to infill walls

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Lack of transverse reinforcement in joints

Weak columns - Strong beams

Edificio in via Poggio S. Maria 8

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Weak columns - Strong beams

Edificio in via XX Settembre 123

Complete collapse (Corriere, Radio Sound City)

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Deficient structural layout, declivity

Hotel Duca degli Abruzzi, in Viale Giovanni XXIII,

Before earthquake (Google Street View)

After earthquake

L’Aquila EQ - Damage suffered by reinforced concrete buildings

Total collapse

Before eq

(Google Street View)

Building in via Campo di Fossa

(Corriere)

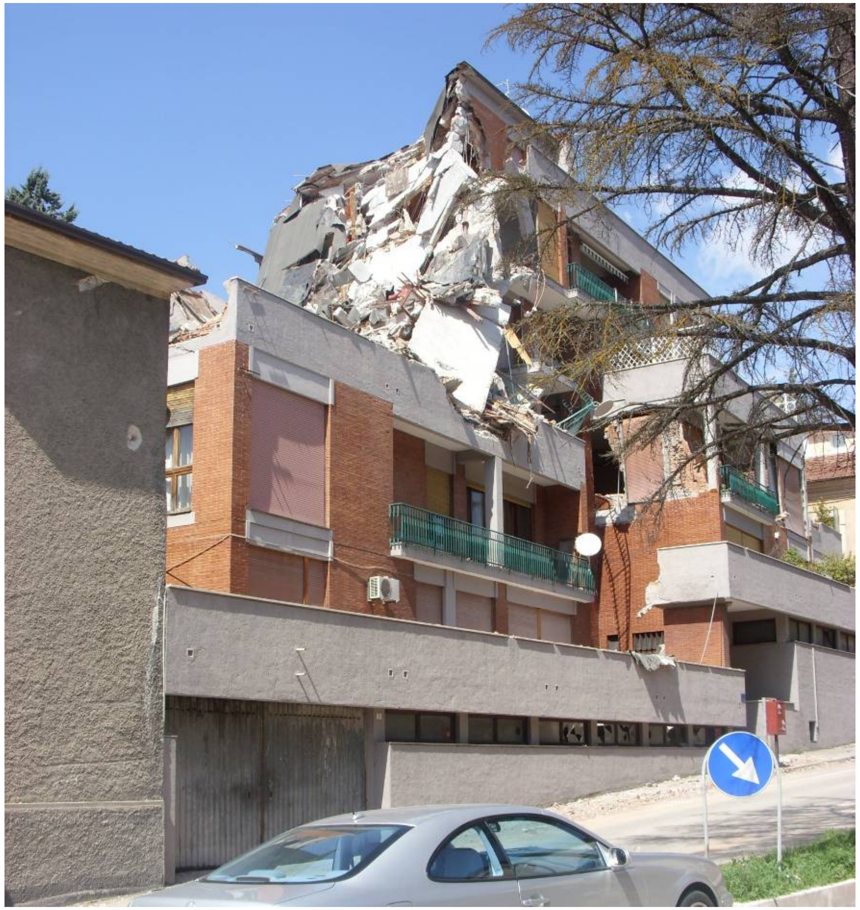
L'Aquila EQ - Damage suffered by reinforced concrete buildings

Abrupt change of strength and stiffness in elevation

Building in via Porta Napoli
Before earthquake

L’Aquila EQ - Damage suffered by reinforced concrete buildings

Abrupt change of strength and stiffness in elevation



Building in via Porta Napoli

L’Aquila EQ - Damage suffered by reinforced concrete buildings

Pancake collapse (third storey)

Building in via G. d’Ocre 12

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Soft storey

Building in via Milonia I

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Soft storey

Building in via Dante Alighieri 2
Before earthquake

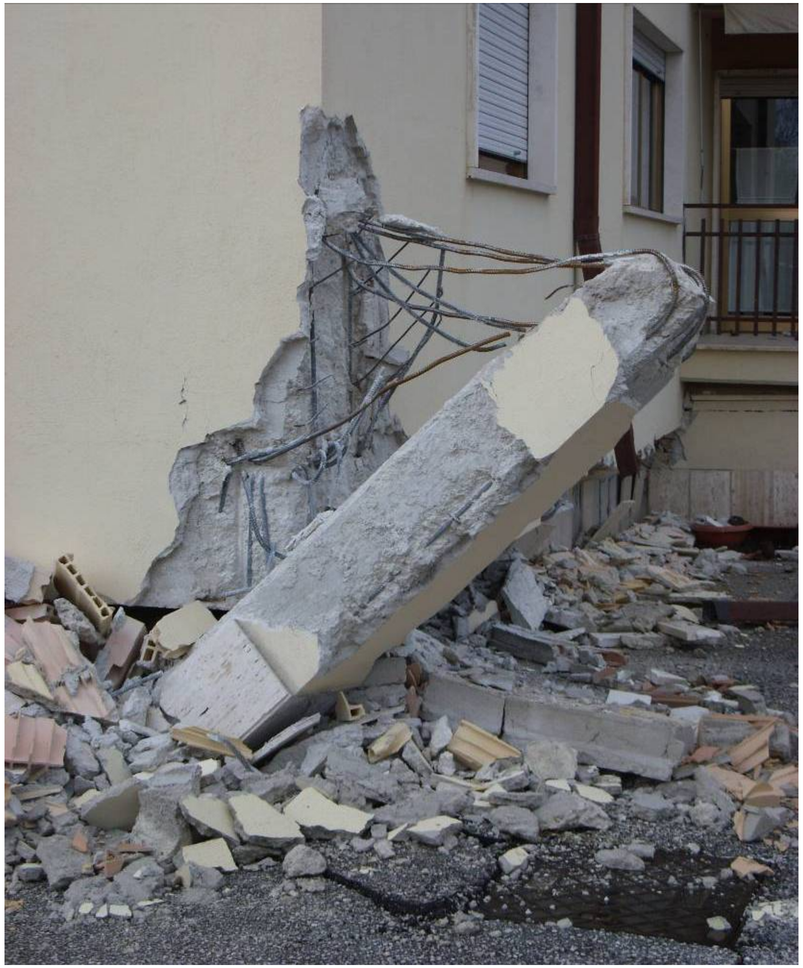
L'Aquila EQ - Damage suffered by reinforced concrete buildings

Soft storey

Building in via Dante Alighieri 2
After earthquake

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Soft storey



Building in via Dante Alighieri 2
After earthquake

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Soft storey

Building in via Dante Alighieri 2
After earthquake

L'Aquila EQ - Damage suffered by reinforced concrete buildings

Damage to columns, lack of adequate transverse reinforcement

Shear failure

L'Aquila EQ - Damage suffered by masonry buildings

Introduction

Damage to historical masonry buildings has been more widespread than that to reinforced concrete buildings.

Often the masonry quality is poor.

The churches have been more affected compared to residential buildings, also due to the higher horizontal and vertical walls slenderness.

The pattern of damage in the churches is similar to that of previous Italian earthquakes.

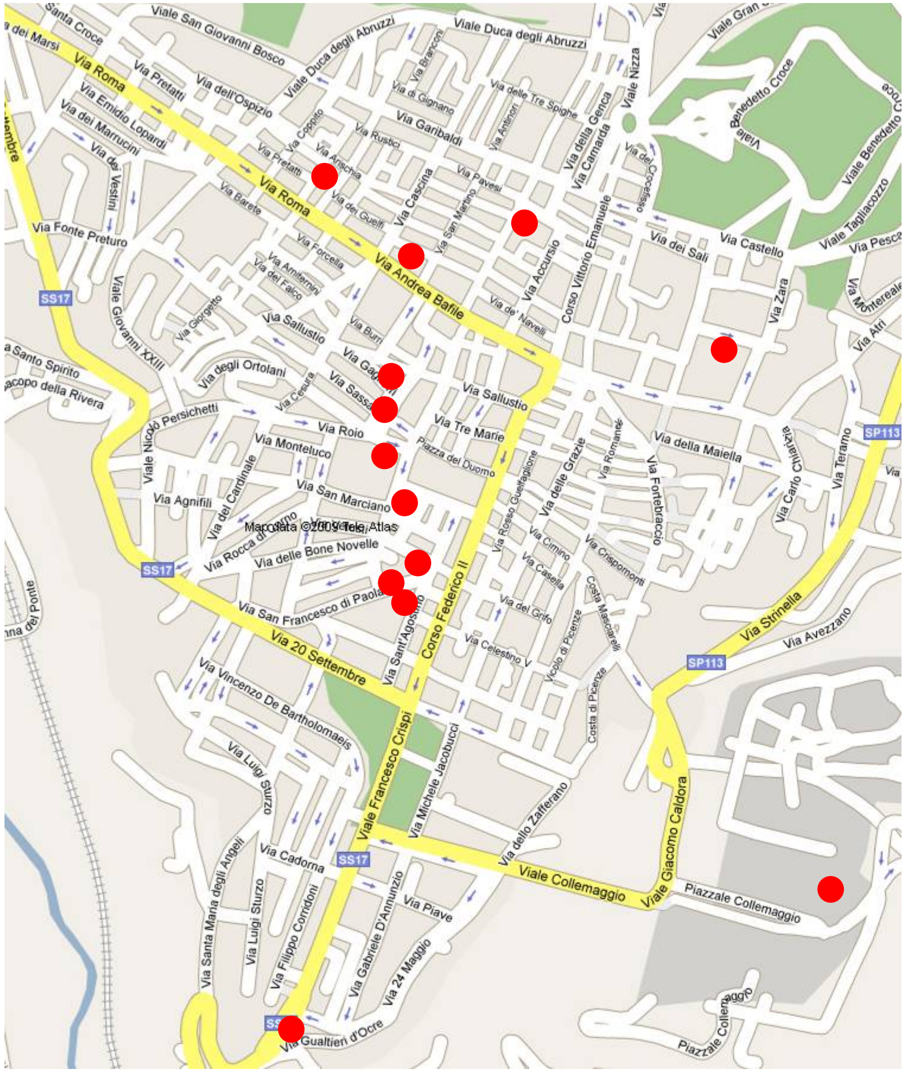
Historical centre have suffered the interruption of several streets due to out-of-plane collapses of façades. This has hampered the evacuation, happened at night perhaps without electrical lighting, and the following relieves.

Past interventions, especially those using reinforced concrete elements, have sometimes caused more damages, compared to similar edifices with traditional details.

L'Aquila EQ - Damage suffered by masonry buildings

Position of some monuments

Historical centre



L'Aquila EQ - Damage suffered by masonry buildings

Santa Maria di Paganica

Before EQ

Built in the second half of the 13th and in the first half of the 14th centuries.
Damaged in 1703 and later raised.

L’Aquila EQ

Santa Maria di Paganica

After EQ

L’Aquila EQ - Damage suffered by masonry buildings

Cathedral

Before EQ

L'Aquila EQ

Cathedral

Collapse of roof and vault
of the left transept

L'Aquila EQ - Damage suffered by masonry buildings

Santa Maria del Suffragio

Built after 1703.
Drum and dome by architect Giuseppe Valadier (1762-1839)

Before EQ

L'Aquila EQ - Damage suffered by masonry buildings

Santa Maria del Suffragio

Collapse of the brick masonry drum and dome (April 7)

Timber ring beams within the masonry

L'Aquila EQ - Damage suffered by masonry buildings

Santa Maria del Suffragio

Damage accumulation (April 29)

L’Aquila EQ - Damage suffered by masonry buildings

Santa Maria di Collemaggio

Built in the second half of the 13th century and consecrated in 1288. The church shrines the mortal remains of Pope Celestino 5th.

L'Aquila EQ - Damage suffered by masonry buildings

Santa Maria di Collemaggio

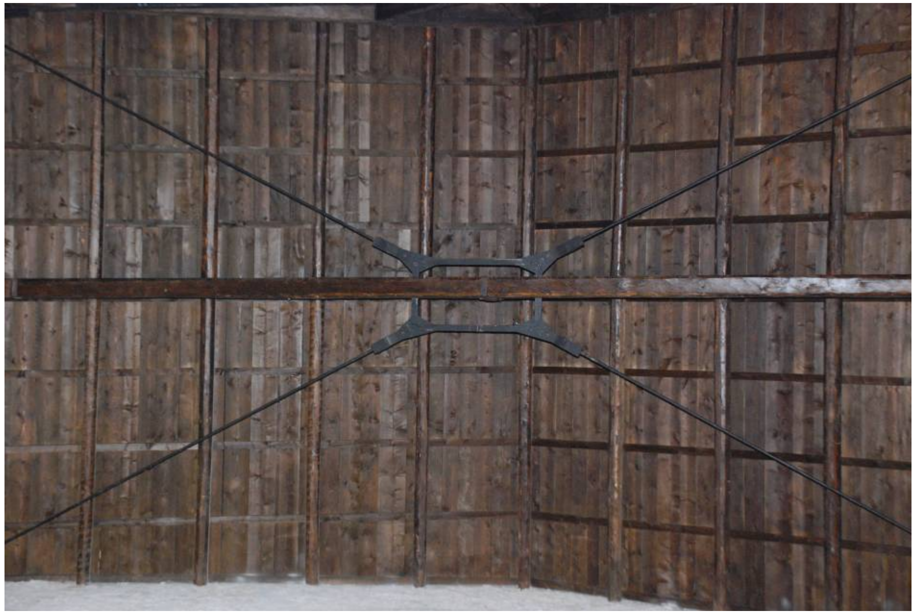
Collapse of the transept vaults

L’Aquila EQ - Damage suffered by masonry buildings

Santa Maria di Collemaggio

Bracing dampers on the roof of the central nave.

Not present in the transept.



L'Aquila EQ - Damage suffered by masonry buildings

Santa Maria di Collemaggio

L'Aquila EQ

Palazzo Quinzi

Damaged by the 1703 EQ. Rebuilt thereafter.

Before EQ.

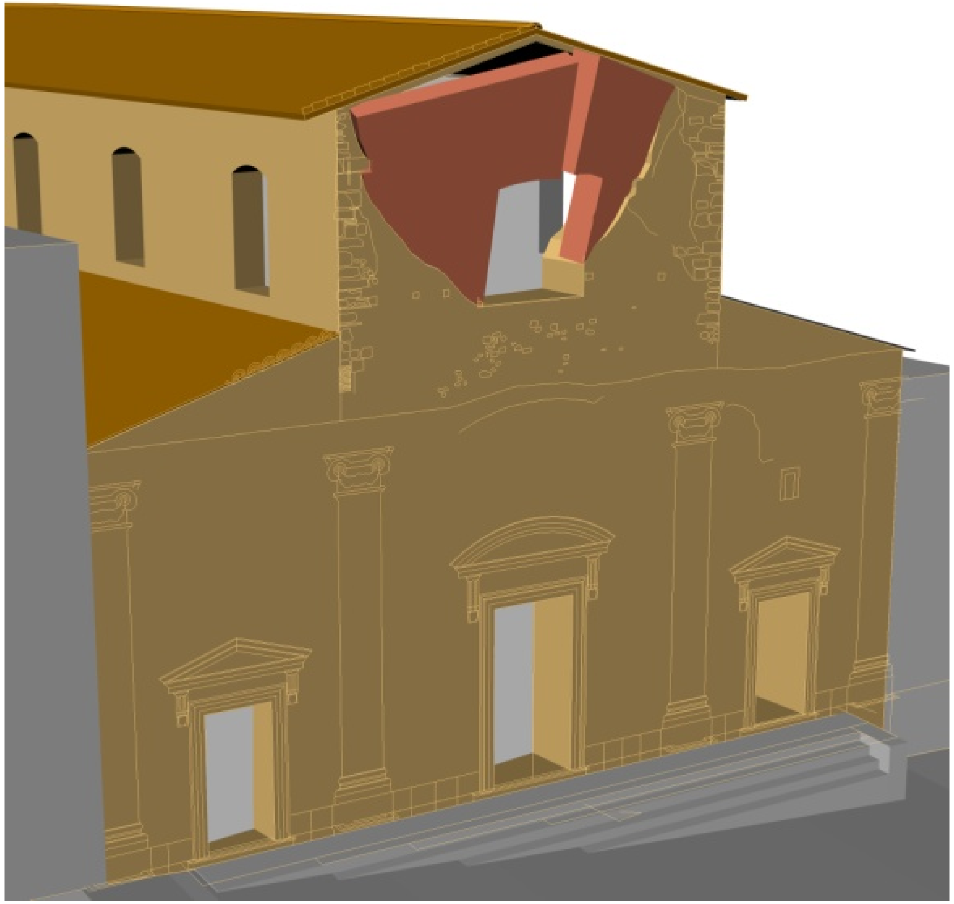
L’Aquila EQ - Damage suffered by masonry buildings

Palazzo Quinzi

L’Aquila EQ - Damage suffered by masonry buildings

San Biagio, analyses by Sorrentino L., Decanini L.D., Liberatore D. and Raglione E.

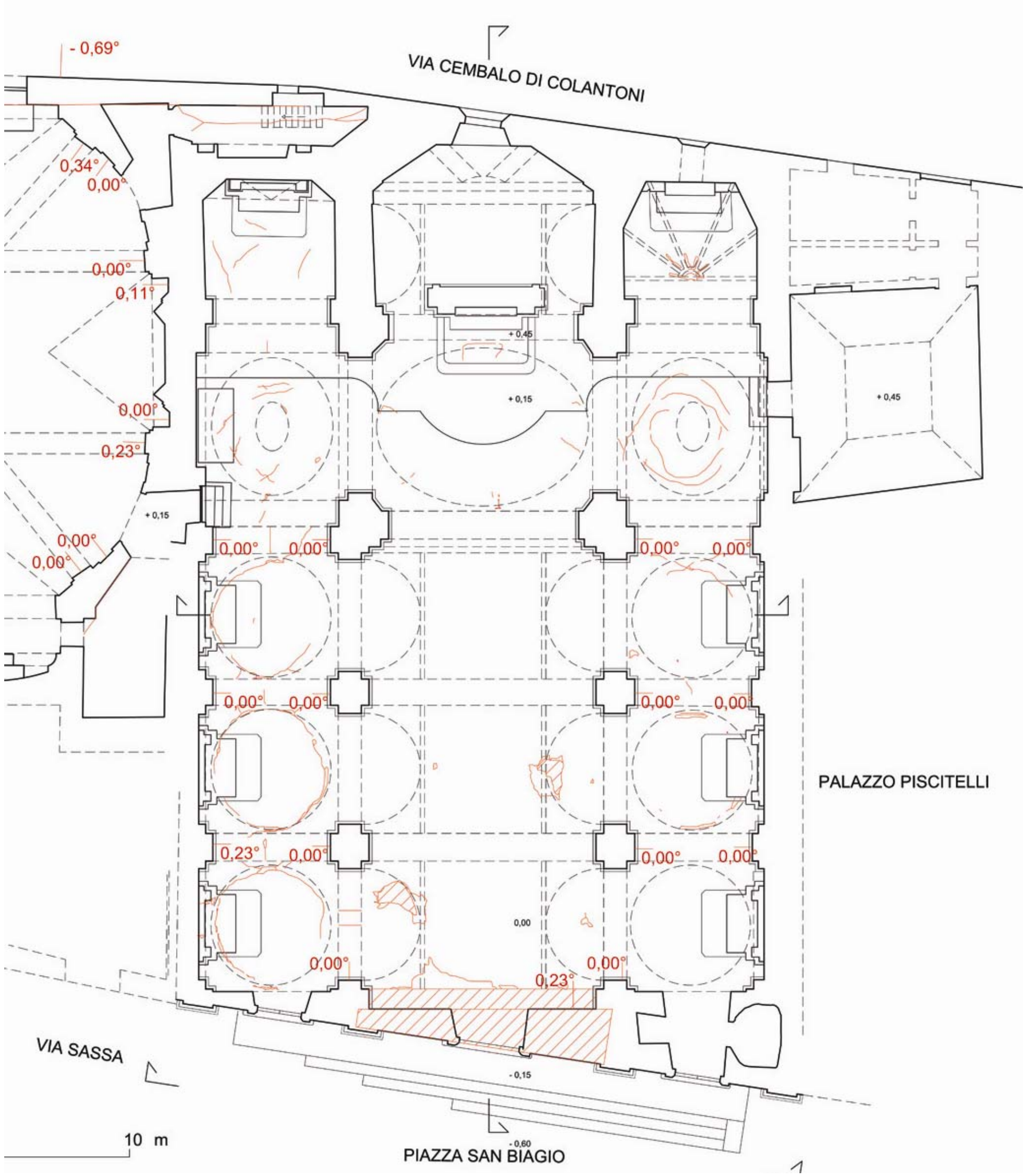
Collapse of the façade gable.



L'Aquila EQ

San Biagio

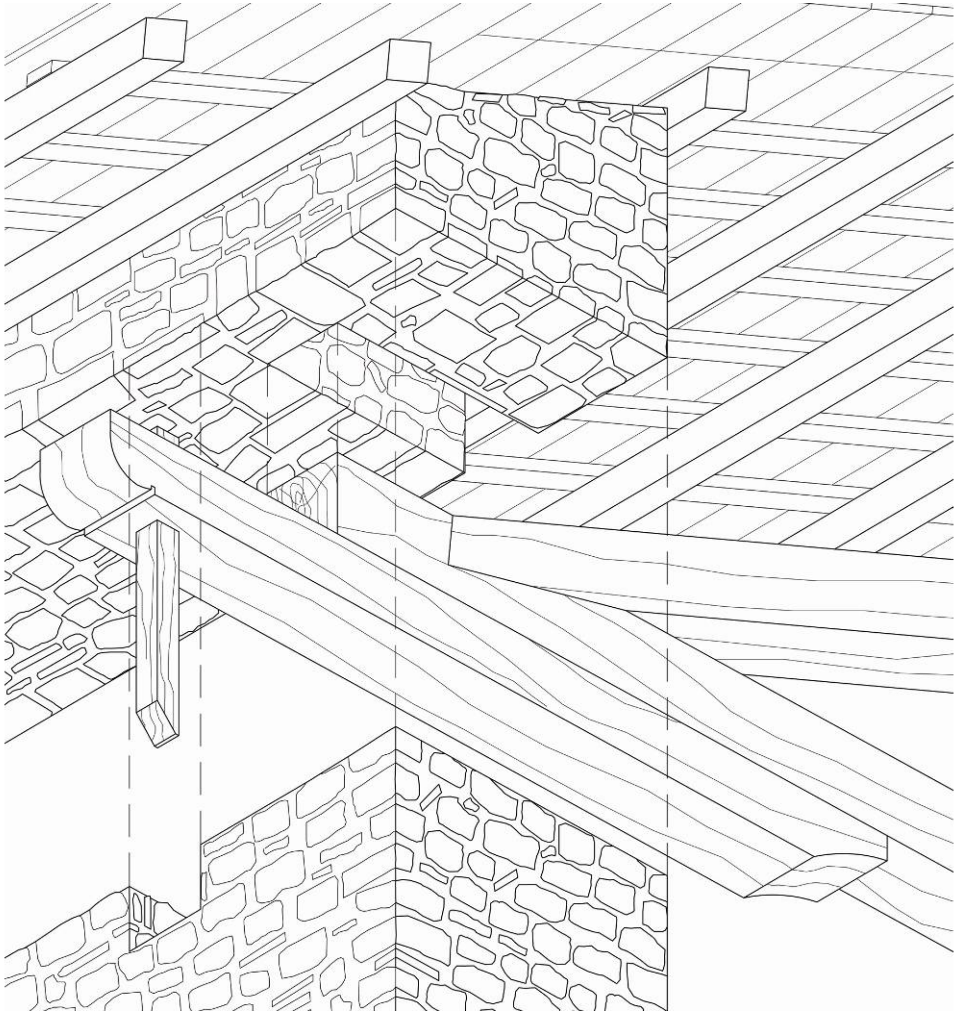
Extensive cracking
of the lateral vaults



L’Aquila EQ - Damage suffered by masonry buildings

San Biagio

Evidence of historical earthquake-resistant details.



L'Aquila EQ - Damage suffered by masonry buildings

San Biagio

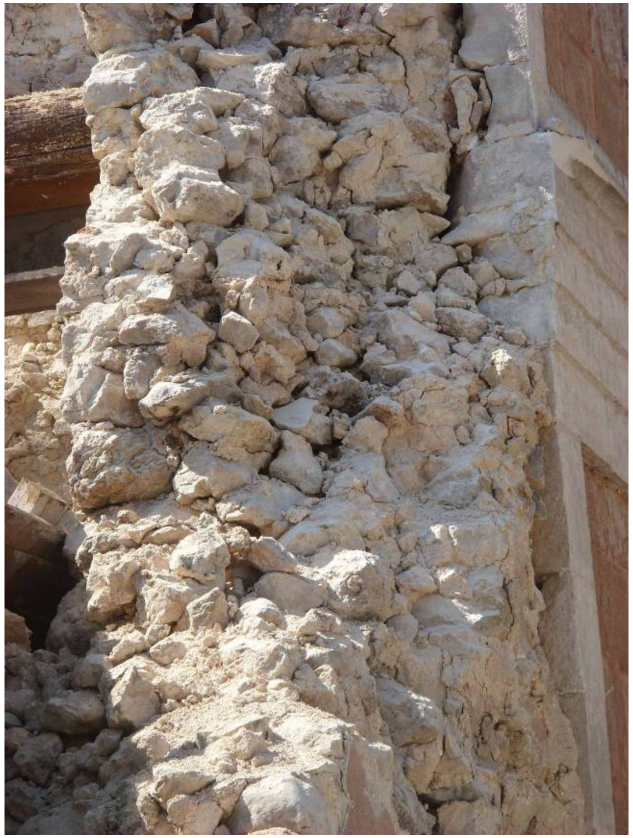
Internal view of the façade gable collapse and damage to the reed mat vault of the central nave.

L'Aquila EQ - Damage suffered by masonry buildings

Poor masonry quality

Palazzo del Governo

Porta Napoli

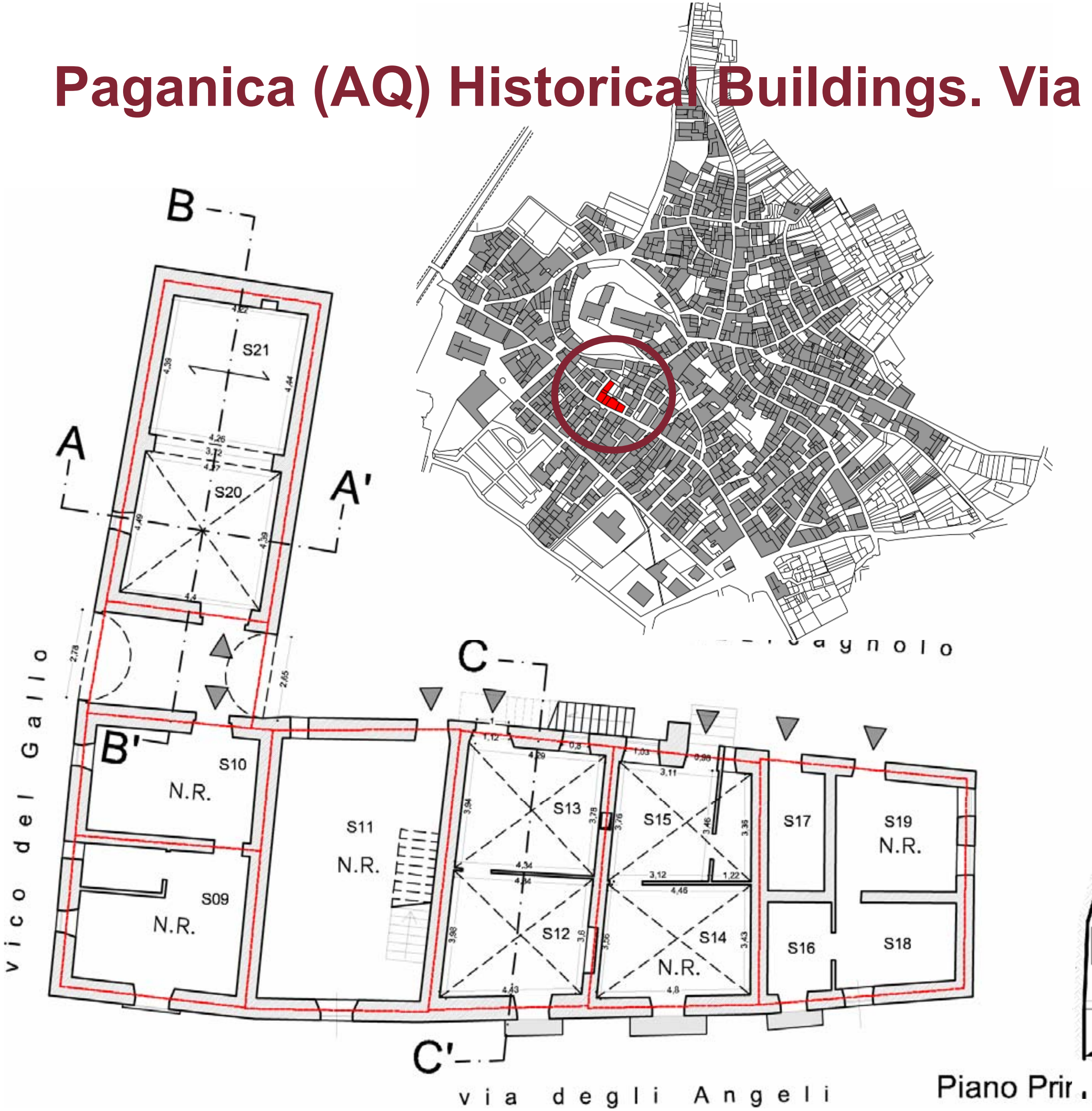


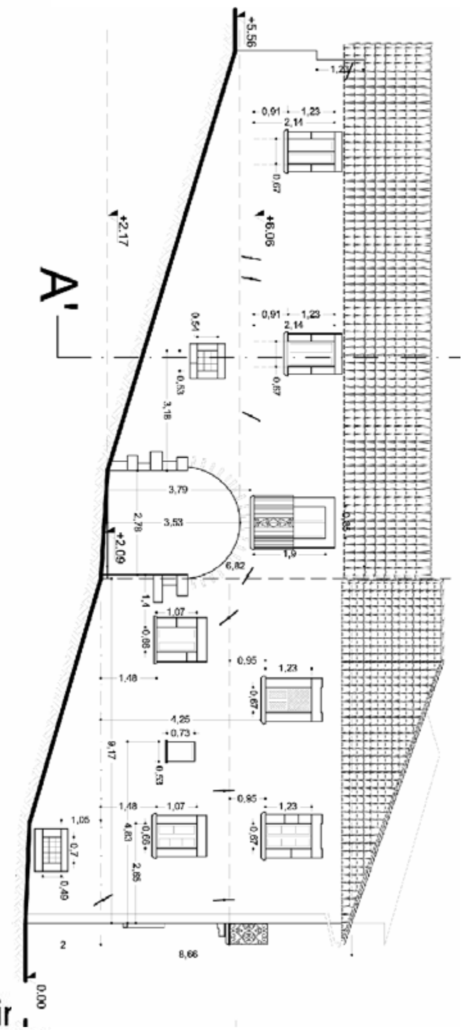
L'Aquila EQ - Damage suffered by masonry buildings

Damage due to roof made heavy

Santi Giovanni Battista ed Evangelista in Succiano

Paganica (AQ) Historical Buildings. Via degli Angeli,





Paganica (AQ) Historical Buildings. Via degli Angeli,

Damages

Prospetto su vico del Gallo

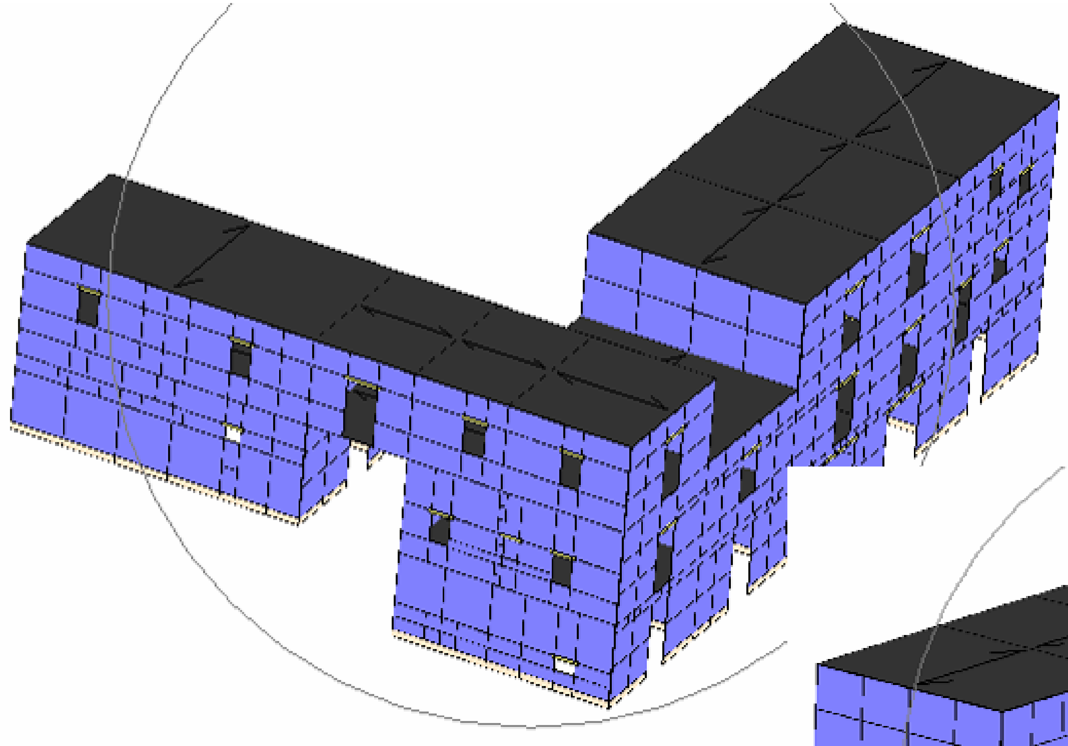
Testata d’angolo su via del Pizzicagnolo

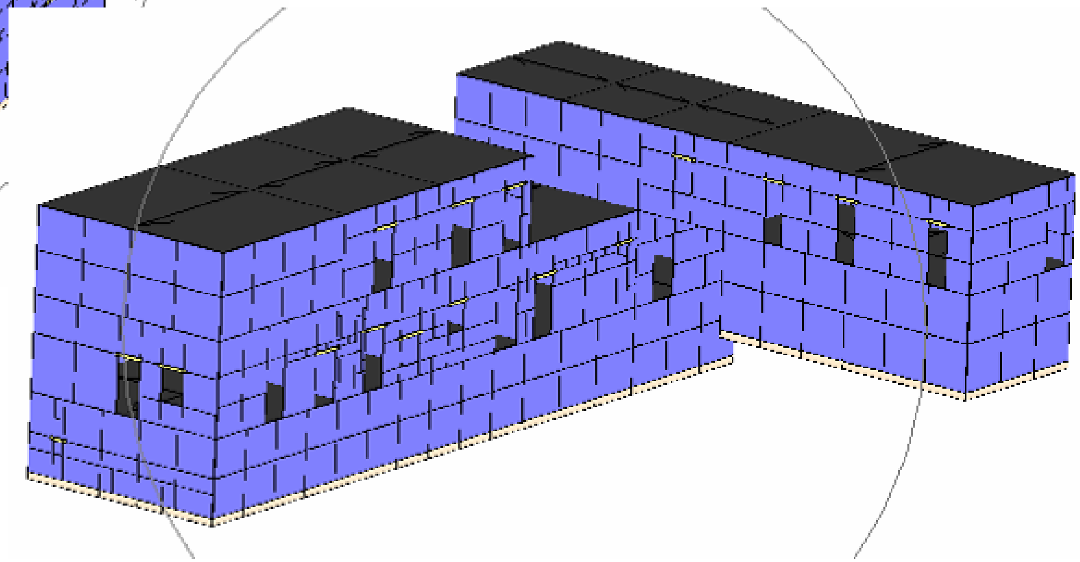
Prospetto su via del Pizzicagnolo

Interni. Collasso degli orizzontamenti

Paganica (AQ) Historical Buildings. Via degli Angeli,

Modelling





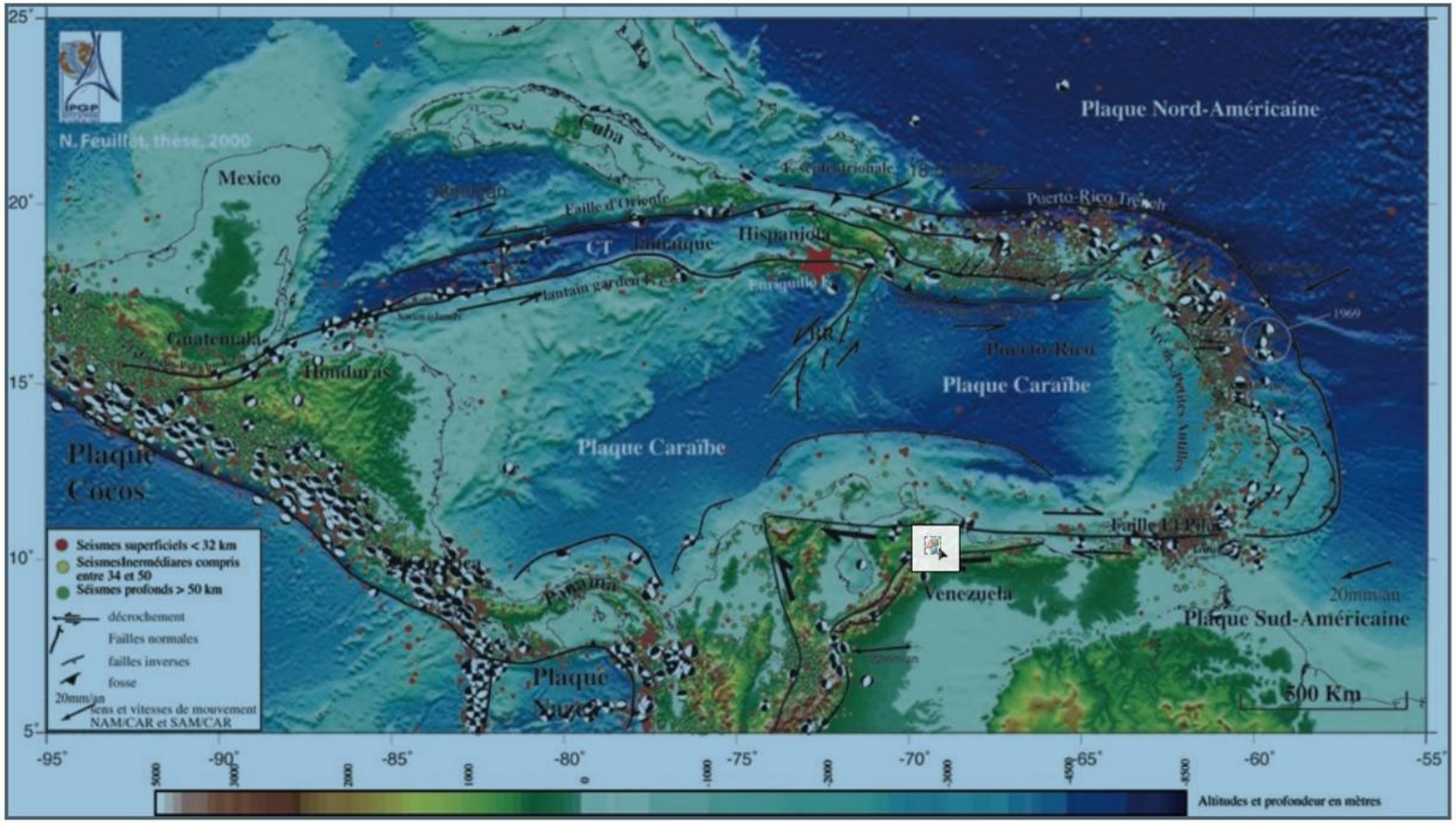
HAITI EARTHQUAKE

JANUARY 12, 2010

SPECIFIC ASPECTS

Seismology of Haiti EQ

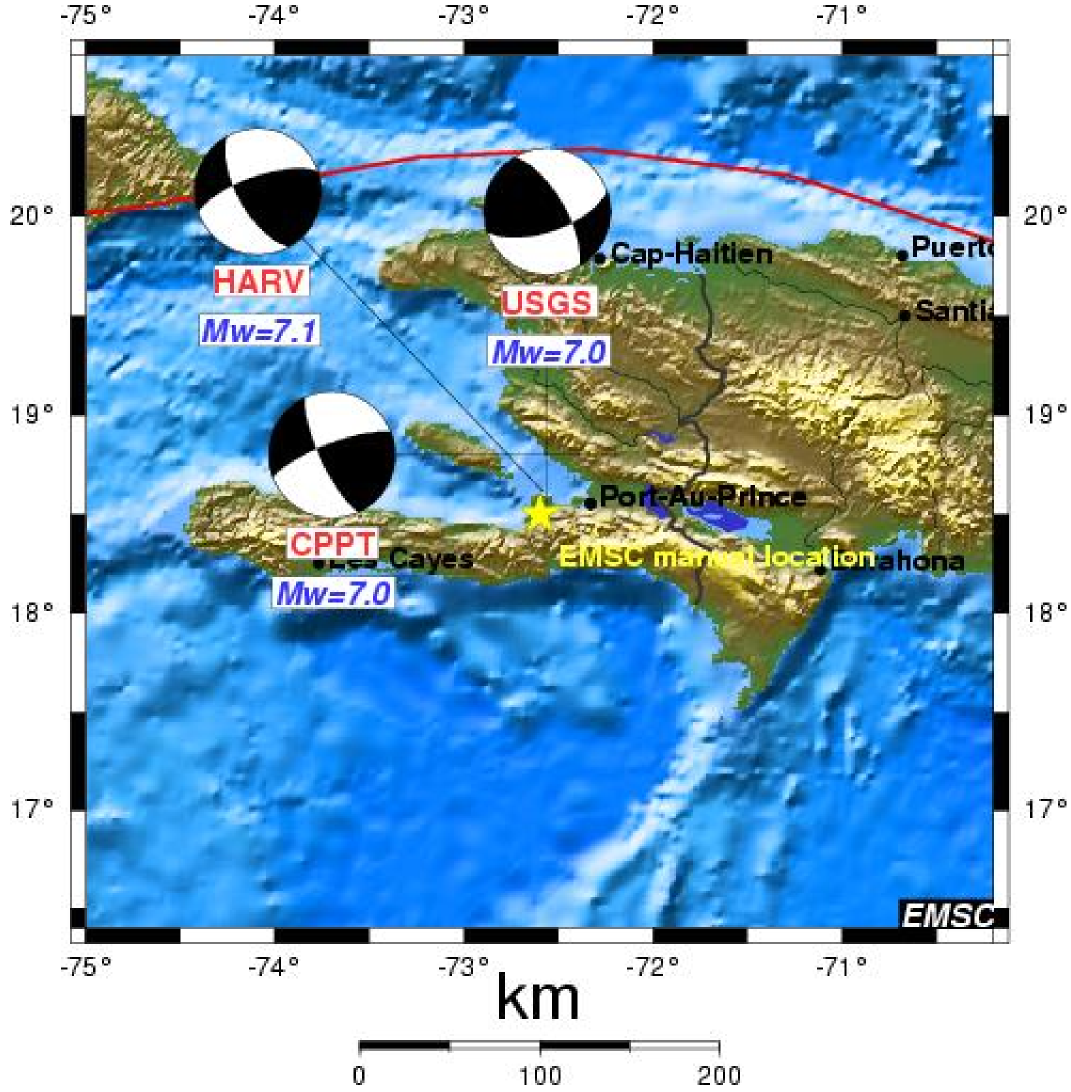
Plate tectonics. Caribbean area



(Lacassin et al 2010)

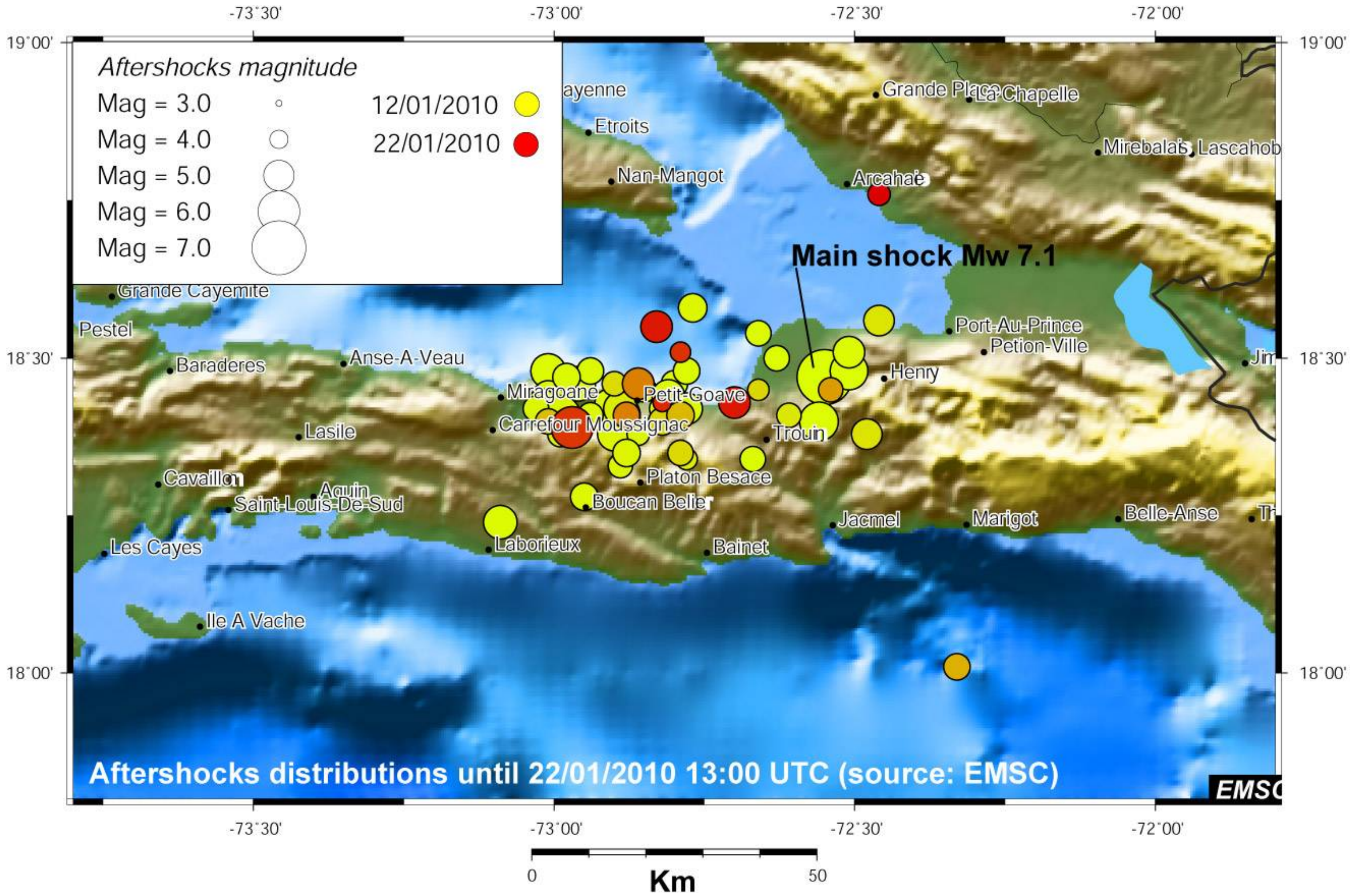
Seismology of Haiti EQ

Focal mechanism



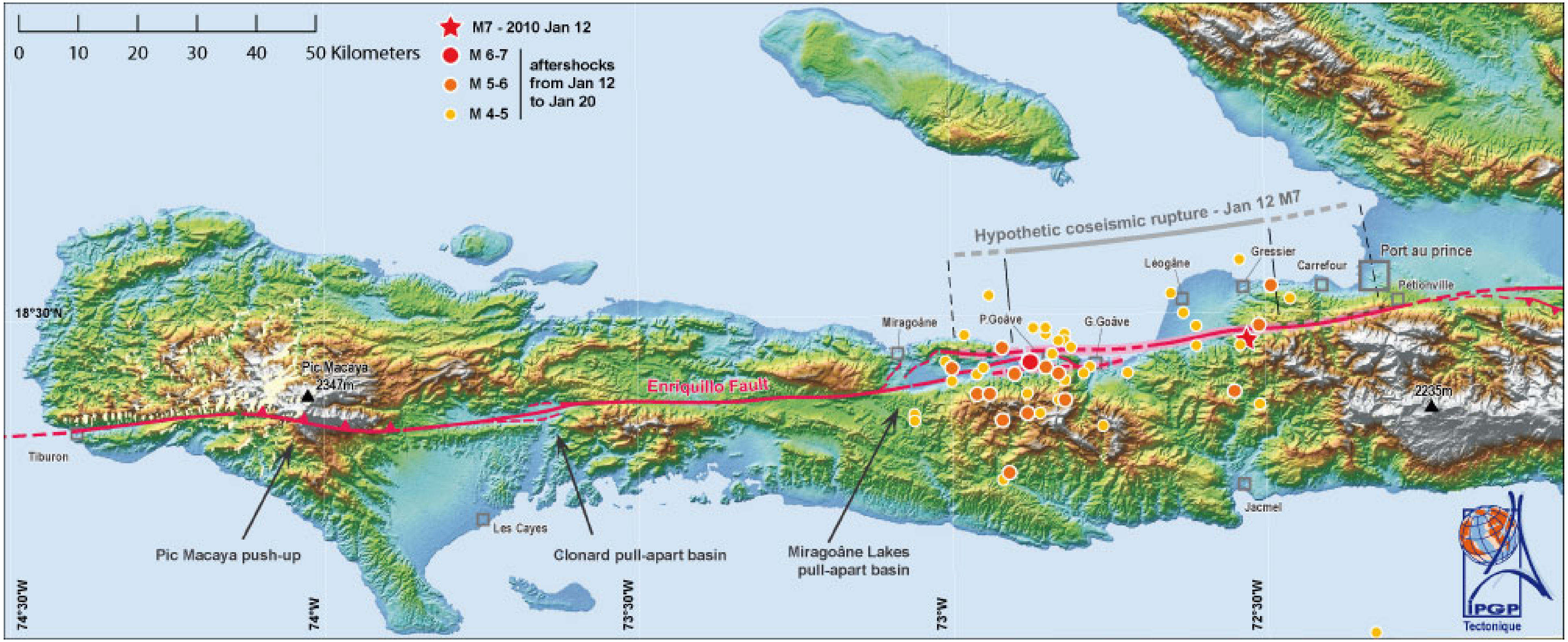
Seismology of Haiti EQ

Seismic sequence



Seismology of Haiti EQ

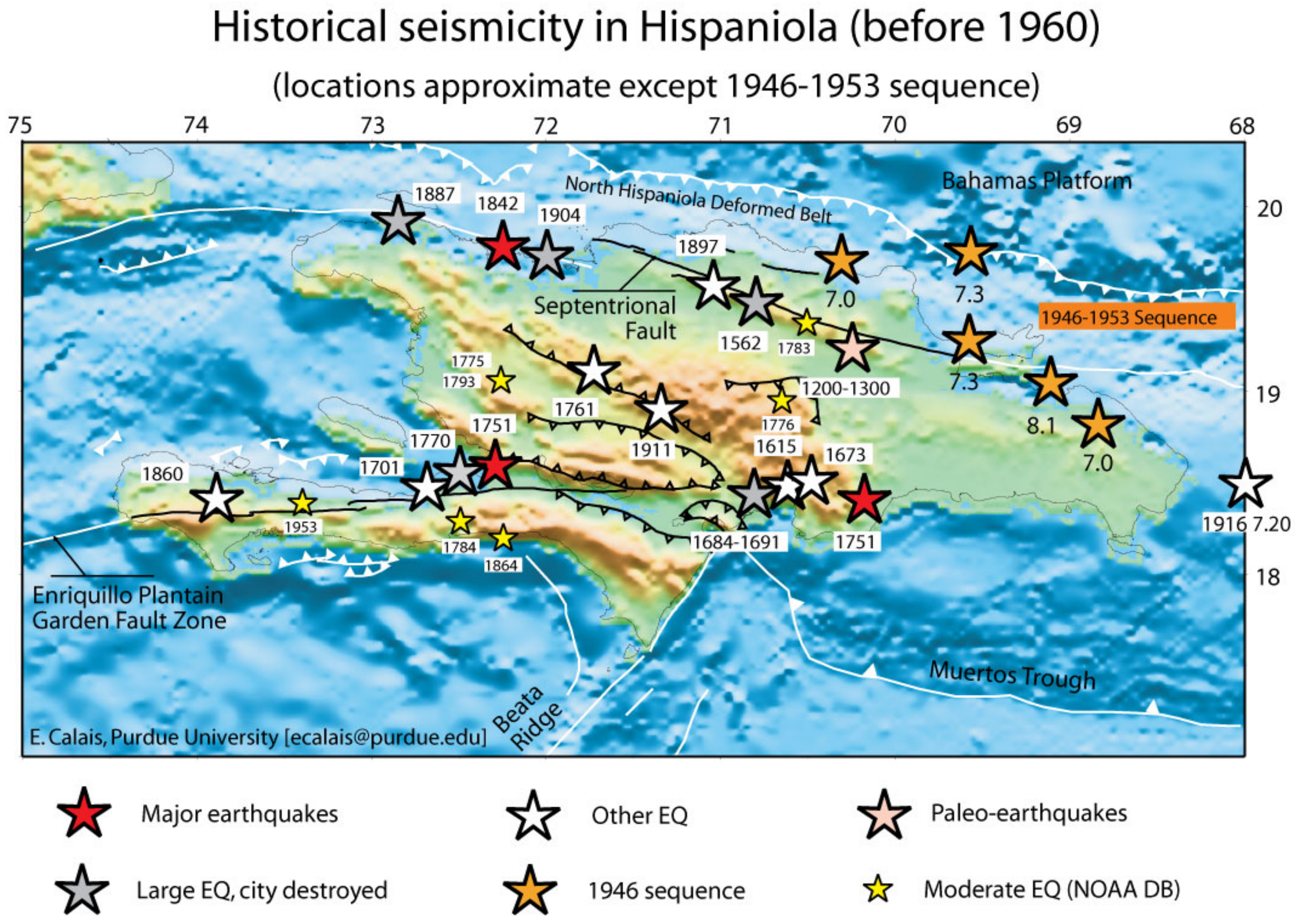
Epicentres, aftershocks and fault surface projection



(Lacassin et al 2010)

Seismology of Haiti EQ

Historical seismicity



Haiti - Ground motion

- There are no known records in the source area of the Haiti EQ.
- Estimated EPA ≥ 0.4 g (from damage, Decanini 2009).

Haiti Earthquake

Damages

Damages of Haiti EQ

Monumental buildings

Port-au-Prince, Cathedral

Damages of Haiti EQ

Monumental buildings

Port-au-Prince, Presidential Palace

Damages of Haiti EQ

Reinforced concrete buildings

Damages of Haiti EQ

Reinforced concrete buildings

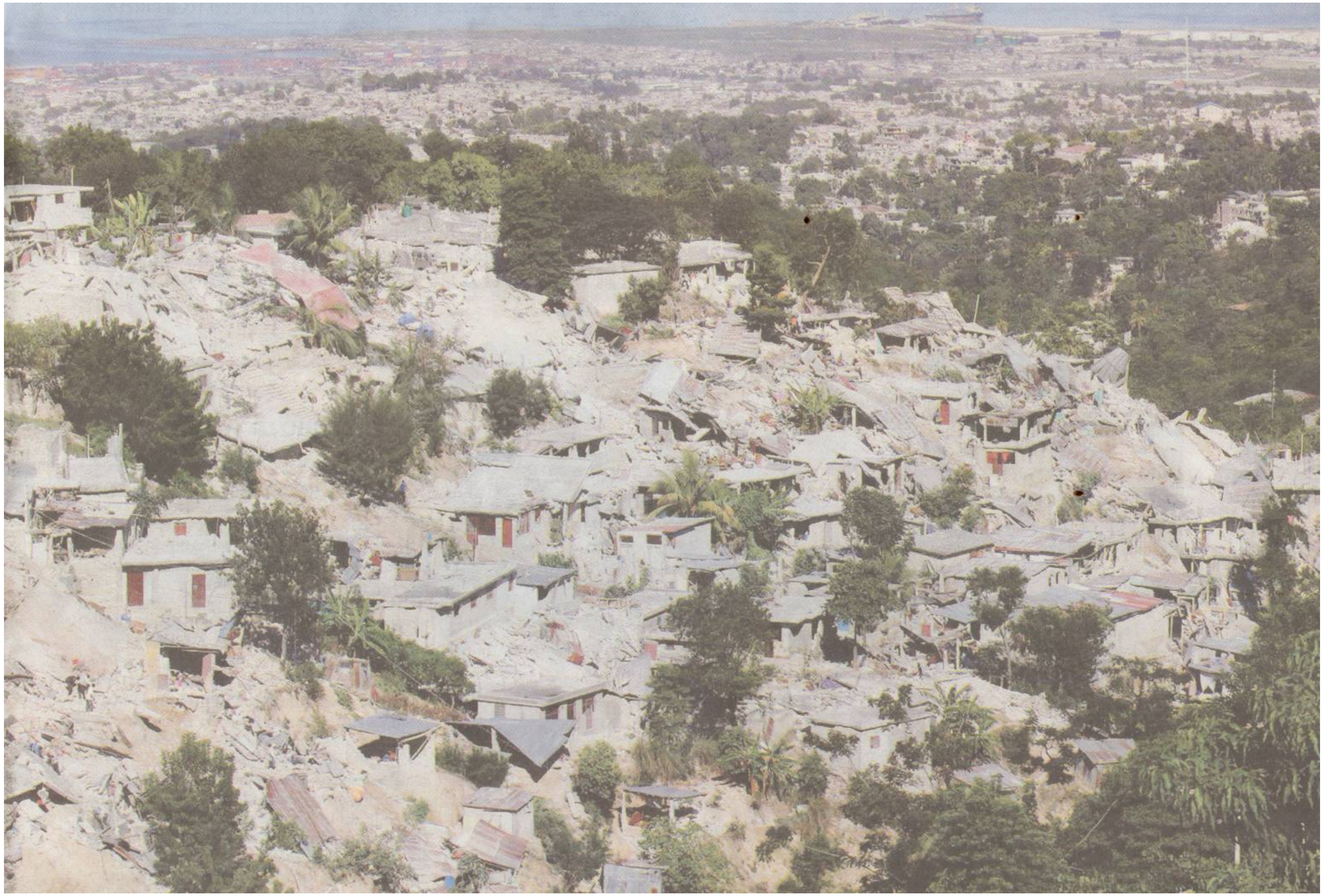
Damages of Haiti EQ

Reinforced concrete buildings

Port-au-Prince, United Nations mission

Damages of Haiti EQ

Poor residential buildings



Damages of Haiti EQ

Unreinforced masonry buildings

Damages of Haiti EQ

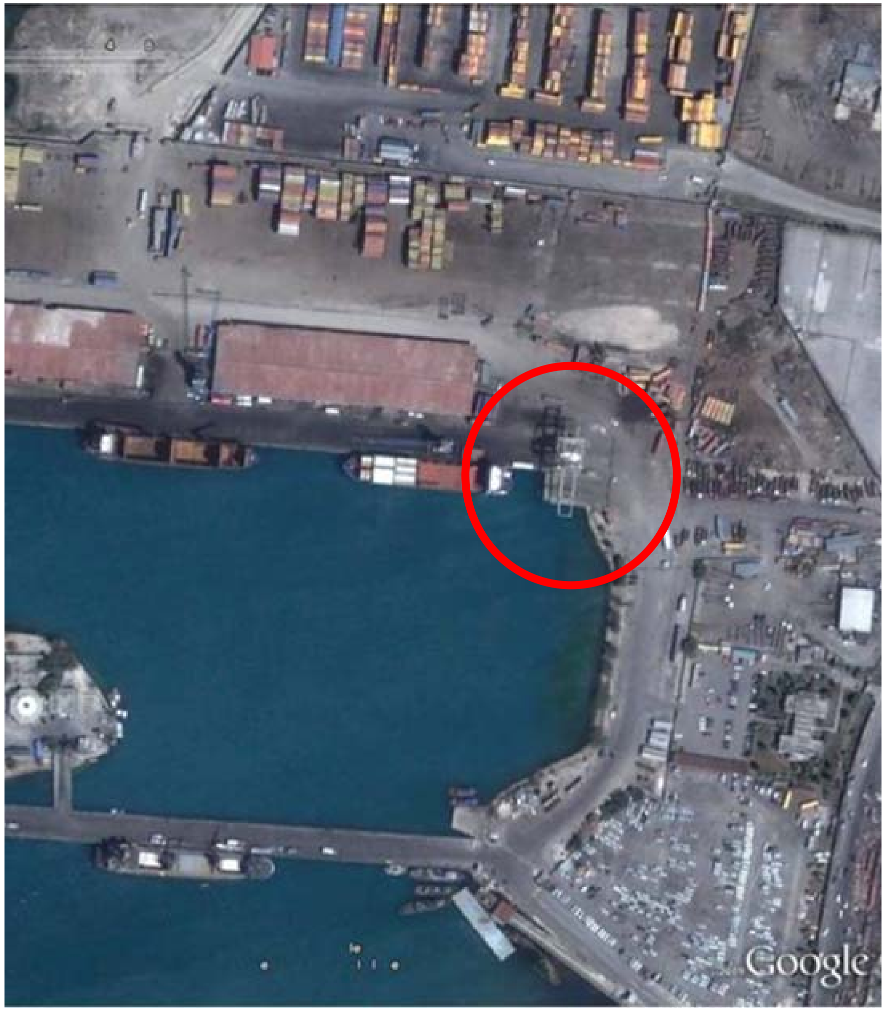
Unreinforced masonry buildings

Damages of Haiti EQ

Port facilities

Damages of Haiti EQ

Port facilities



before

after

Damages of Haiti EQ

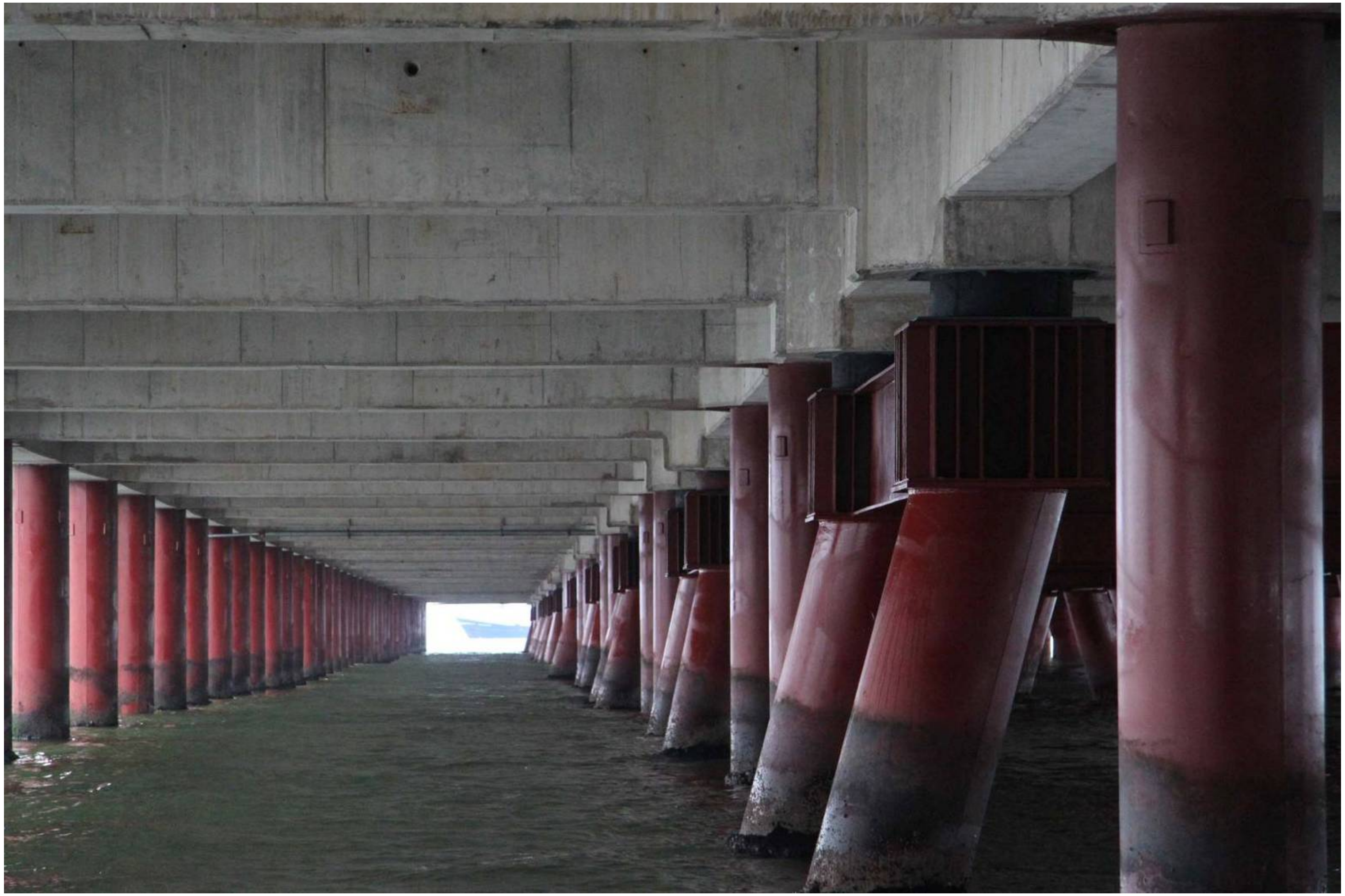
Port facilities

Damages of Chile EQ

Port facilities. Coronel

Damages of Chile EQ

Port facilities. Coronel



CHILE EARTHQUAKE

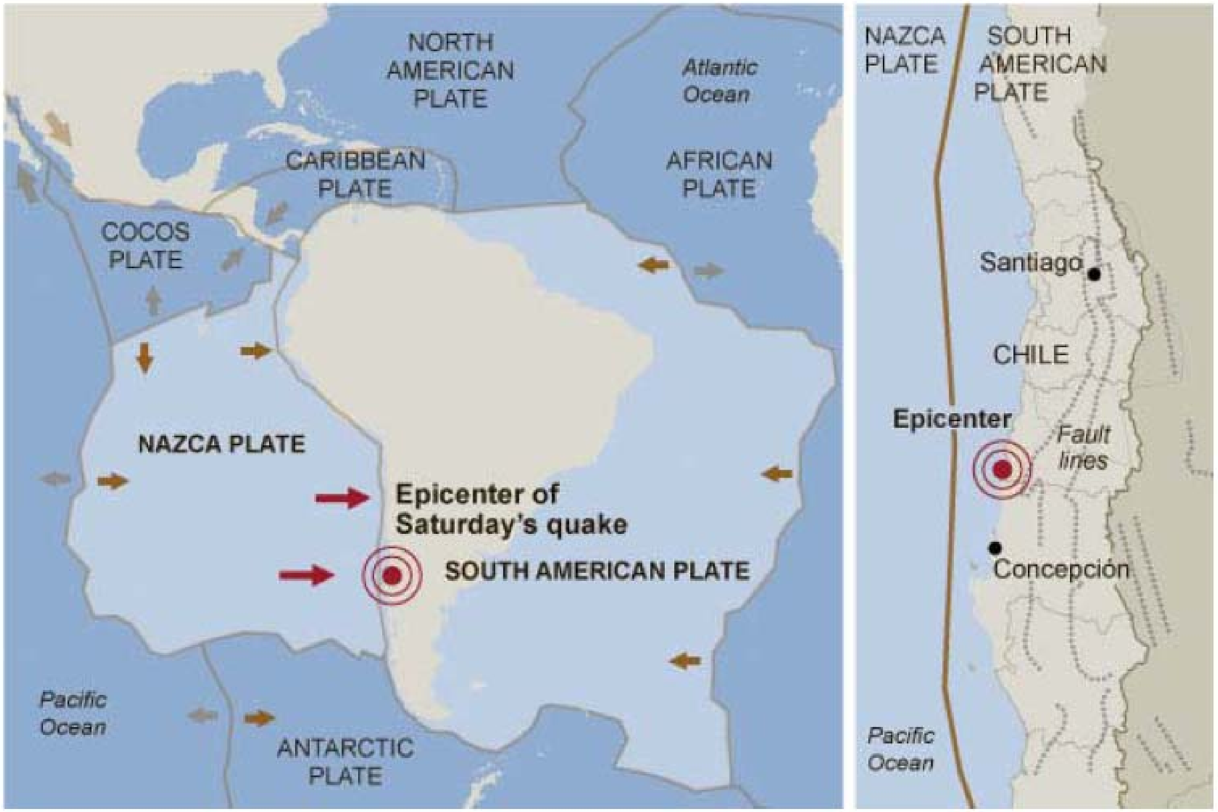
FEBRUARY 27, 2010

SPECIFIC ASPECTS

Trieste, May 13, 2010

Seismology of Chile EQ

Plate tectonics. South-American region



Geophysical evidence indicates the subduction of the Nazca plate along the coast of Chile and Peru is at a rate of approximately 10 cm per year. (Riddell, 1986)

Seismology of Chile EQ

Focal mechanism

USGS Centroid Moment Solution

```
10/02/27 06:34:08.34
OFFSHORE BIO-BIO, CHILE
Epicenter: -36.027  -72.834
MW 8.8

USGS CENTROID MOMENT TENSOR
10/02/27 06:35:27.50
Centroid:  -35.766  -72.473
Depth  30          No. of sta:187
Moment Tensor;   Scale 10**22 Nm
  Mrr= 1.13        Mtt=-0.06
  Mpp=-1.07        Mrt= 0.09
  Mrp=-1.43        Mtp=-0.12
 Principal axes:
  T  Val=  1.84  Plg=63  Azm= 80
  N       -0.06       4      180
  P       -1.78      26      272

Best Double Couple:Mo=1.8*10**22
 NP1:Strike= 14 Dip=19 Slip= 104
 NP2:       179     71        85
```

```
             ---####
        -------########--
      ---------##########--
    ----------#############--
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---   -------#######   #######---
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```
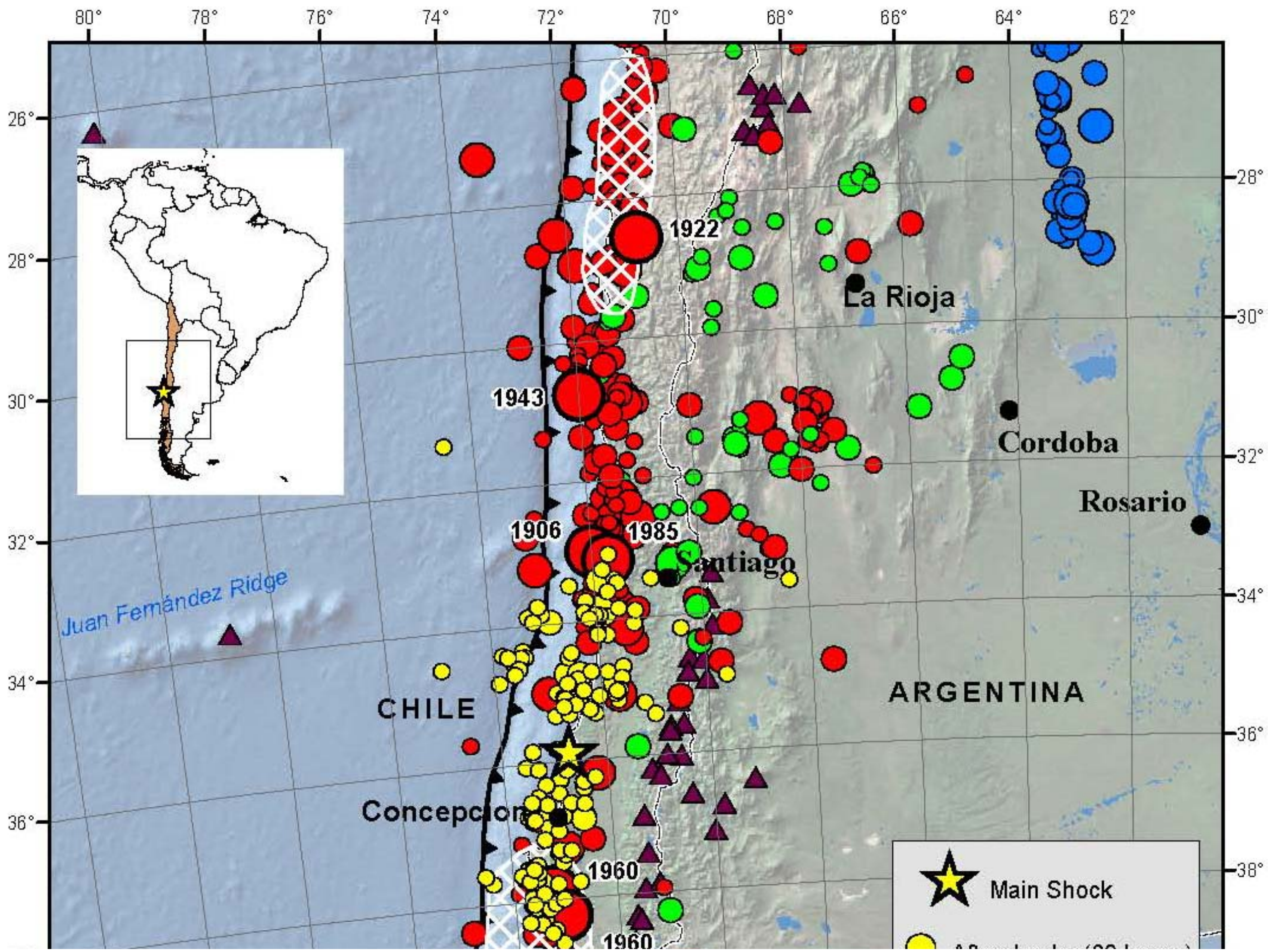

Seismology of Chile EQ

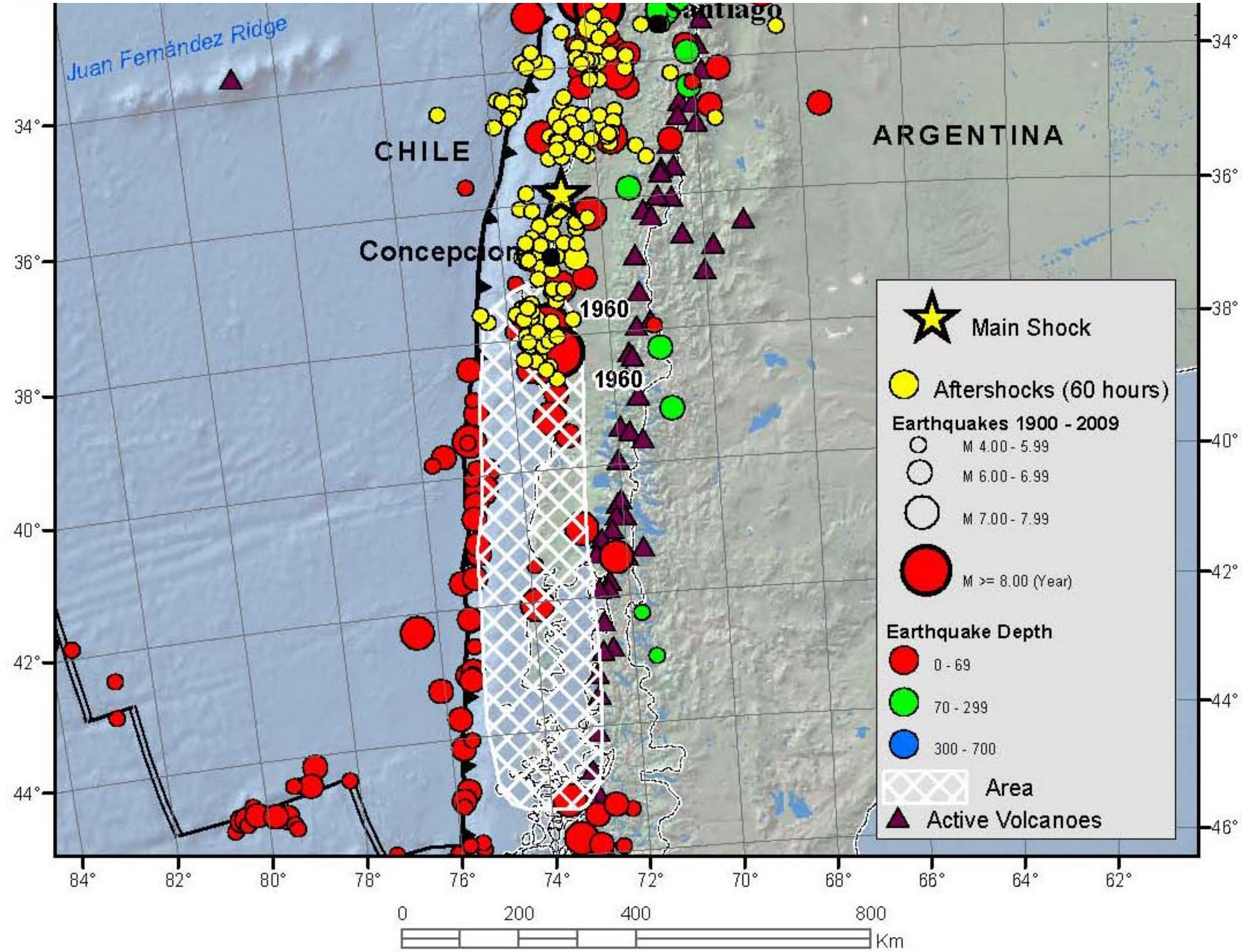
Epicentres, aftershocks and fault surface projection (I)

(Wald et al 2010)



Seismology of Chile EQ

Epicentres, aftershocks and fault surface projection (II)

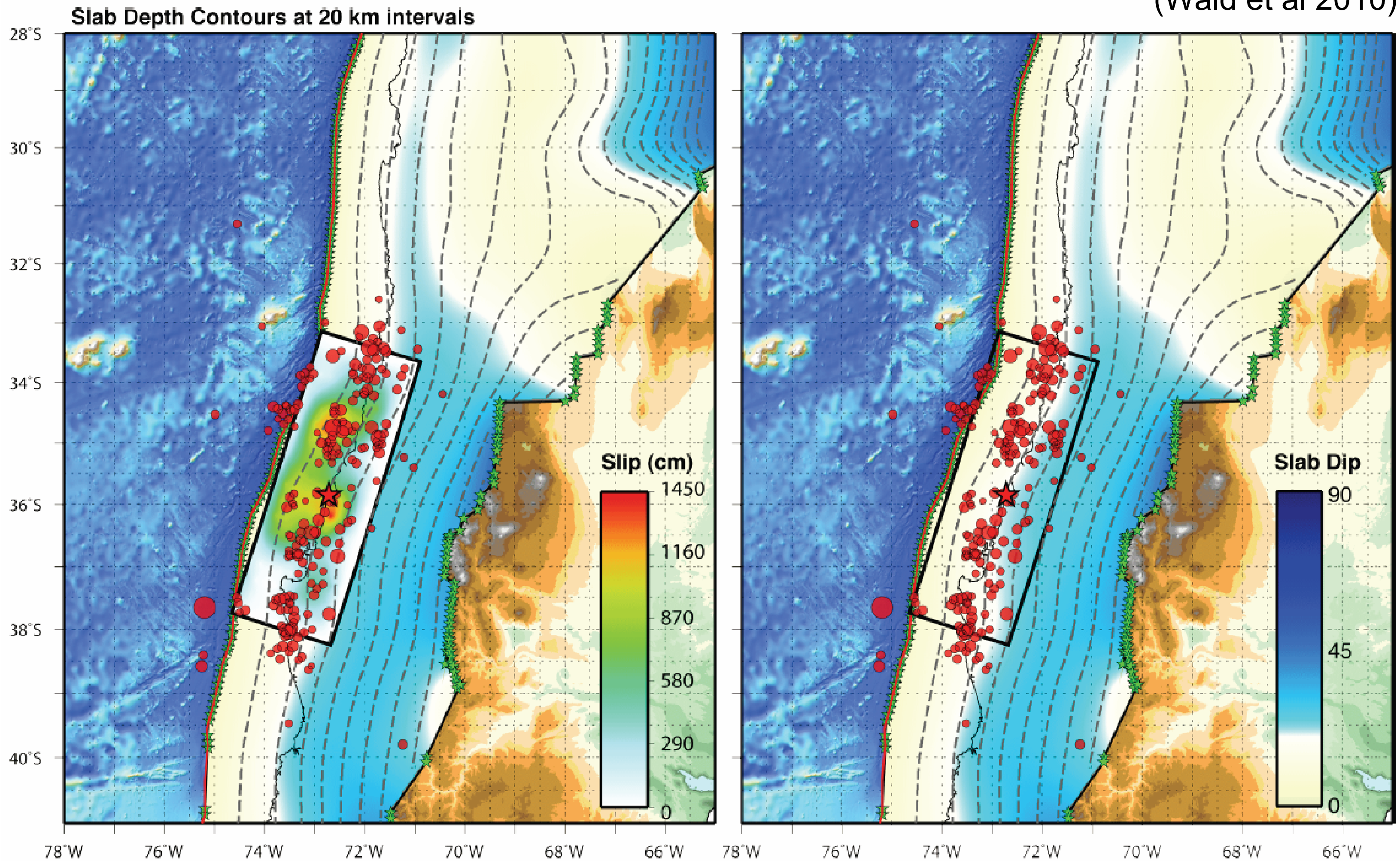


(Wald et al 2010)

Seismology of Chile EQ

Epicentres and rupture surface projection

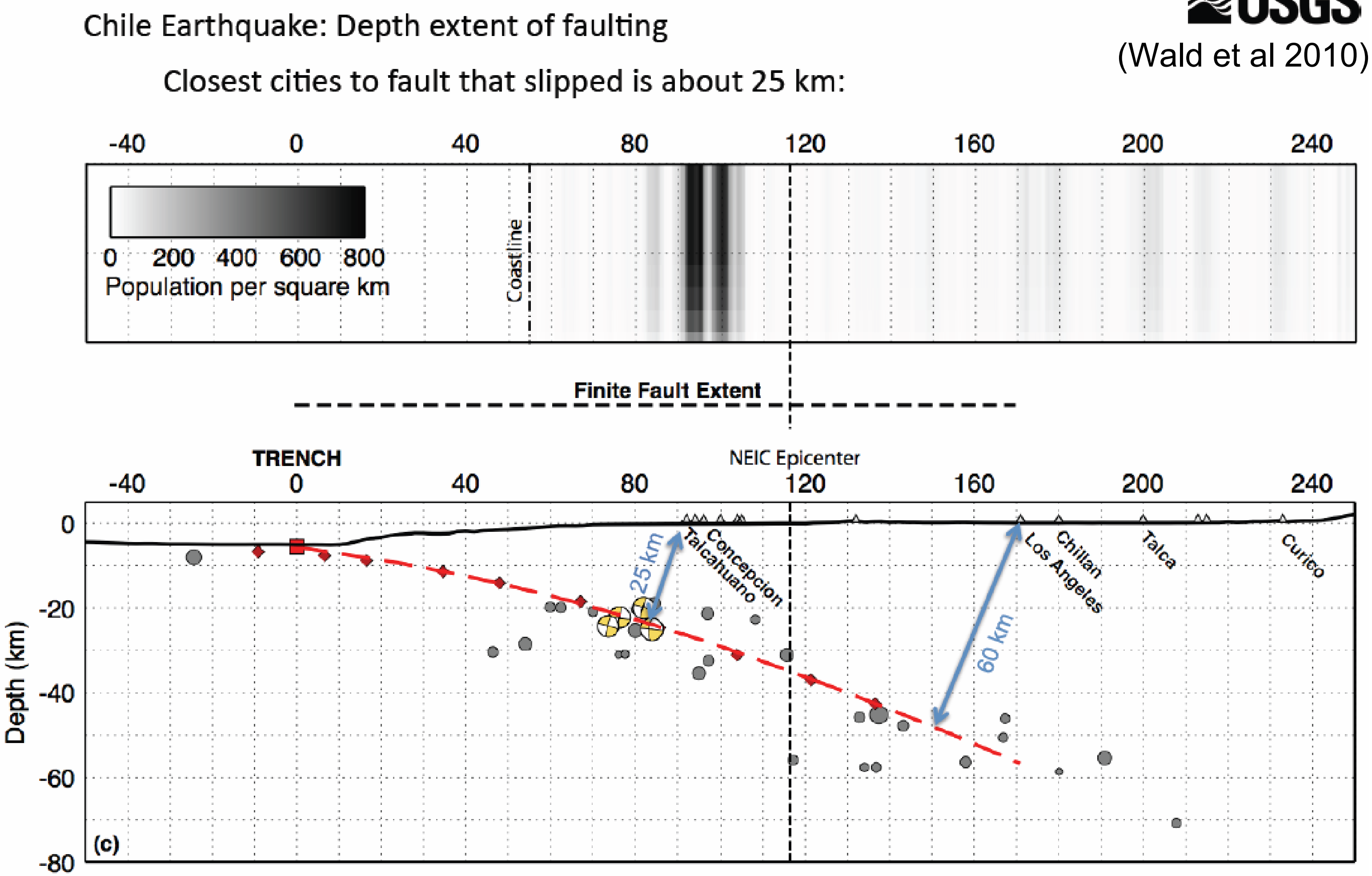
(Wald et al 2010)



Seismology of Chile EQ

Epicentres and rupture surface projection

(Wald et al 2010)



Maximum accelerations (uncorrected)

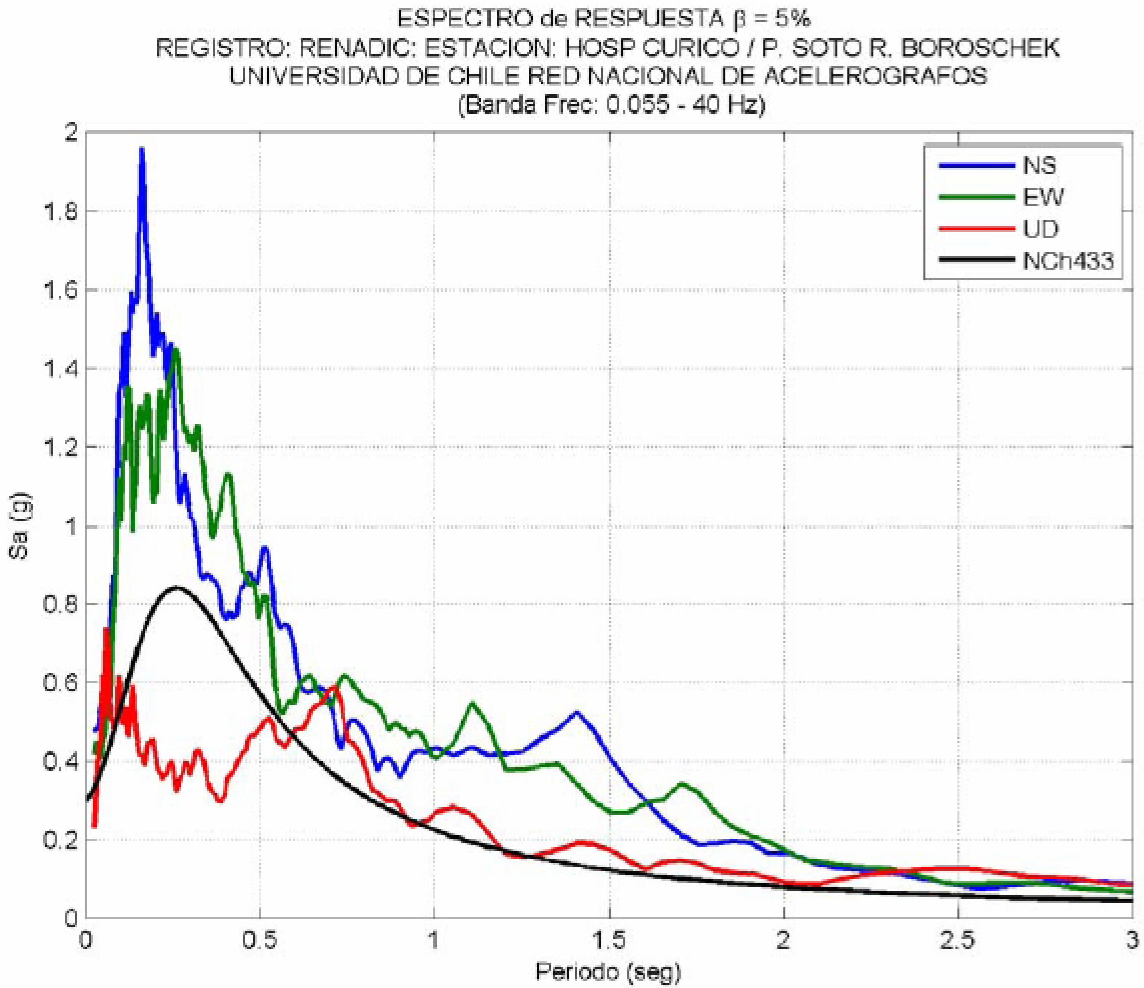
Tabla 1. VALORES EXTREMOS (sin corregir)

Estación	Aceleración Máxima Horizontal (g)	Aceleración Máxima Vertical (g)	OBSERVACION
Universidad de Chile Depto Ing. Civil (Interior Edificio) Santiago	0.17	0.14	
Estación Metro Mirador Santiago	0.24	0.13	
CRS MAIPU RM	0.56	0.24	QDR. Clasificación Suelo Pendiente. Interacción Instrumento-Estructura poco probable. Pendiente Suelo-Estructura
Hosp. Tisne RM	0.30	0.28	QDR. Clasificación Suelo Pendiente
Hosp. Sotero de Río RM	0.27	0.13	QDR. Clasificación Suelo Pendiente
Hosp. Curico	0.47	0.20	QDR
Hosp. Valdivia	0.14	0.05	QDR
Viña del Mar (Marga Marga)	0.35	0.26	
Viña del Mar (Centro)	0.33	0.19	QDR

renadic

Boroschek et al. (2010)

Station Hospital Curico, response spectra – comparison with NCh 433



renadic

Boroschek et al. (2010)

Chile Earthquake

Damages

Damages of Chile EQ

Tsunami

Talcahuano

Damages of Chile EQ

Tsunami

Constitucion. Reinforced concrete building survived the tsunami

Damages of Chile EQ

Viaducts

Ruta 5, Paso Inferior de la Merced. Lateral displacement

Damages of Chile EQ

Viaducts

Ruta 5, Paso Inferior de la Merced. Loss of support

Damages of Chile EQ

Bridges

Concepcion, Puente Viejo

Damages of Chile EQ

Bridges

Concepcion, Puente Llacolen

Damages of Chile EQ

Lateral spreading and subsidence

Talcahuano

Damages of Chile EQ

Reinforced concrete buildings

Considering only buildings erected between 1985 and 2009:

Collapsed:	4	(approximately)
To be demolished:	50	(estimation)
Having more than 3 stories	9.974	
Having more than 9 stories	1.939	

Failures in bldgs with more than 3 stories: 0.5 %
Failures in bldgs with more than 9 stories: 2.8 %

(Moehle 2010)

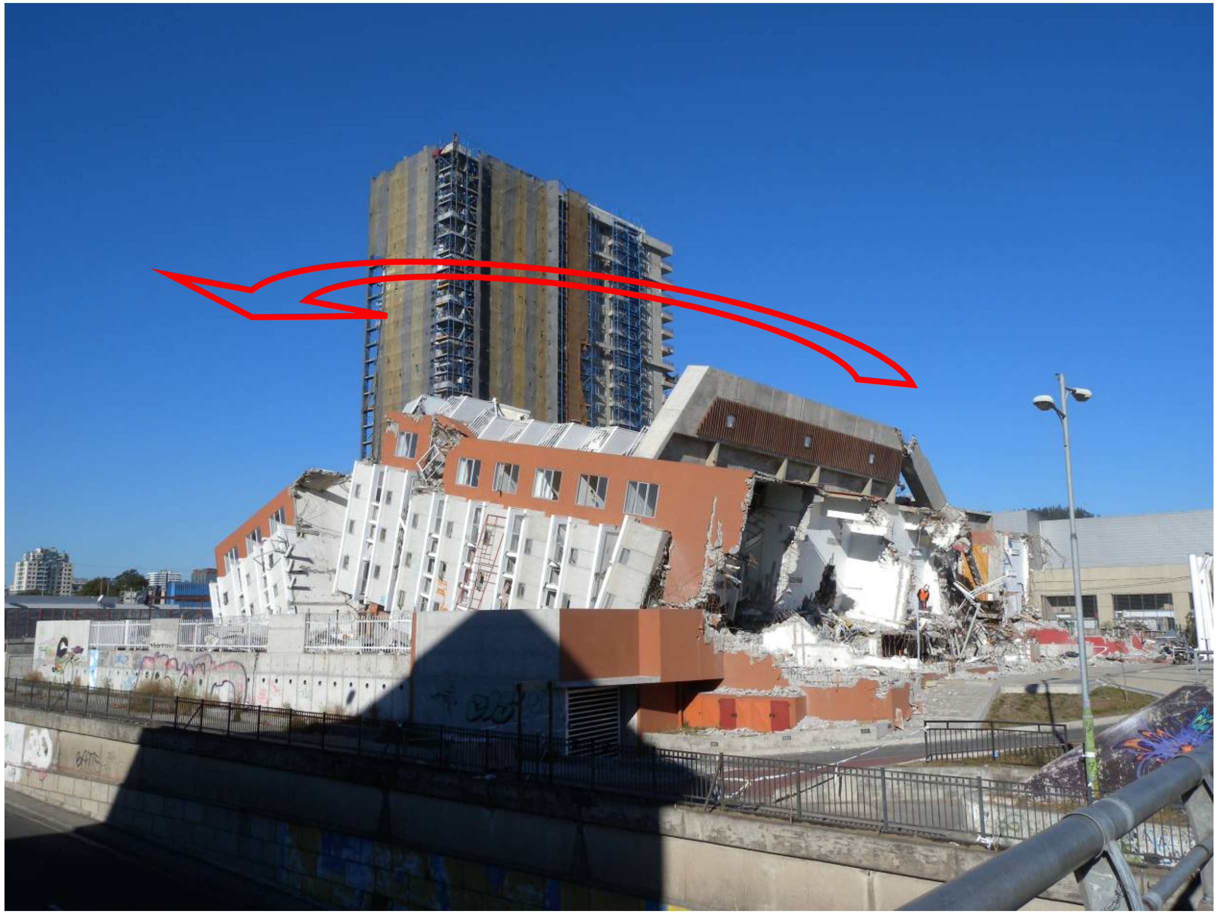
Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Alto Rio. 13 stories above grade. Before EQ.

Damages of Chile EQ

Reinforced concrete buildings



Concepcion, Alto Rio. 8 casualties. Total collapse and overturning.

Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Centro Mayor.

Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Centro Mayor.

Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Centro Mayor.

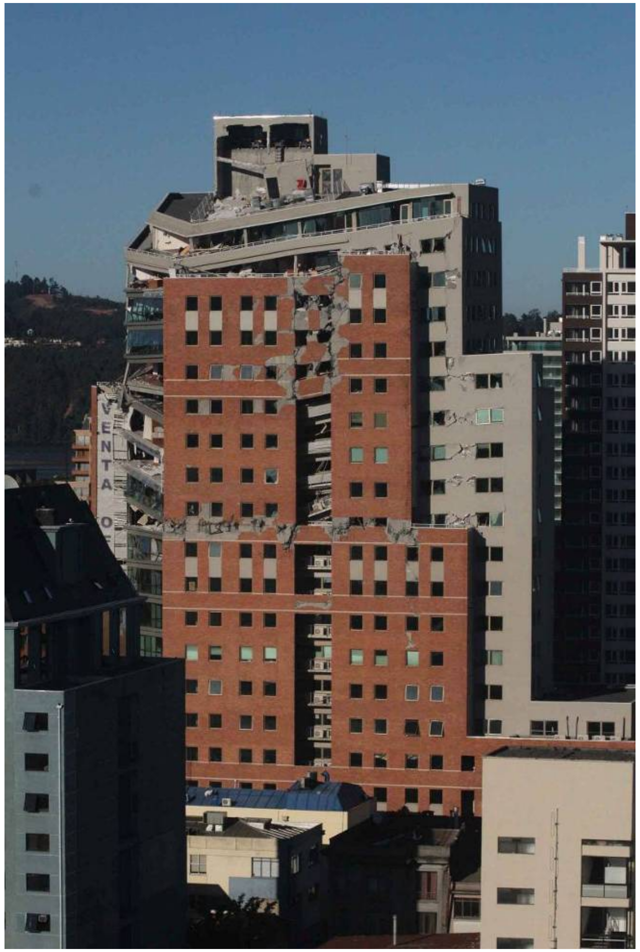
Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Centro Mayor.

Damages of Chile EQ

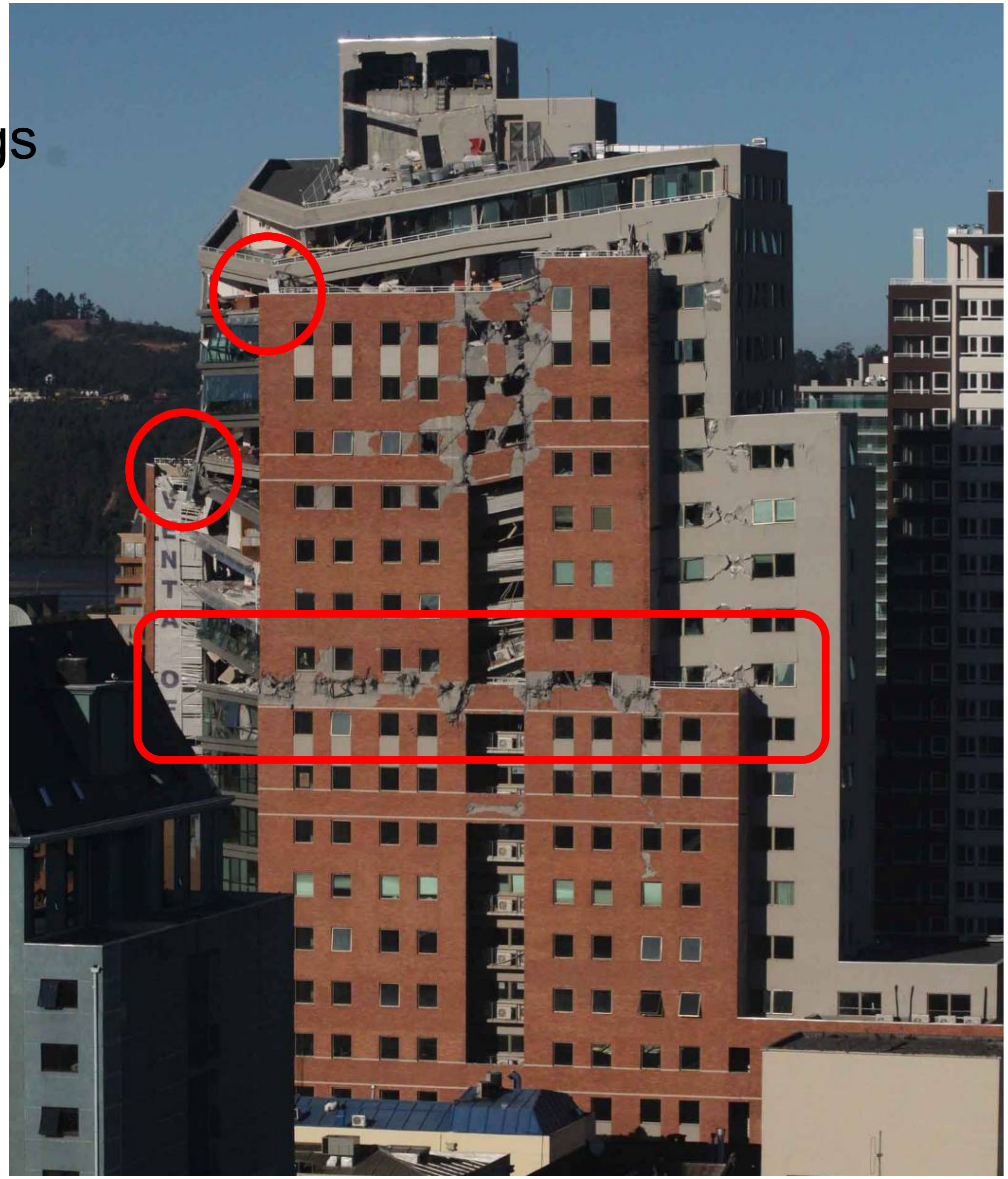
Reinforced concrete buildings



Concepcion, Torre O'Higgins. Completed in 2008.

Damages of Chile EQ

Reinforced concrete buildings



Concepcion, Torre O'Higgins.
Dramatic failure above the 10th floor due vertical stiffness discontinuity

Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Torre O'Higgins

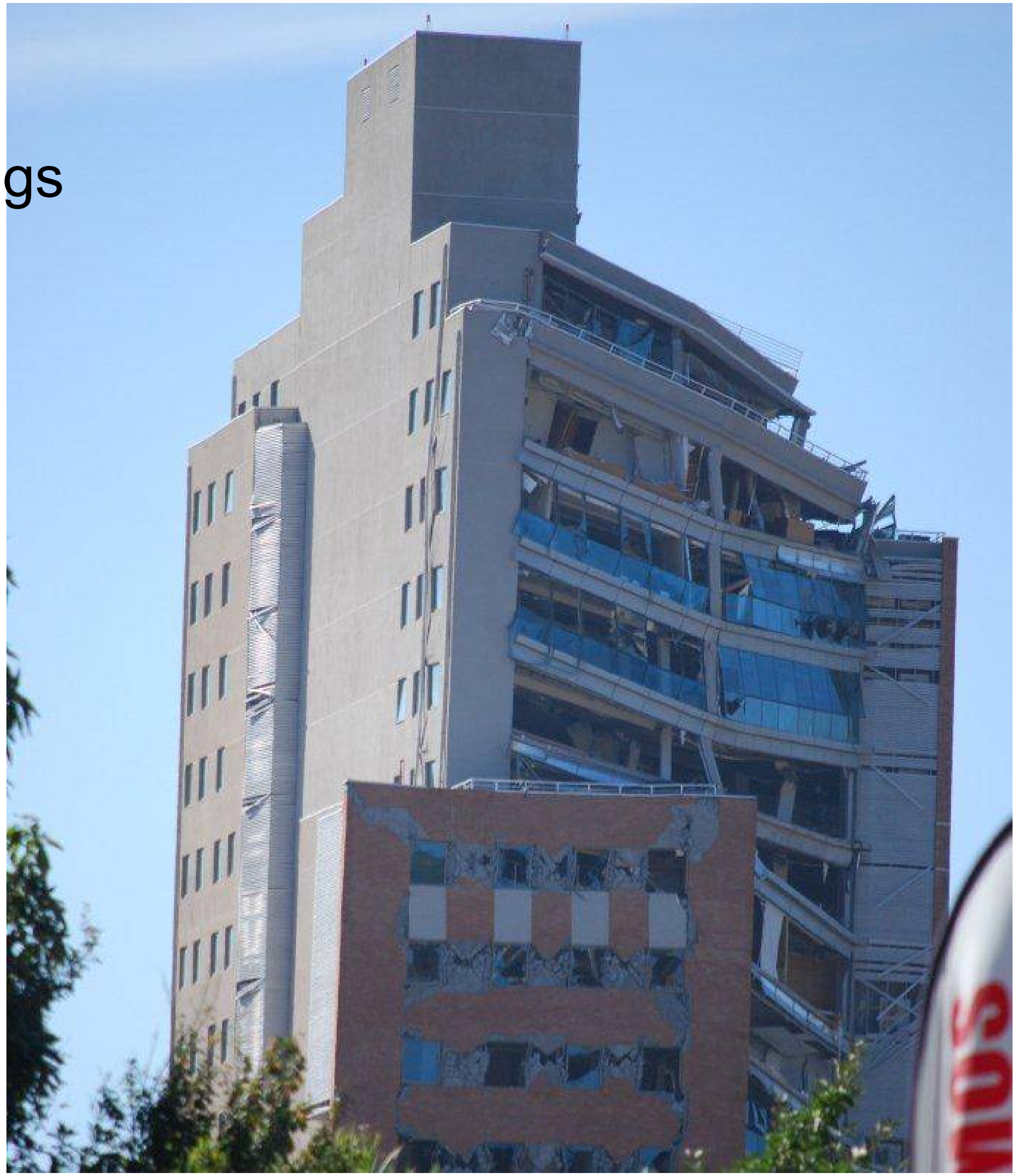
Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Torre O'Higgins

Damages of Chile EQ

Reinforced concrete buildings



Concepcion, Torre O'Higgins

Damages of Chile EQ

Reinforced concrete buildings

Concepcion, Torre O'Higgins (right)

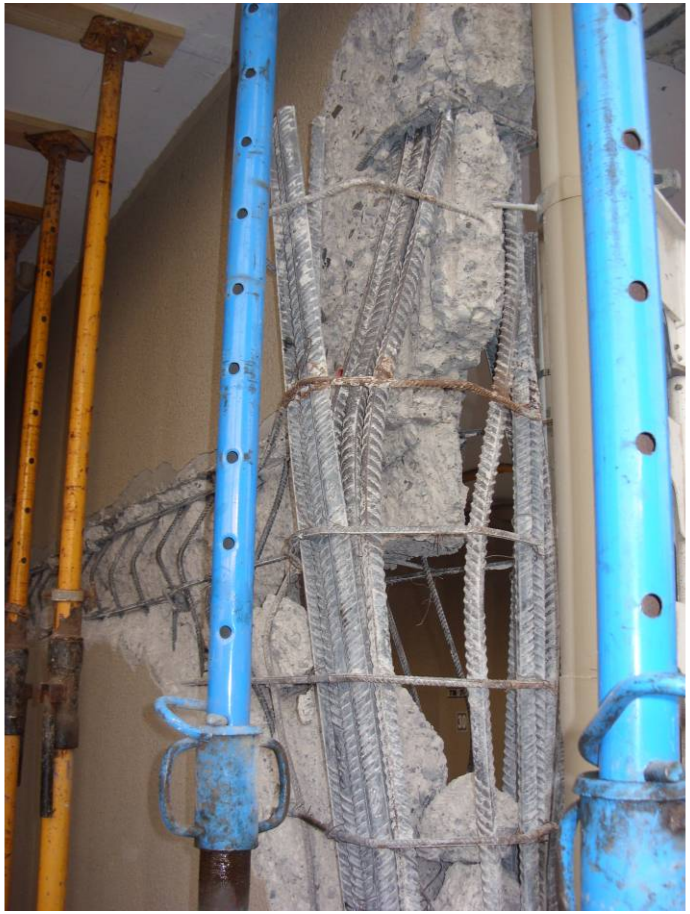
Damages of Chile EQ

Reinforced concrete buildings

Talca, Hospital Viejo, to be demolished

Damages of Chile EQ

Reinforced concrete buildings



Santiago, Av. Hipodromo

Damages of Chile EQ

Reinforced concrete buildings

Santiago, Edificio Emerald

Damages of Chile EQ

Reinforced concrete buildings

Santiago, Edificio Emerald.
Severe damage in the basement's shear walls.

Damages of Chile EQ

Reinforced concrete buildings

Santiago, Maipú, Don Luis

Damages of Chile EQ

Reinforced concrete buildings

Santiago, Maipú, Don Tristán

Damages of Chile EQ - Masonry buildings

Masonry buildings (Astroza 2010)

Adobe (unfired bricks) buildings have shown a very poor performance, characterised by extensive collapses.
This is the case especially in Regions VI and VII (O'Higgings and Maule). Chilean investigators professor Maximiliano Astroza and Mister Francisco Cabezas, Universidad de Chile, use the term *adobicide*.
A large number of such buildings are currently unsafe to use, pending a demolition order. Therefore, the demand for residential units has markedly increased. This phenomenon has been worsened by the coming on of the winter.
Chilean academics are inclined **to forbid adobe constructions.**

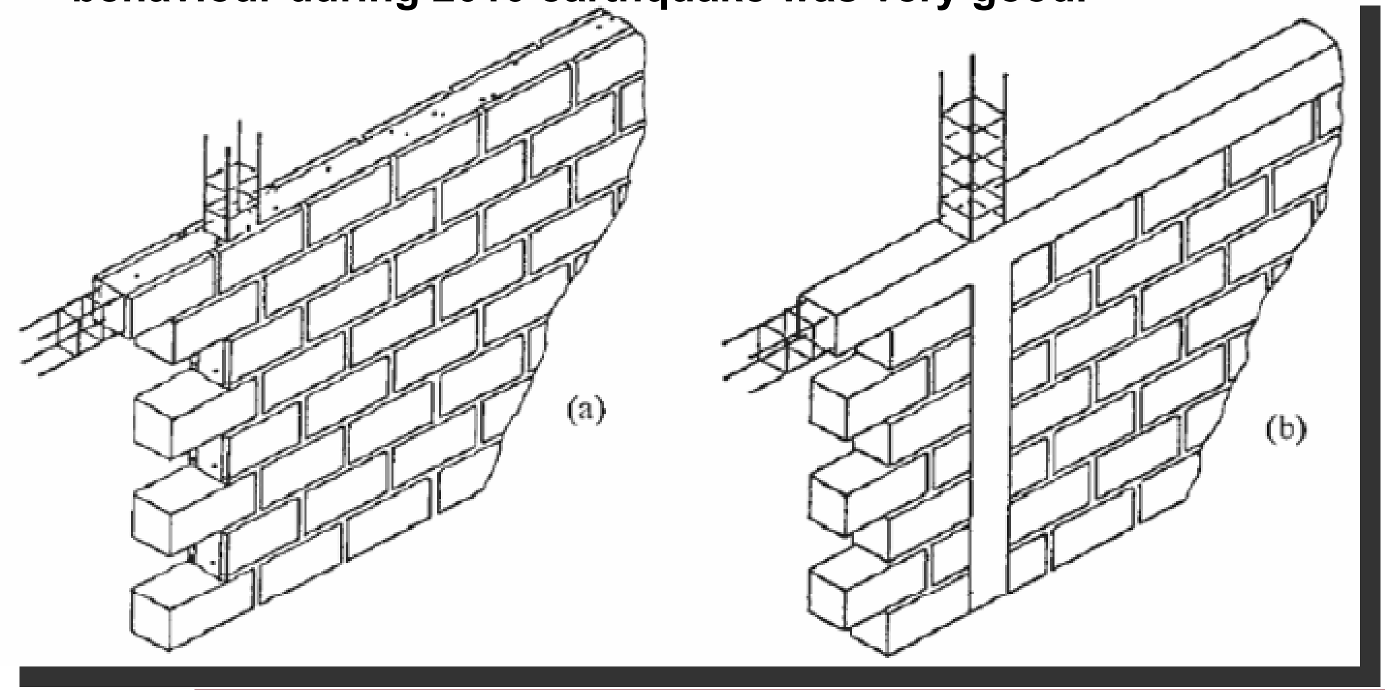
Damages of Chile EQ - Masonry buildings

Masonry buildings (Astroza 2010)

- The behaviour of **confined masonry** buildings has been usually **very satisfactory**, even when they have been built directly by the owners.
- The percentage of severely damaged masonry edifices has been low. Moreover, such damages has been observed mainly in buildings that have been tampered with (removed walls, cut vertical and/or horizontal RC beams) or where site effects have been very marked (building on or at the top of steep slopes).
- These observations confirm what already highlighted by all severe earthquakes since the Chillan 1939 event.
- **Therefore the use of confined masonry shall be encouraged for buildings up to 4 stories**.

Confined masonry

In *confined masonry* RC members are adherent to masonry walls, which are vertical load bearing.
This structural type is not considered in Italian Codes, while it is included in EC8 regulation.
The seismic behaviour of confined masonry buildings during several destructive earthquakes has been very satisfactory (Decanini e D'Amore 1993, Decanini 2005).
In Chile confined masonry buildings of one ore two storey are usual, their behaviour during 2010 earthquake was very good.



(Tomazevic 1999)

Damages of Chile EQ - Masonry buildings

Masonry buildings, comparison between different kind of masonry

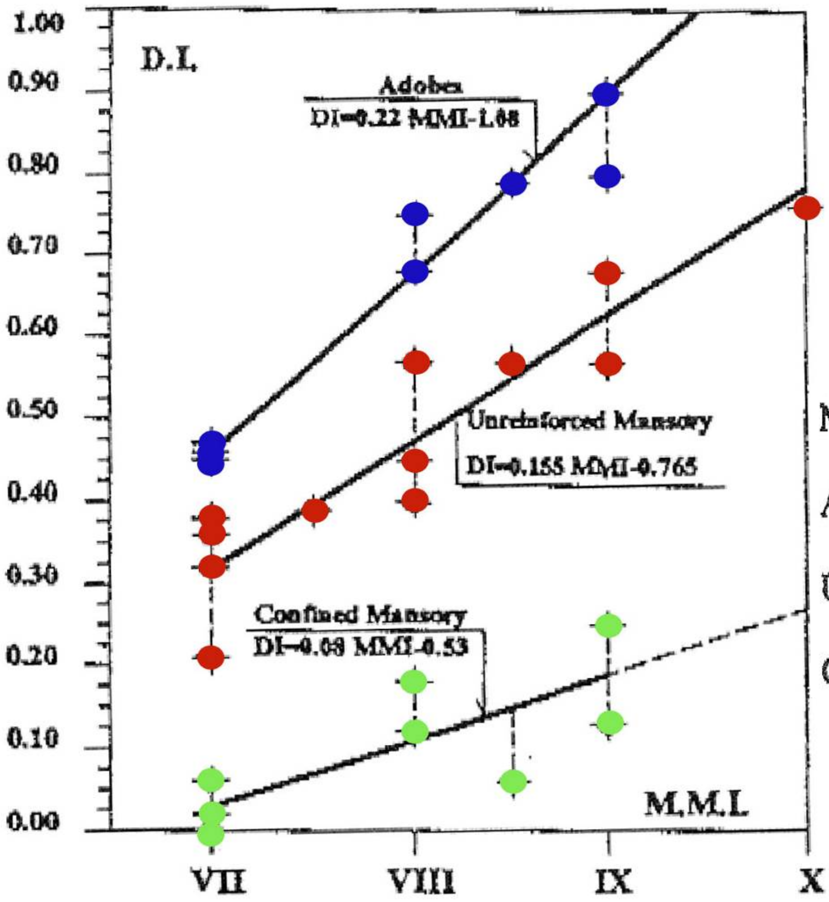


Figure-1. Expressions relating the damage index (D.I) with the MMI

Masonry type	Damage index	MMI range
Adobes	$D.I. = 0.22 \times MMI - 1.08$	VII to IX
Unreinforced	$D.I. = 0.155 \times MMI - 0.765$	VII to X
Confined	$D.I. = 0.08 \times MMI - 0.53$	VII to X

Decanini & D'Amore (1992)

Confined masonry

Confined masonry

Damage to masonry buildings

Talca, Chile – URM/Adobes

Damage to adobe buildings

Talca, Chile – Adobes

Damage to unreinforced masonry buildings

Concepcion, Chile – URM

Damage to masonry buildings

Vina del Mar, Chile – URM, overturning of façade in upper storey

Damage to masonry buildings

Talca, Chile – Adobe

Damages of Chile EQ - Churches

- **The performance of masonry churches has been usually poorer than that of residential buildings, due to higher vertical and horizontal slenderness**.
- This is true especially for those edifices built by European architects in the second half of 19th century.
- However, their response need a specific study.

Basílica El Salvador

Santiago, Huérfanos esquina S.O de Almirante Barroso

Neogotic church (1870 -1872). Severely damaged (partial collapses and shoring) during 1985 EQ. Only a chapel was used up to 1990. Thereafter closed. Dimensions: 98 x 37 m, internal height 30 m (capable of 5000 persons).

Basílica El Salvador

Santiago, Huérfanos esquina S.O de Almirante Barroso

Brick masonry. Partial collapse of the left and right walls in the first bay; collapse of the left wall in the third bay; collapse of the second right pillar; third and fourth pillars reinforced concrete after the 1985 EQ; collapse of a large part of the timber false vault.

Basílica El Salvador

Santiago, Huérfanos esquina S.O de Almirante Barroso

Basílica El Salvador

Santiago, Huérfanos esquina S.O de Almirante Barroso

Iglesia de Santa Ana

Santiago, Catedral con San Martin

Historical tie rods.

Basílica de Los Sacramentinos

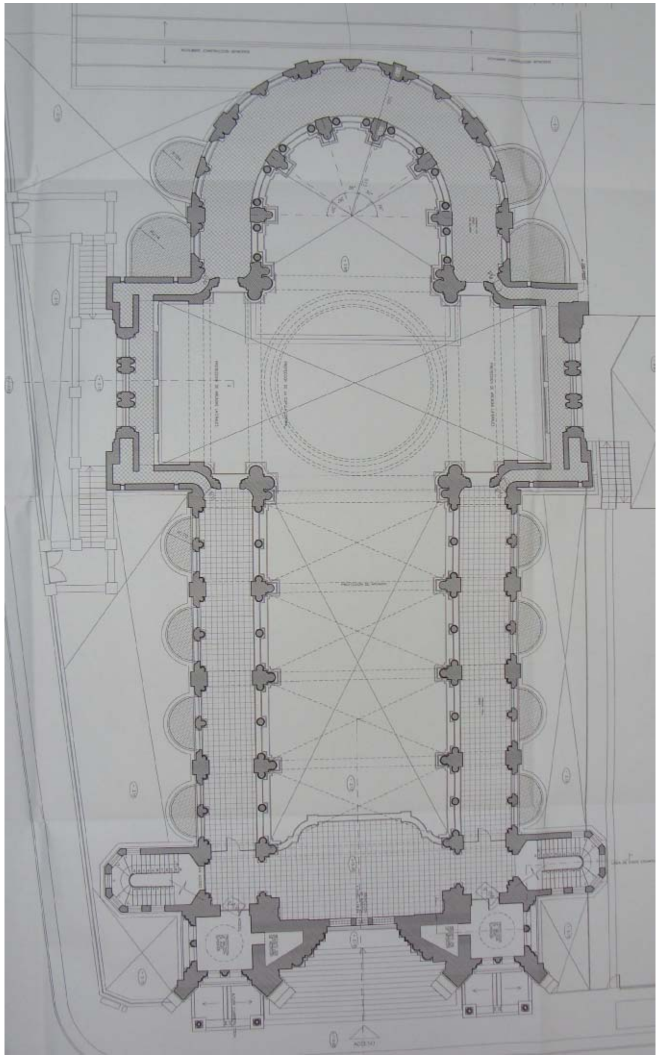
Santiago, Santa Isabel con Arturo Prat

Two superimposed churches. Central nave: 10.93x21.65 m; lateral: 3.60x.7.16 m. Entrance hall – altar length: 44.02 m. Dome interior height: 38.82 m. Bottom church interior height: 5.90 m. Ossuary adjacent to façade.
National votive church: foundation stone laid in 1910, on the independence centennial.

Basílica de Los Sacramentinos

Santiago, Santa Isabel con Arturo Prat

Design drawing dating 1923, by architect Ricardo Larrain Bravo. He spent several months in France after his graduation.
The church is inspired to Sacre-Coeur, Paris. The 1923 design was much higher.



Basílica de Los Sacramentinos

Santiago, Santa Isabel con Arturo Prat

The church is completely built of reinforced concrete. It was one among the first in Chile. In the same era in Santiago other churches have been built using different techniques.
Cold joints and gravel pockets are clearly visible.

Basílica de Los Sacramentinos

Santiago, Santa Isabel con Arturo Prat

Damages to drum windows and overturning of the crosses on top of the façade lateral pinnacles (the south one due to the March 11th, aftershock).
Torsion of the bell gable of the right pinnacle.
Very limited cracks inside in the first bay of the central nave.
In 1985 damages to façade crosses and dome.

Iglesia del Convento de la Congregación de María (Dulce Nombre de María)

Santiago, Carmen 180 esq. Calle Curicó

Built 1856-1878; altars and sculptures came from Italy.
In 1985 statues and the timber parapet of the chancel collapsed.
The façade seems to have moved away from the naves. Damages in the sacristy.
Collapse of the Virgin statue in the façade.

Iglesia San Francisco

Curicò, España con Las Heras

Severe damages and
partial collapse.

Iglesia San Francisco

Curicò, España con Las Heras

Timber columns

Iglesia San Francisco

Curicò, España con Las Heras

Brick masonry walls,
timber false vault.
Severe damages

Santuario del Carmen

Curicò, San Martín con Carmen

Partial collapse of
adobe apse.

Acknowledgements

Professor Giuliano Panza, University of Trieste, for the continuous discussion of our ideas

Research group

Professor Domenico Liberatore

Associate Professor Fabrizio Mollaioli

Assistant Professor Laura Liberatore

Assistant Professor Luigi Sorrentino

Engineer Omar Al Shawa, PhD candidate

Architect Annachiara Bertino

Thank you very much

Advanced Conference on Seismic Risk Mitigation
and Sustainable Development
Trieste, May 13 2010

Some remarks on the earthquakes in L'Aquila, Haiti and Chile. Seismology and damages

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