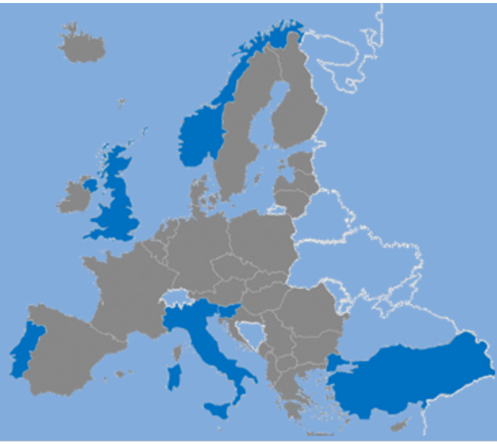
European Commission

Horizon 2020
European Union funding
for Research & Innovation

liquefACT



EARTHQUAKE INDUCED LIQUEFACTION RISK:
HOLISTIC ASSESSMENT AND MITIGATION

Wednesday 20th June 2018 - 11:30-13:00

ROOM: CR2 (building M2 - Thessaloniki Concert Hall/16ECEE Conference Venue)

Empirical damage and liquefaction fragility curves

Andrea Prota, Alessandro Flora, **Marco Di Ludovico**, Emilio Bilotta,
Anna Chiaradonna, Pietro Caputo

UNIVERSITY OF NAPOLI FEDERICO II

INTRODUCTION

• DATA COLLECTION ON LIQUEFACTION INDUCED DAMAGE

RegioneEmilia-Romagna
DIREZIONE GENERALE CURA DEL TERRITORIO E DELL' AMBIENTE

servizio geologico sismico e dei suoli

Agenzia regionale per la Ricostruzione Sisma 2012

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

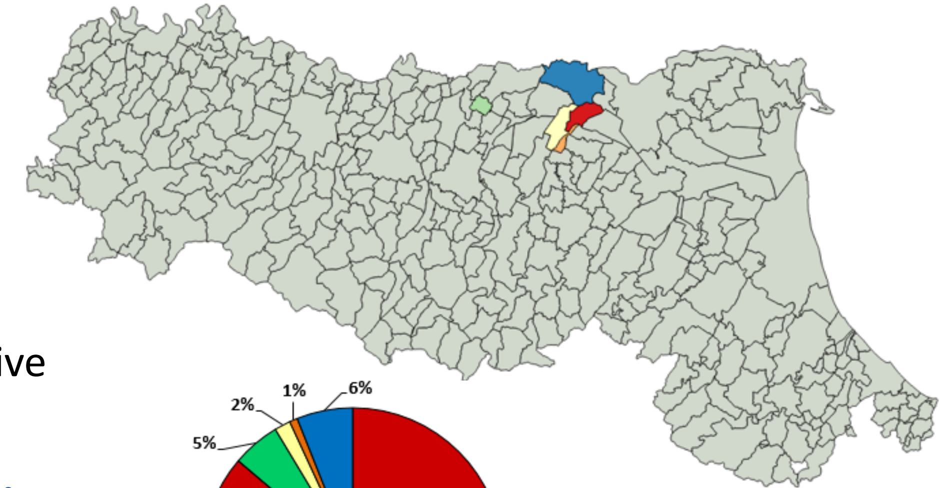
2017 - Scientific agreement

DATA COLLECTION ON DAMAGED BUILDINGS

(Municipality of Mirabello, San Carlo (Sant'Agostino), Bondeno, Cavezzo, Cento, and Pieve di Cento)

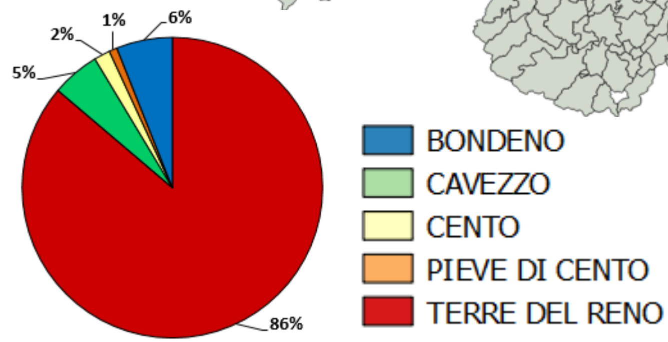
DATA BY USABILITY SURVEY FORMS AND PRACTITIONERS' REPORT

(Level and extent of damage on structural and non structural memebers, photo reports of damage, destructive and non destructive tests on materials and ground, etc.)



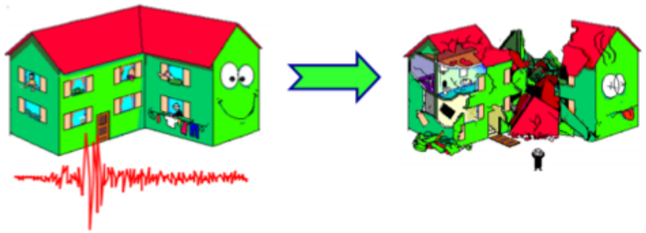
Liquefied Ground Buildings (LG): 116 masonry buildings
with public grant for liquefaction induced damage

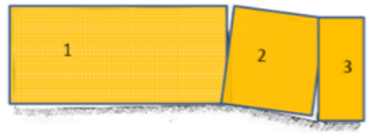
Unliquefied Ground Buildings (UG): 993 masonry buildings
with public grant for seismic inertial forces induced damage



OBJECTIVES

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE:
Can we clearly distinguish liquefaction induced damage from seismic one?



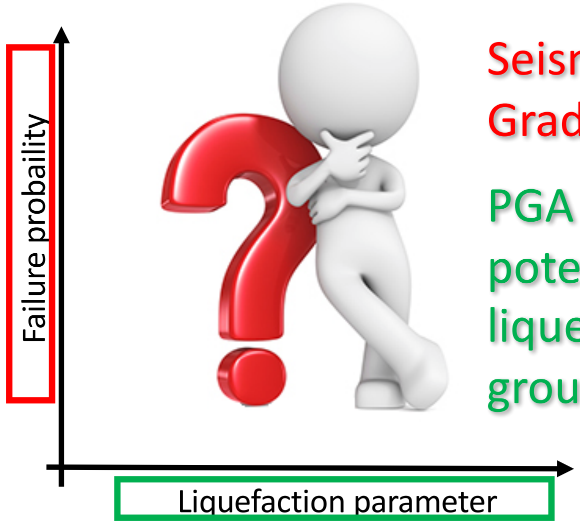


Level - extension / Structural component / Pre-existing damage	DAMAGE									
	D4-D5 Very heavy			D2-D3 Medium-severe			D1 Slight			Null
	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
	A	B	C	D	E	F	G	H	I	L
1 Vertical structures	□	□	□	□	□	□	□	□	□	○
2 Floors	□	□	□	□	□	□	□	□	□	○
3 Stairs	□	□	□	□	□	□	□	□	□	○
4 Roof	□	□	□	□	□	□	□	□	□	○
5 Infills-partitions	□	□	□	□	□	□	□	□	□	○
6 Pre-existing damage	□	□	□	□	□	□	□	□	□	○

The AeDES form (Baggio et al. 2008)

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE:
How much the global building damage is affected by liquefaction?

III. LIQUEFACTION FRAGILITY CURVES:
Which parameters should be used and what is the fragility curve trend?

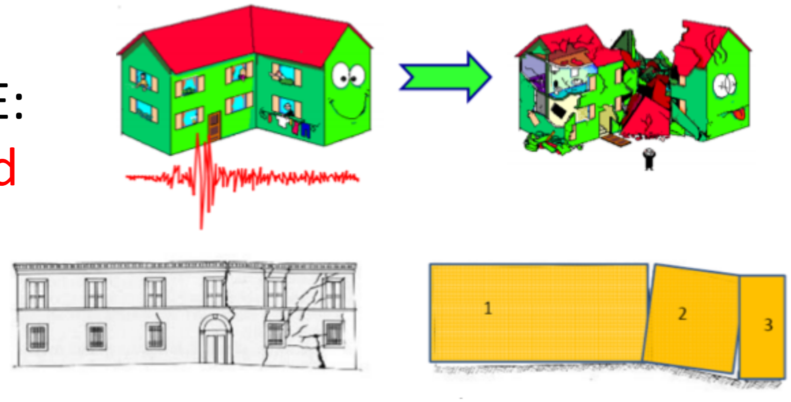


Seismic Damage Grades?

PGA and relevant potential liquefaction of ground?

OBJECTIVES

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE:
Can we clearly distinguish liquefaction induced damage from seismic one?



DAMAGE ANALYSIS – CRACK PATTERN

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

Summary table report

FOR EACH BUILDING:

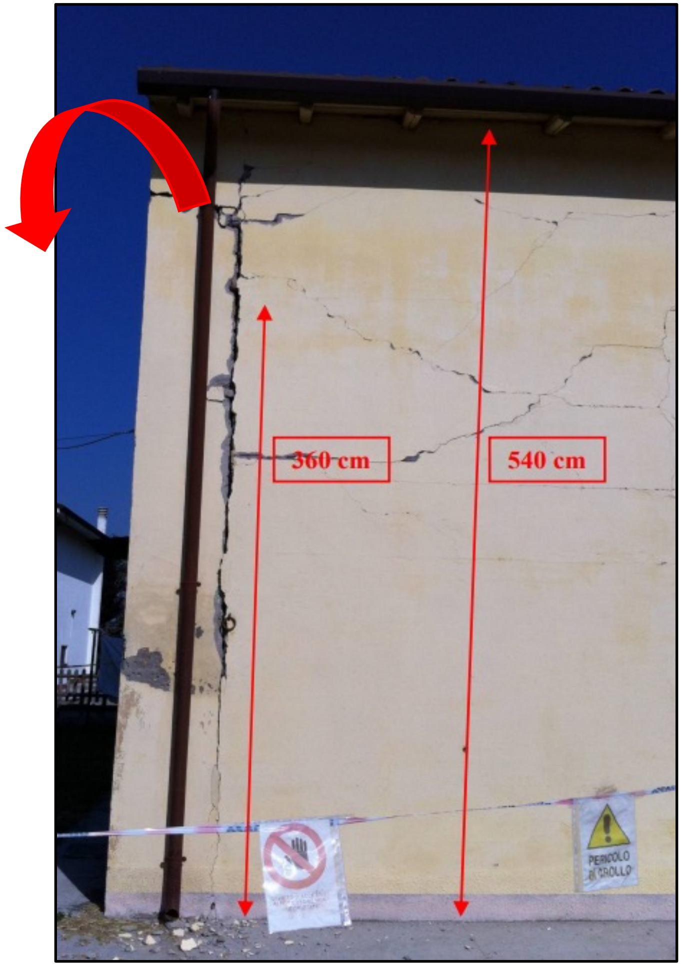
- Plan, elevation and section view;
- Damage photos;
- Damage localization;
- Analysis of damage

DAMAGE ANALYSIS – CRACK PATTERN

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

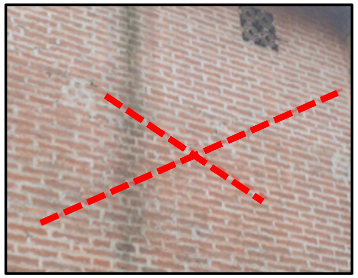
Damage - Seismic Inertial actions

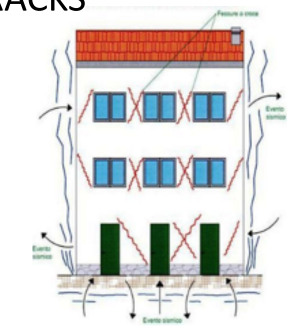
WALL SIMPLE OVERTUNING



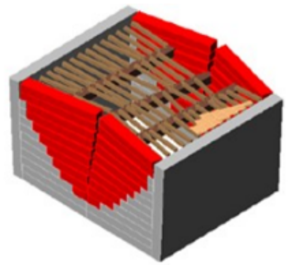
ROOF OVERTURNING

DIAGONAL CRACKS





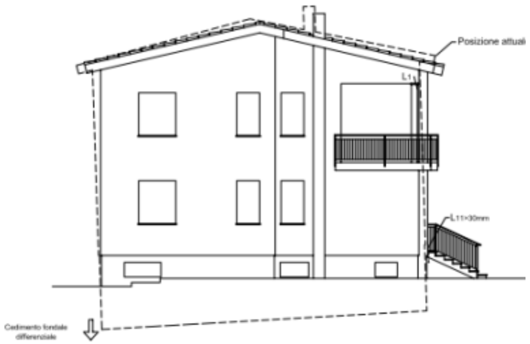
FLOOR WALL CONNECTION



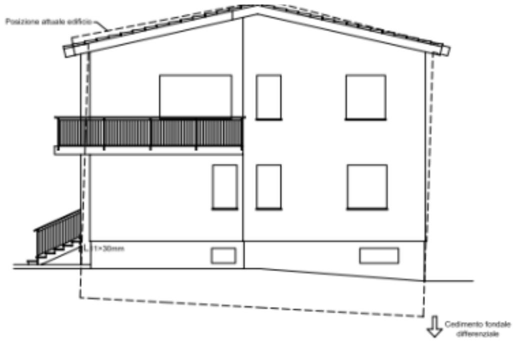
DAMAGE ANALYSIS – CRACK PATTERN

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

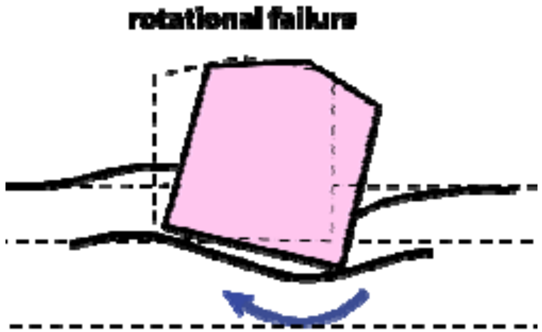
Damage - Liquefaction



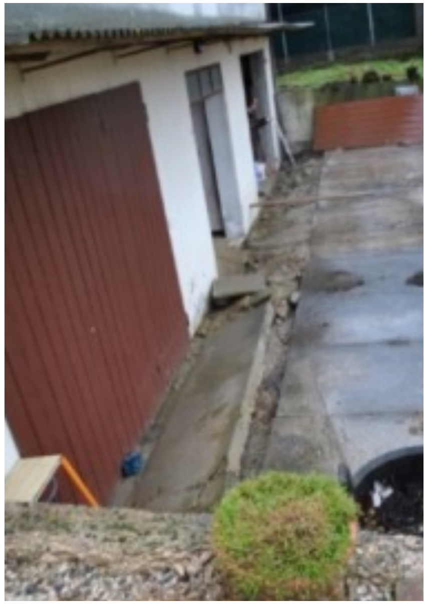
Prospetto Ovest



Prospetto Est



SETTLEMENTS- RIGID ROTATION OF BUILDING

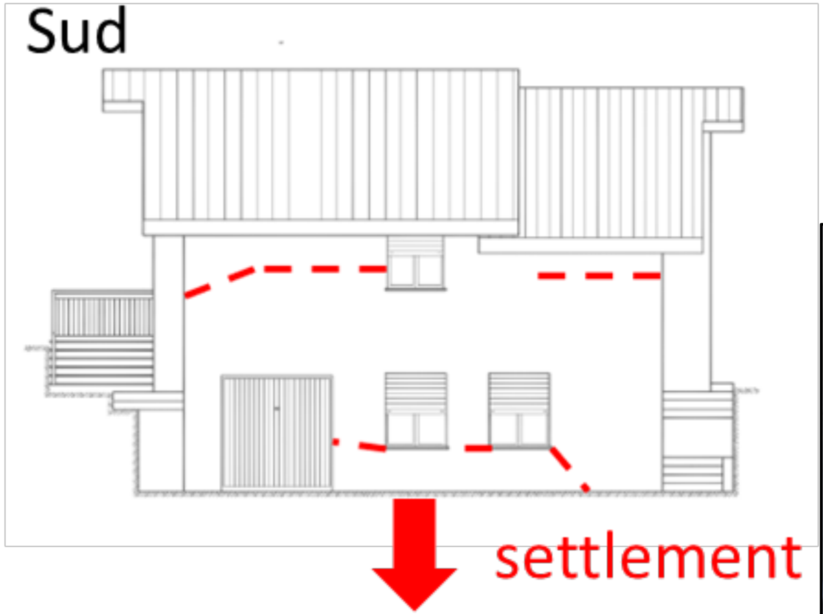


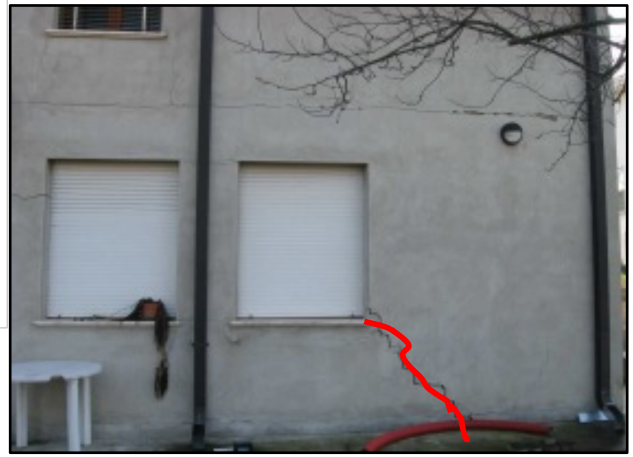
Damage Analysis – Crack Pattern

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

Damage - Liquefaction

LOCALIZED SETTLEMENTS

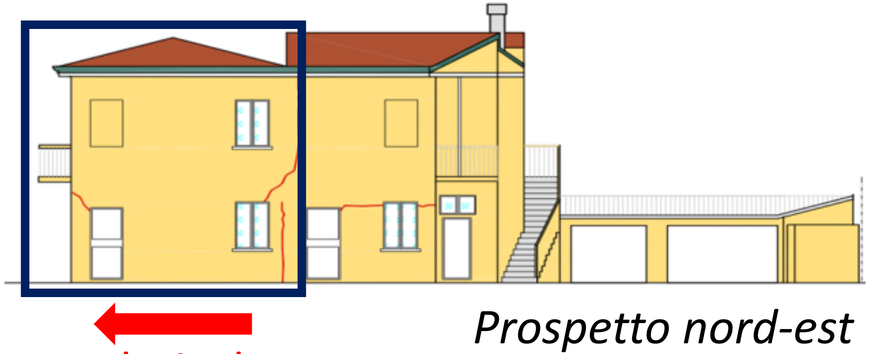




DAMAGE ANALYSIS – CRACK PATTERN

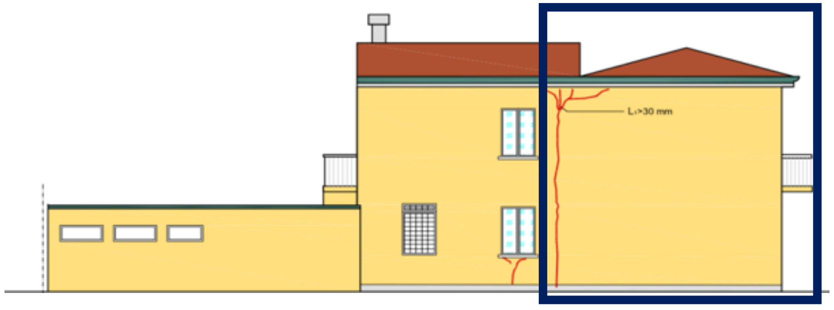
I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

Damage - Liquefaction



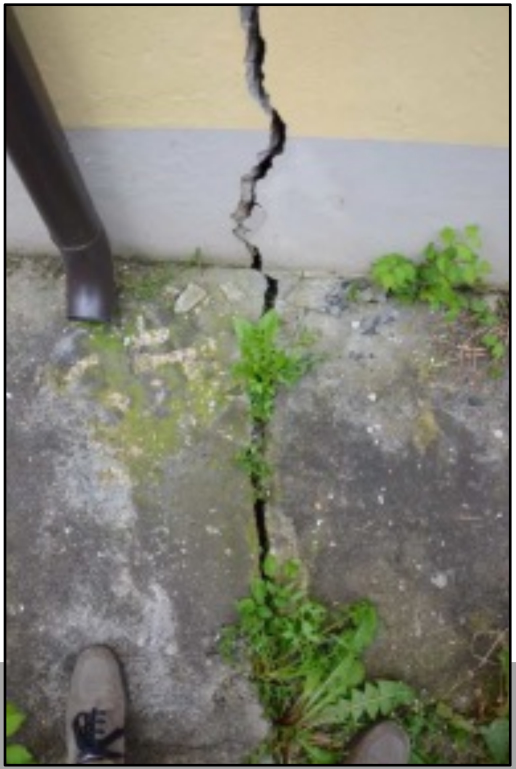
Lateral Displacement

Prospetto nord-est



Prospetto sud

Lateral Displacement



DAMAGE ANALYSIS – CRACK PATTERN

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

Damage - Liquefaction

settlments

LOCALIZED SETTLEMENTS

DAMAGE ANALYSIS – CRACK PATTERN

I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

Damage – Liquef. + Inertial forces

PROSPETTO SUD

...in several cases both typical damage induced by inertial forces and liquefaction (settlment) is detected on buildings
...the liquefaction is a «filter» to seismic actions on superstructure but it can be not immediate

DAMAGE ANALYSIS – CRACK PATTERN

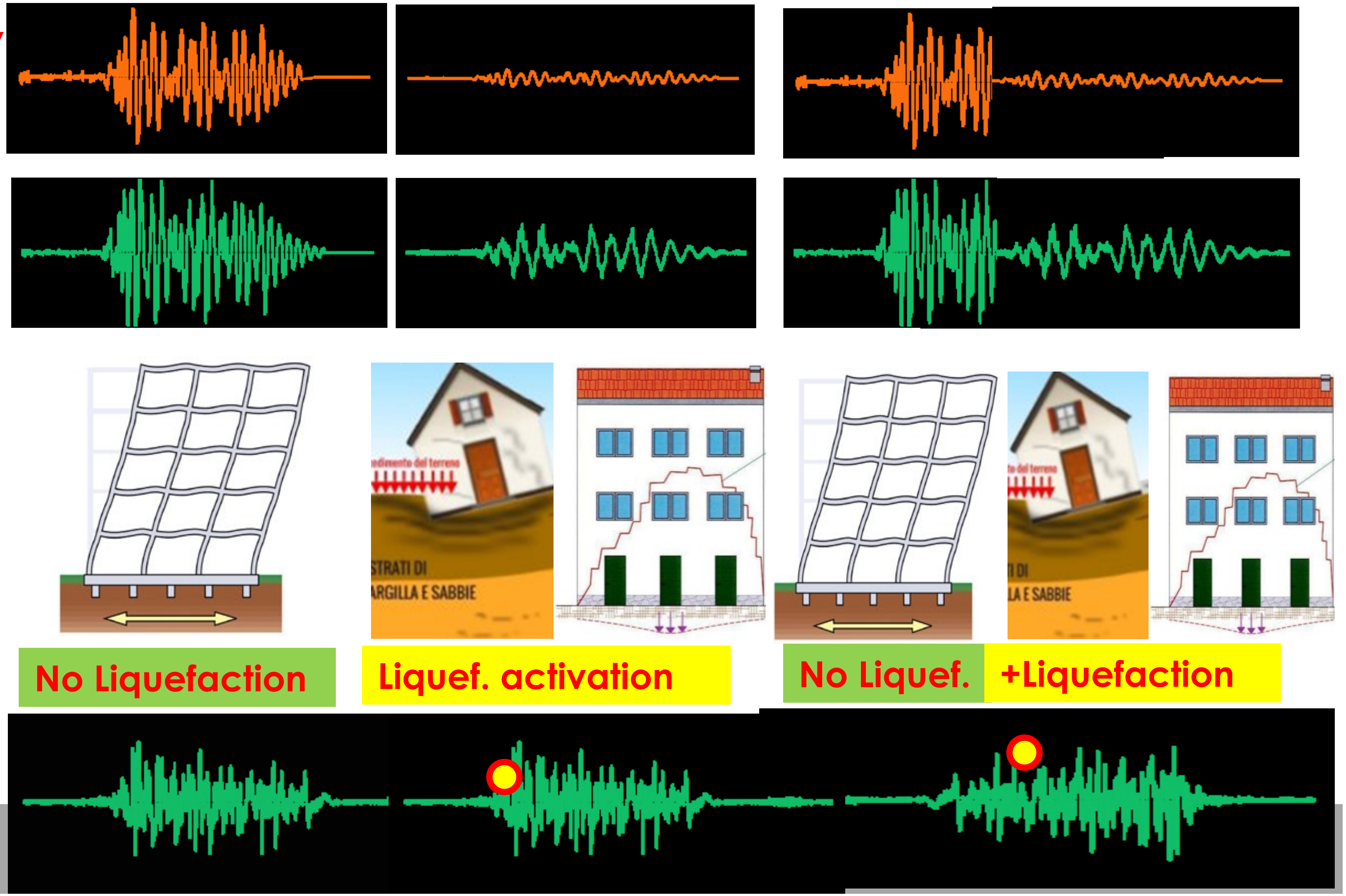
I. ANALYSIS OF LIQUEFCTION INDUCED DAMAGE

Damage – Liquef. + Inertial forces

Interstorey Drift

Structural response (accerel.)

Acceler. Input



OBJECTIVES

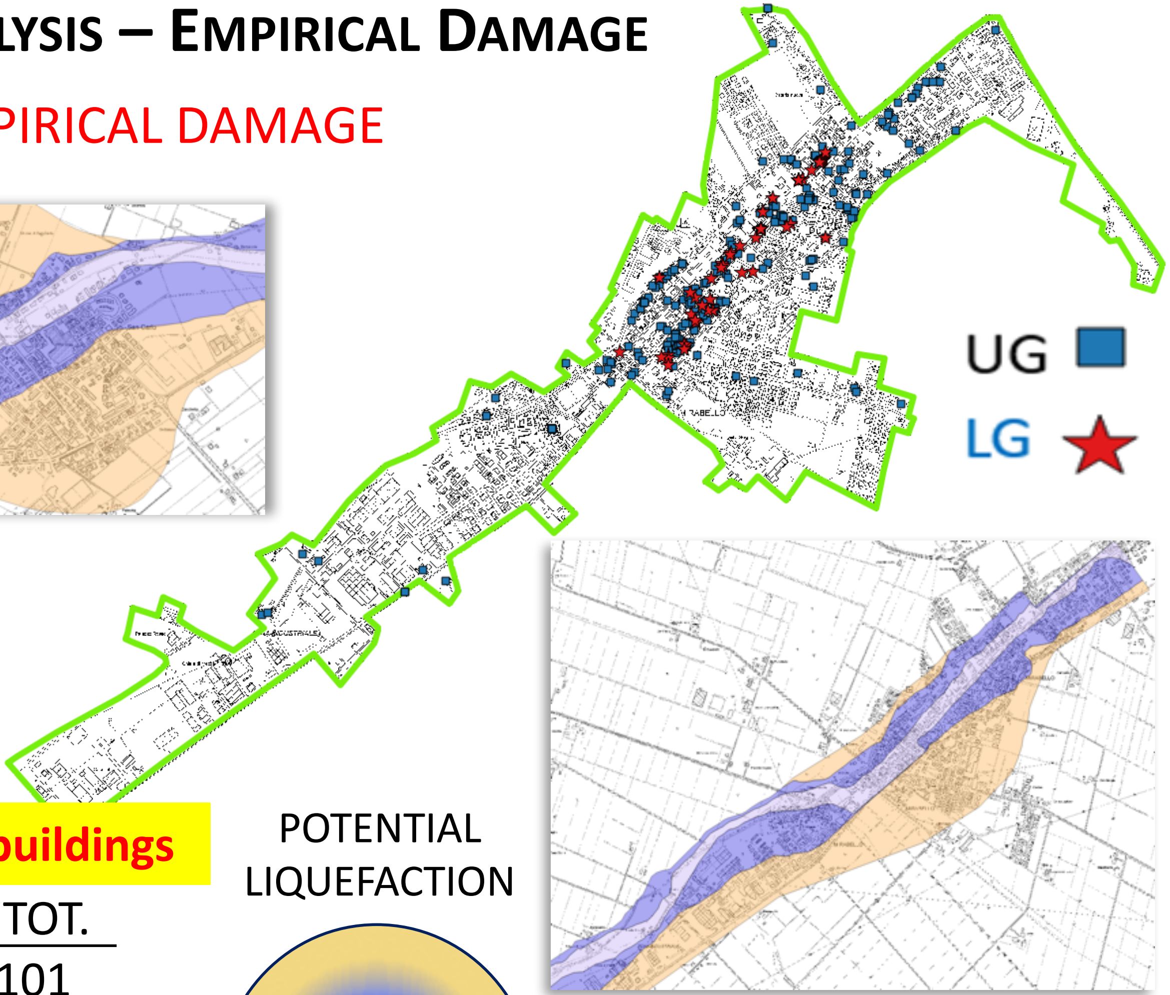
Level - extension / Structural component / Pre-existing damage		DAMAGE									
		D4-D5 Very heavy			D2-D3 Medium-severe			D1 Slight			Null
		> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
		A	B	C	D	E	F	G	H	I	L
1	Vertical structures	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
2	Floors	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
3	Stairs	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
4	Roof	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
5	Infills-partitions	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
6	Pre-existing damage	☐	☐	☐	☐	☐	☐	☐	☐	☐	○

The AeDES form (Baggio et al. 2008)

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE:
How much the global building damage is affected by liquefaction?

Damage Analysis – Empirical Damage

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

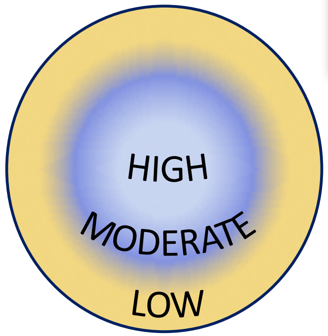


Empirical damage information on 1094 buildings

	SAN CARLO	MIRABELLO	TOT.
LG BUILD.	46	55	101
UG BUILD.	393	600	993

According to census data (ISTAT) there are 439+675= 1114 masonry buildings in San Carlo and Mirabello (no damage assumed on unsurveyed buildings, 363 build.)

POTENTIAL LIQUEFACTION



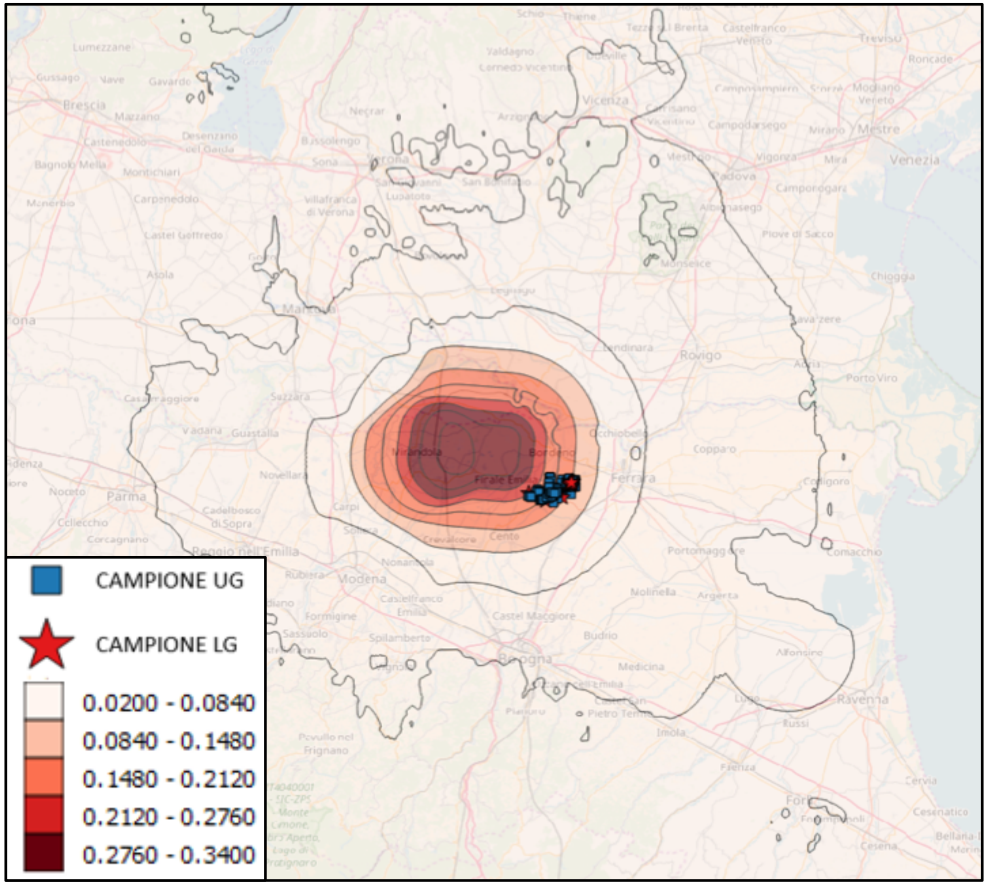
PLAIN
PALEO-BANK
PALEO-RIVERBED

DAMAGE ANALYSIS – EMPIRICAL DAMAGE

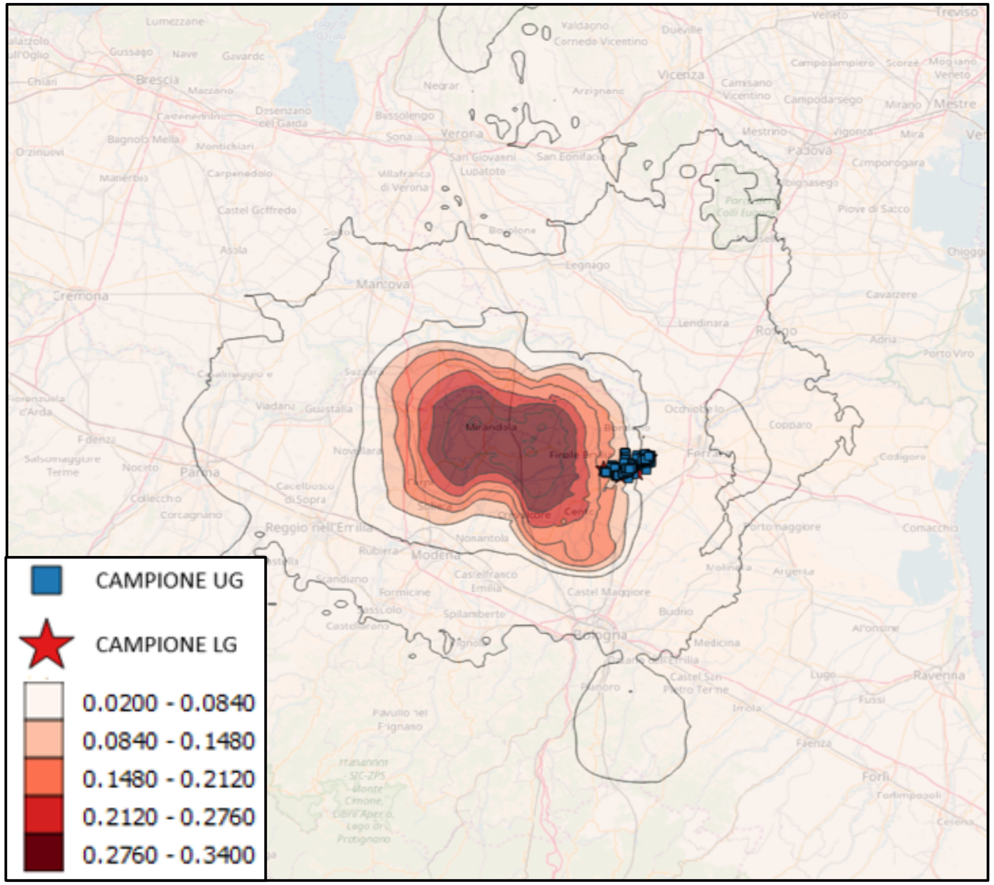
II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: How much set of buildings are comparable?

INGV ShakeMap: 20 May 2012 02:03:50 UTC M 5.9



INGV ShakeMap: 29 May 2012 07:00:03 UTC M 5.8

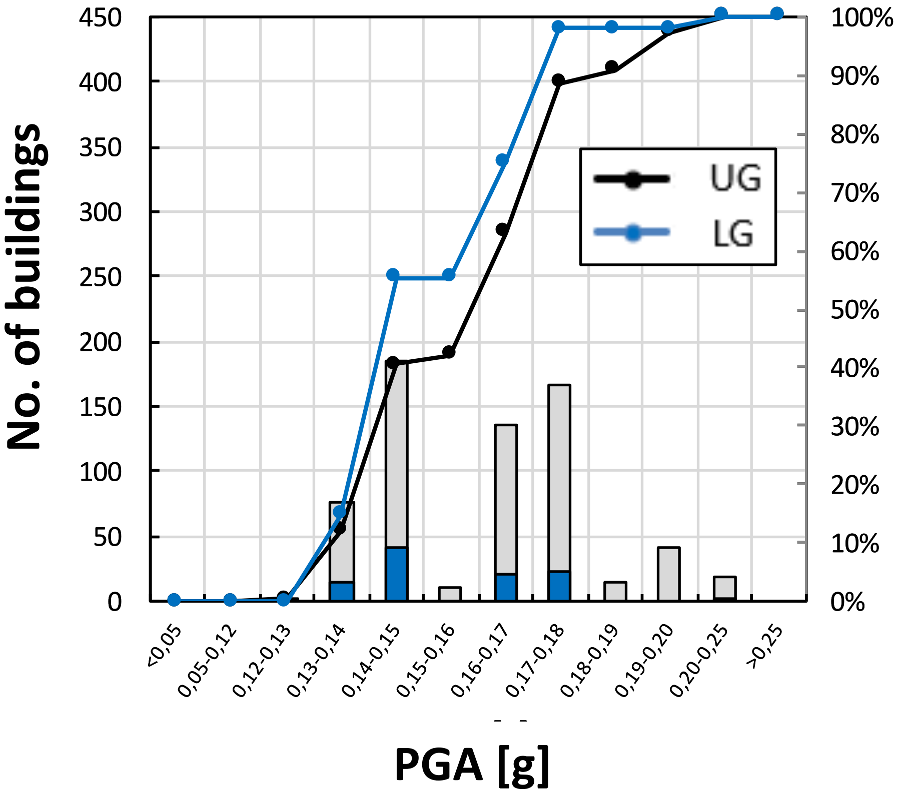


DAMAGE ANALYSIS – EMPIRICAL DAMAGE

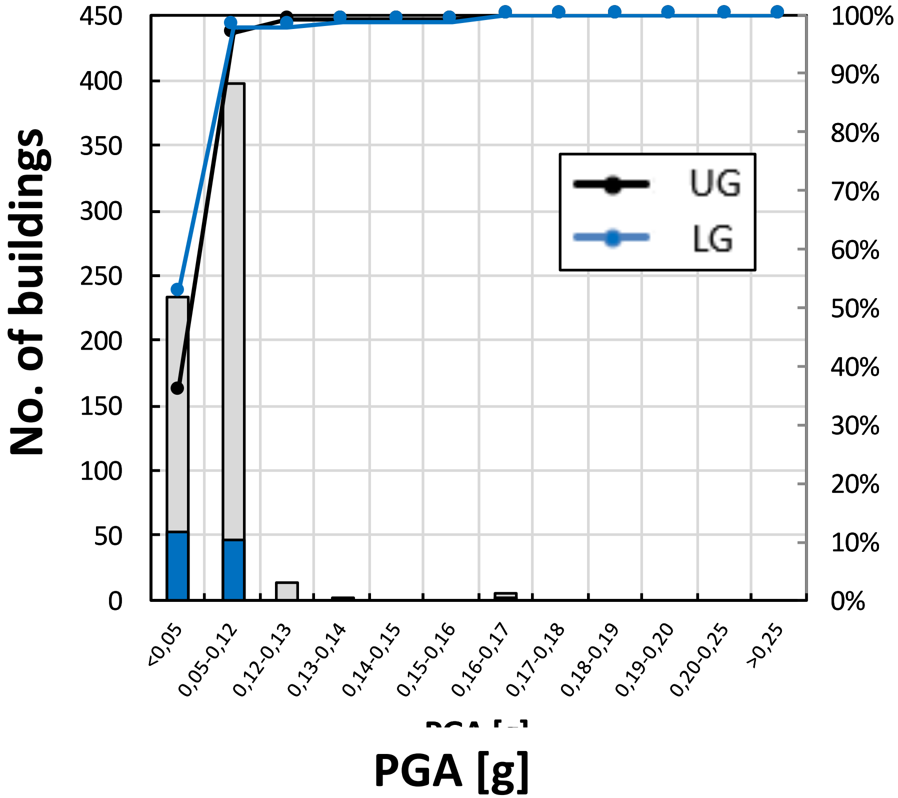
II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: How much set of buildings are comparable?

❖ PGA MAY 20th



❖ PGA MAY 29th



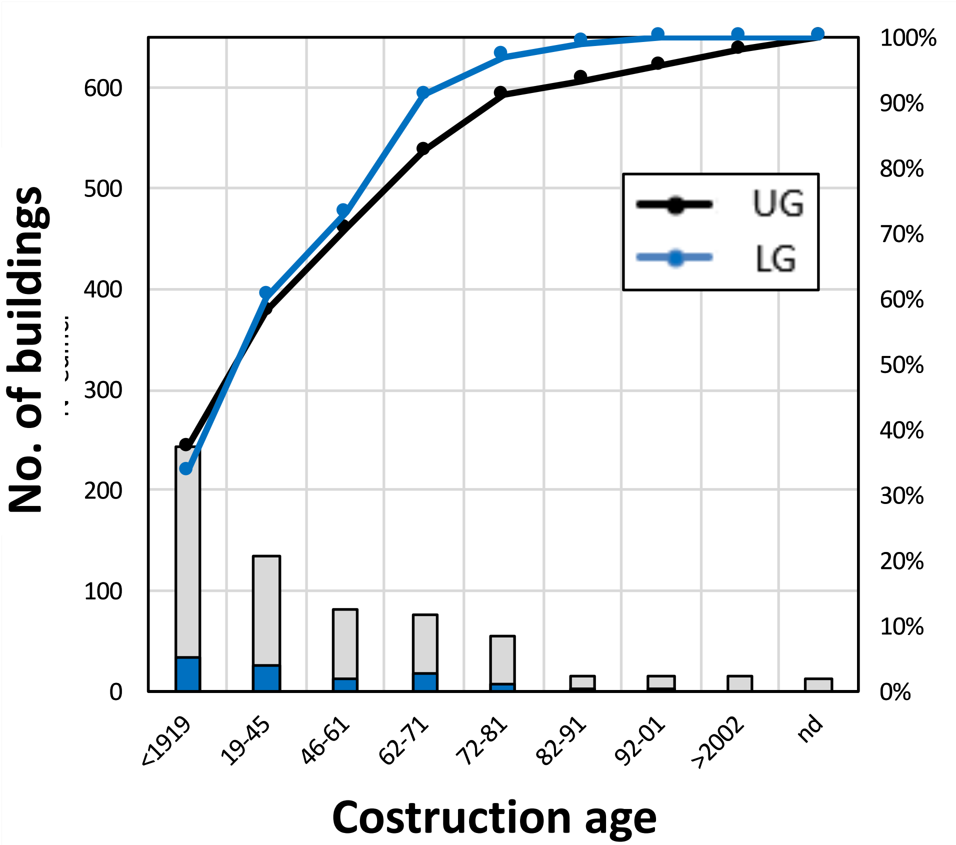
…… similar PGA values mainly within the range 0.13 -0.18 g

DAMAGE ANALYSIS – EMPIRICAL DAMAGE

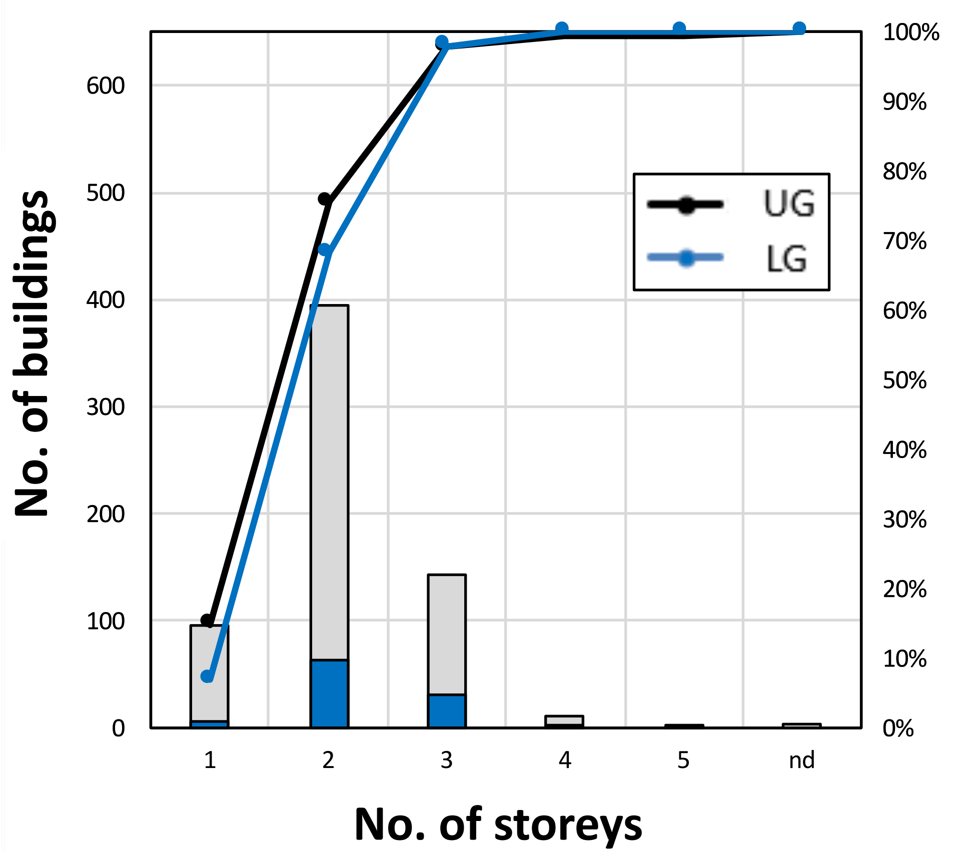
II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: How much set of buildings are comparable?

❖ CONSTRUCTION AGE



❖ NUMBER OF STOREYS



… very similar trend in terms of construction age and number of storeys

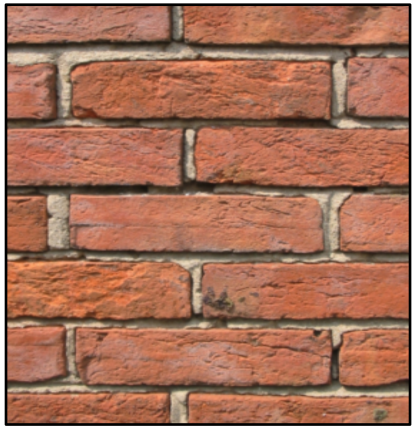
DAMAGE ANALYSIS – EMPIRICAL DAMAGE

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: How much set of buildings are comparable?

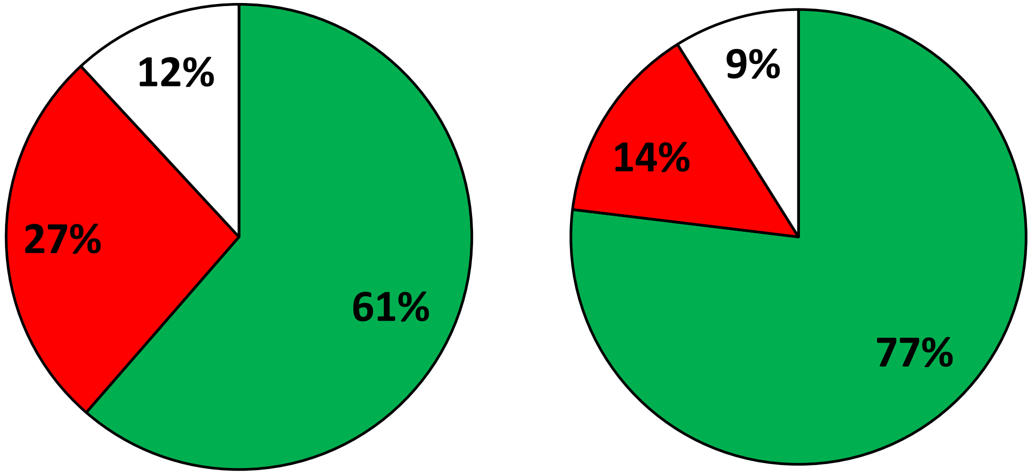
❖ MASONRY QUALITY

GOOD QUALITY MASONRY	BAD QUALITY MASONRY



UNKNOWN MASONRY QUALITY

LG Buildings. Vs. UG Buildings:



…… according to macro parameters the set of data (UG and LG) are certainly comparable in terms of vulnerability (against inertial forces)

DAMAGE ANALYSIS – EMPIRICAL DAMAGE

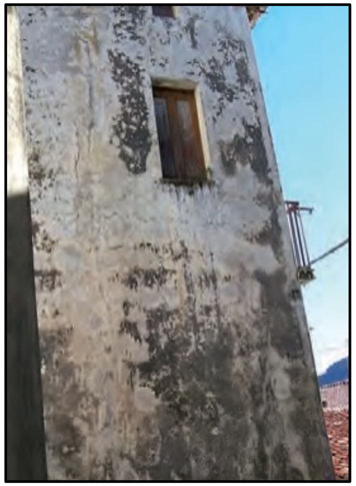
II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

DETECTED DAMAGE GRADE
(LEVEL AND EXTENT)
structural and non structural members
according to AeDES form filled by team of experts in the post-earthquake emergency

Damage level - extension / Structural component Pre-existing damage	DAMAGE (1)									
	D4-D5 Very Heavy			D2-D3 Medium-Severe			D1 Light			Null
	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
	A	B	C	D	E	F	G	H	I	L
1 Vertical structures	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
2 Floors	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
3 Stairs	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
4 Roof	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
5 Infills and partitions	☐	☐	☐	☐	☐	☐	☐	☐	☐	○

DAMAGE D0

DAMAGE D1



DAMAGE D2-D3

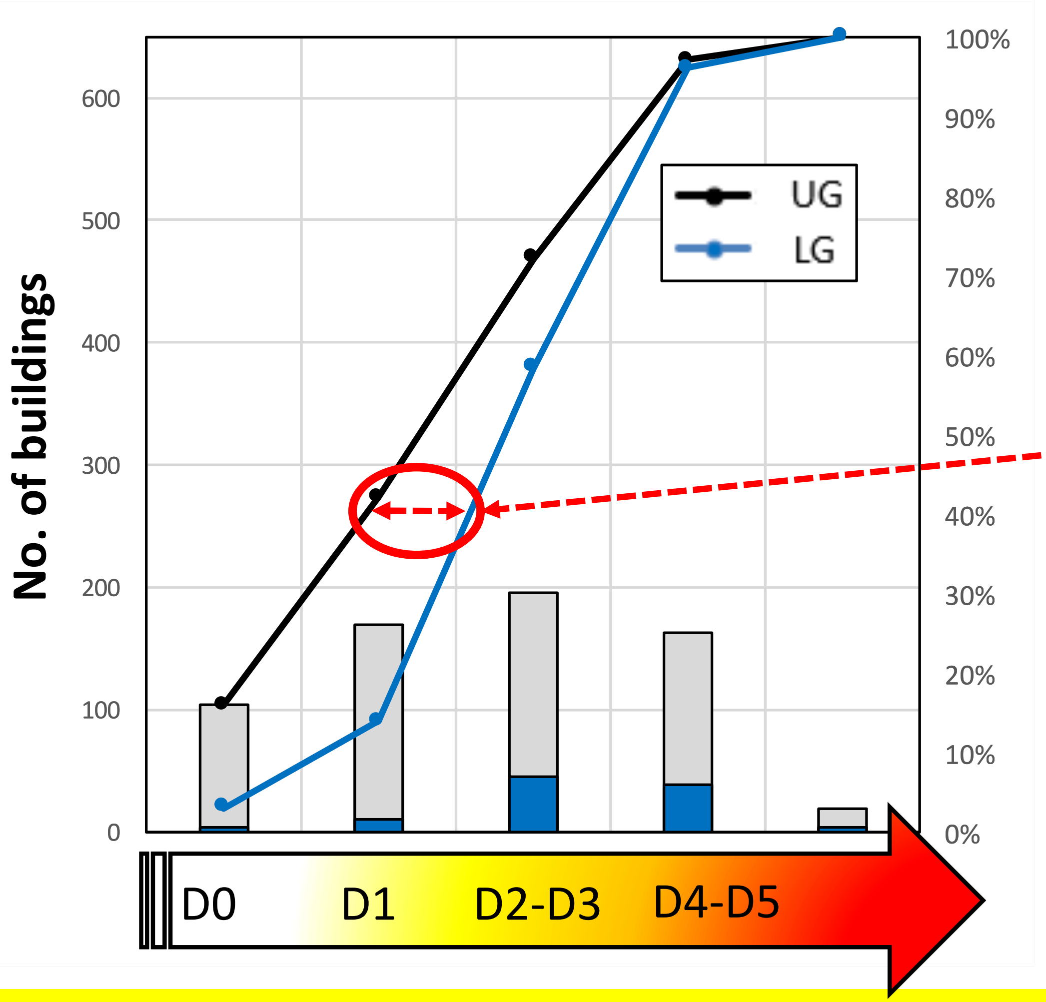
DAMAGE D4-D5

NULL — LIGHT — MEDIUM-SEVERE — VERY HEAVY

Damage Analysis – Empirical Damage

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: Damage level?



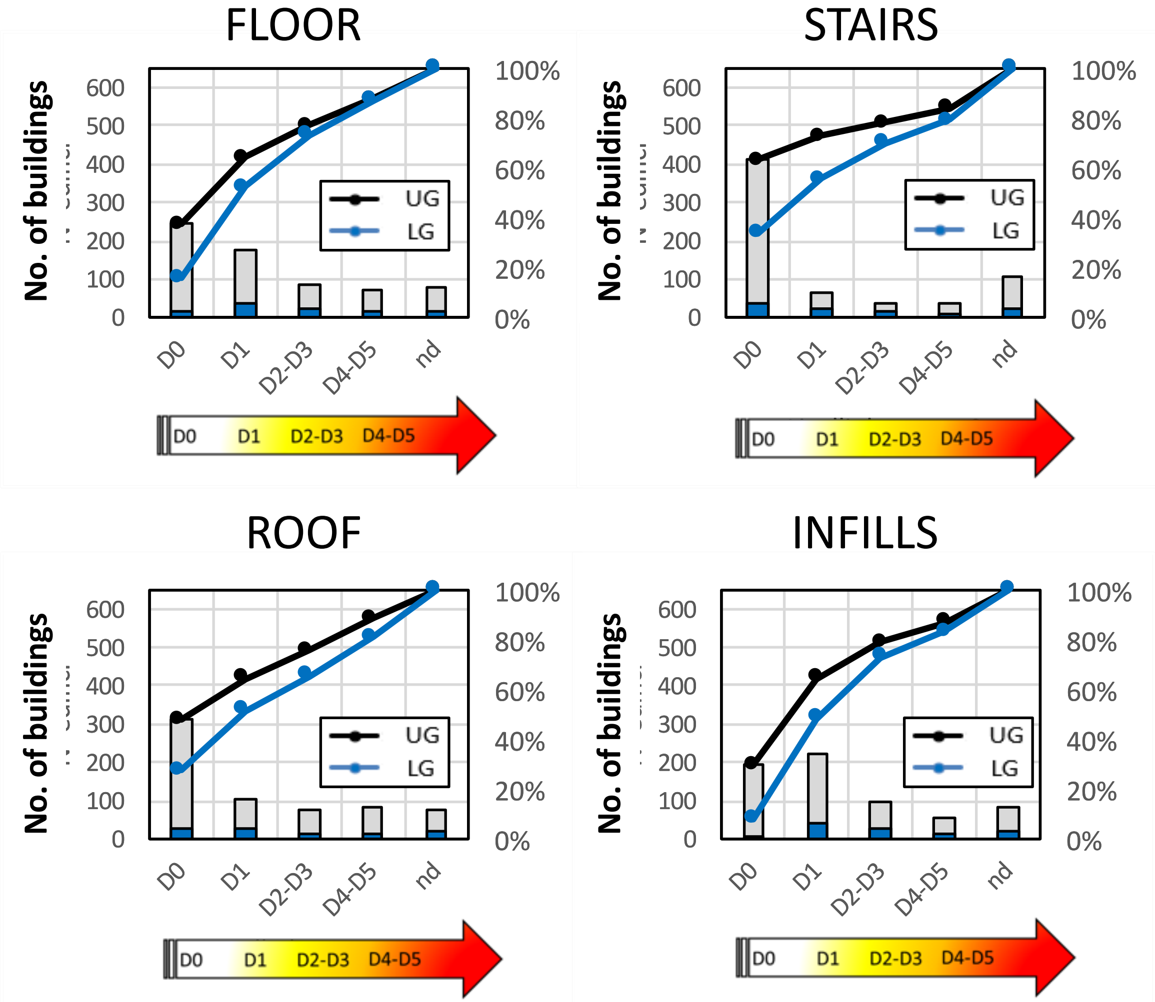
Cumulative trend
Buildings subjected to liquefaction (LG) show a higher average damage than that detected on buildings not affected by liquefaction (UG)

- ➢ **...liquefaction provides different types of damage but they are severe;**
- ➢ **...liquefaction damage may be added to seismic damage due to inertial forces**

DAMAGE ANALYSIS – EMPIRICAL DAMAGE

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: Damage level?

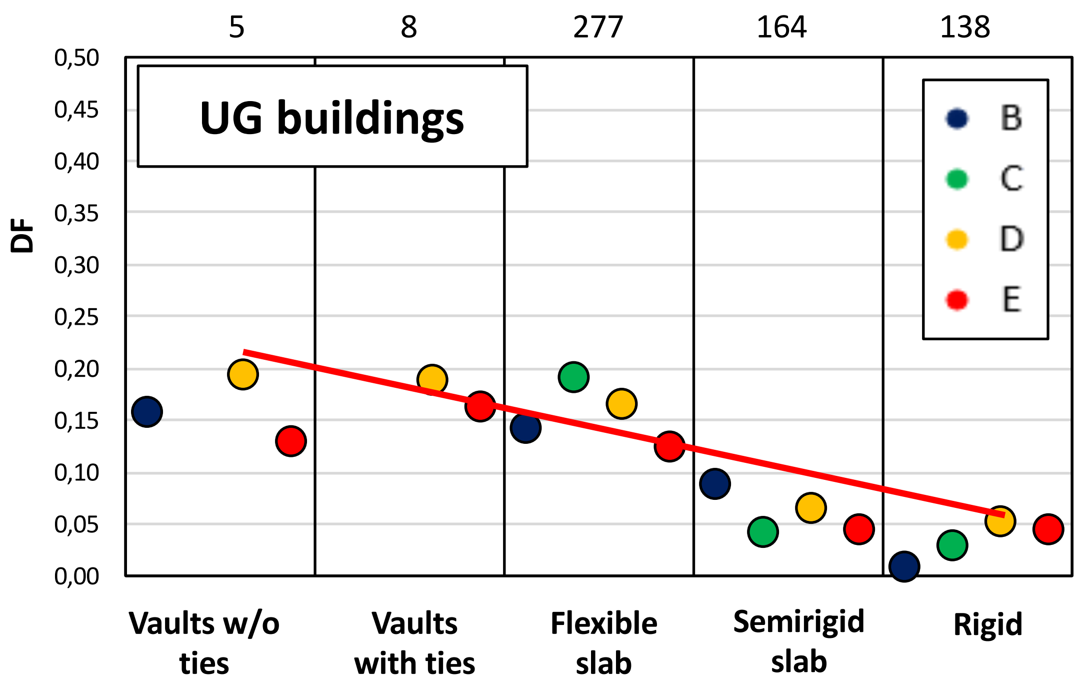


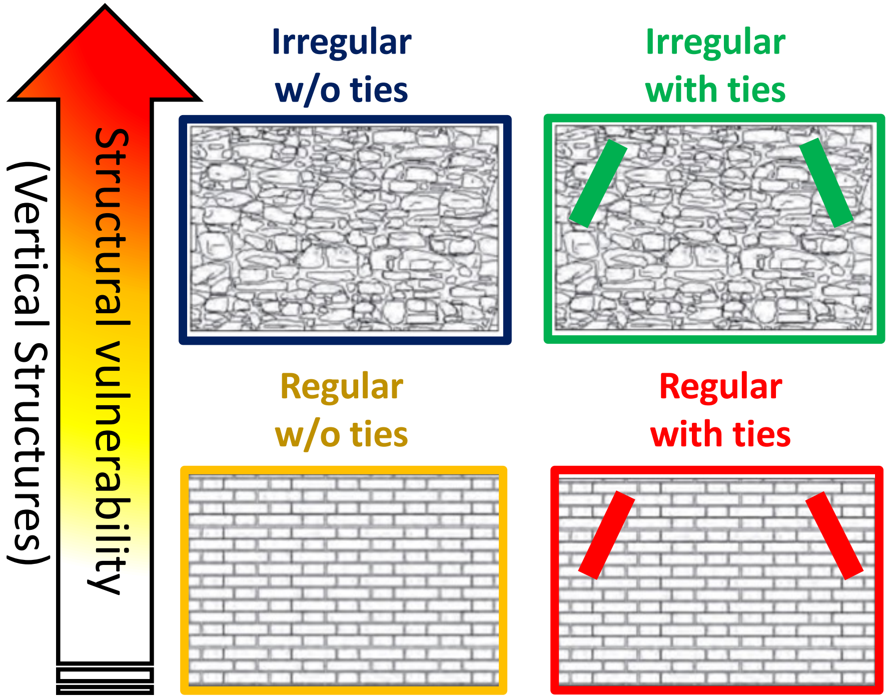
- ...a similar trend has been found for all structuraland non structural components
- ....max difference observed on stairs (commonly sligthly damaged due to inertial forces)

Damage Analysis – Empirical Damage

II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: Vulnerability influence?





DF – Global Damage factor

$$DF = \sum_j D_j \cdot \gamma_j$$

(Dolce et al. 2001)

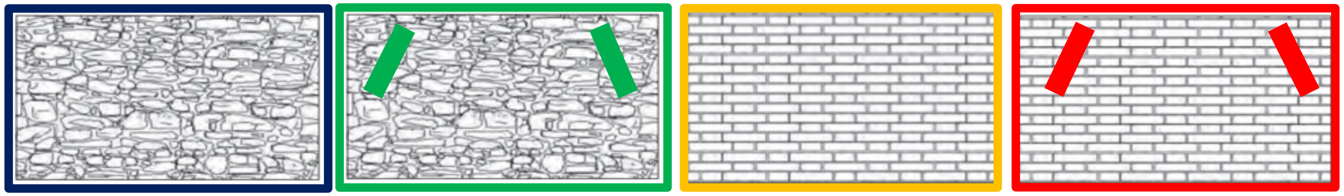
➢ ...sesimic vulnerability clearly affected the empirical damage on UG set of buildinmgs

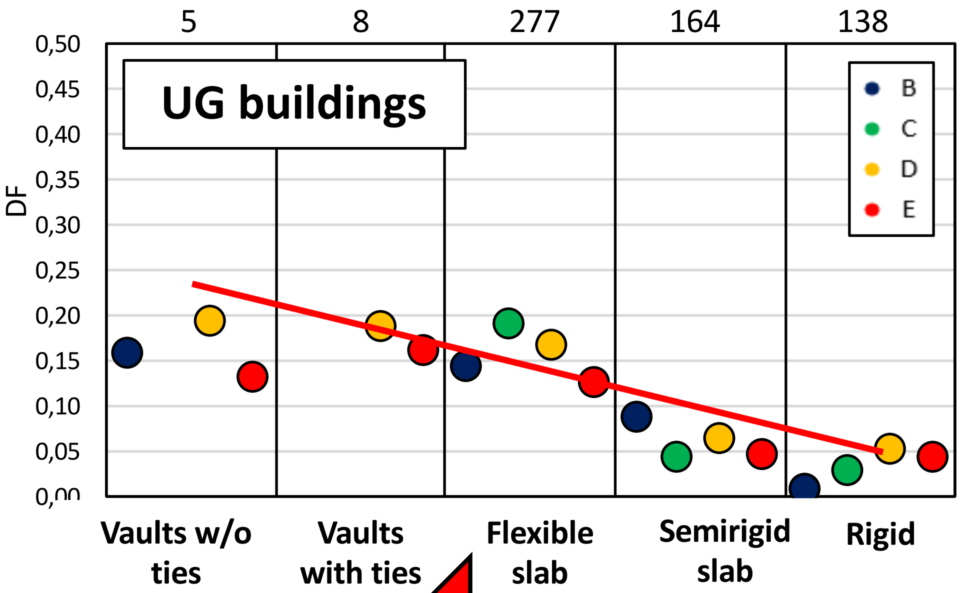
Damage Analysis – Empirical Damage

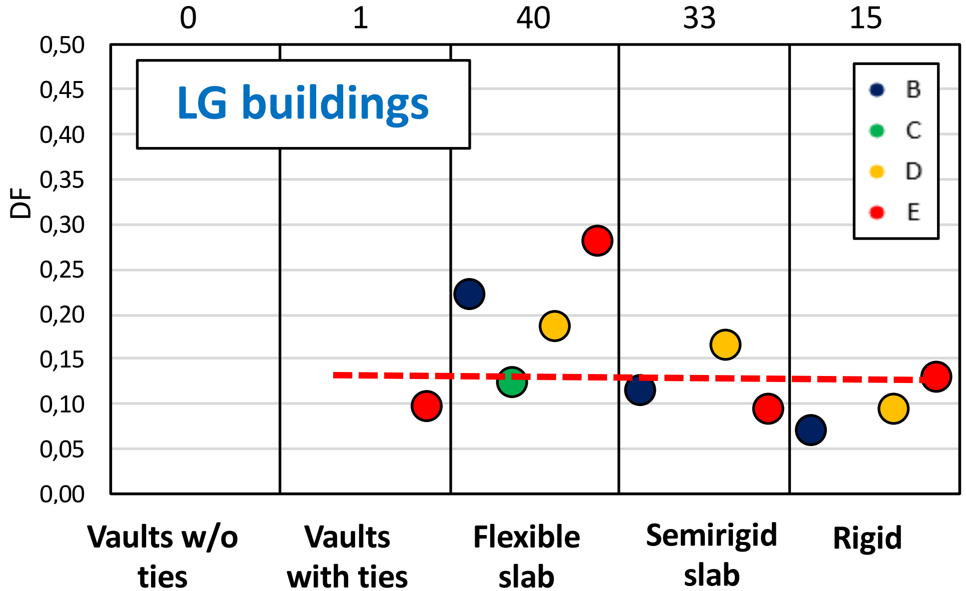
II. COMPARATIVE ANALYSIS OF EMPIRICAL DAMAGE

LG Buildings. Vs. UG Buildings: Vulnerability influence?

Irregular w/o ties | Irregular with ties | Regular w/o ties | Regular with ties





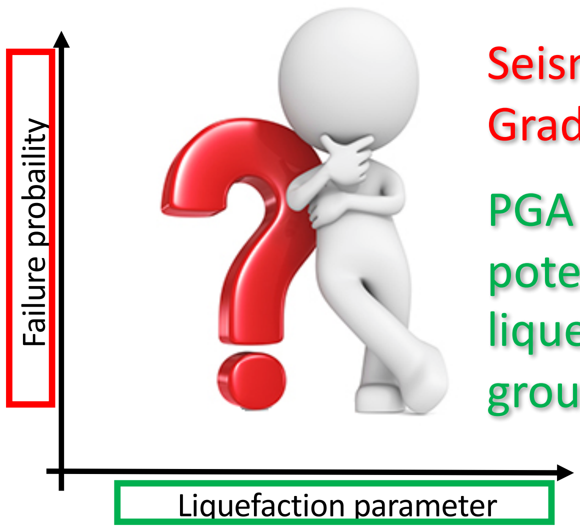


Structural Vulnerability (Horizontal structures)

- ➢ **...sesimic vulnerability clearly affected the empirical damage on UG set of buildings while it seems not correlated to the empirical damage of LG buildings**

OBJECTIVES

III. LIQUEFACTION FRAGILITY CURVES:
Which parameters should be used and what is the fragility curve trend?



Seismic Damage Grades?

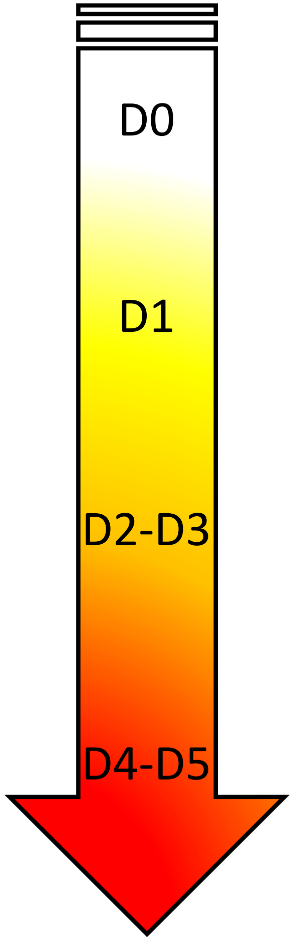
PGA and relevant potential liquefaction of ground?

Damage Analysis – Probability of Damage

III. LIQUEFACTION FRAGILITY CURVES

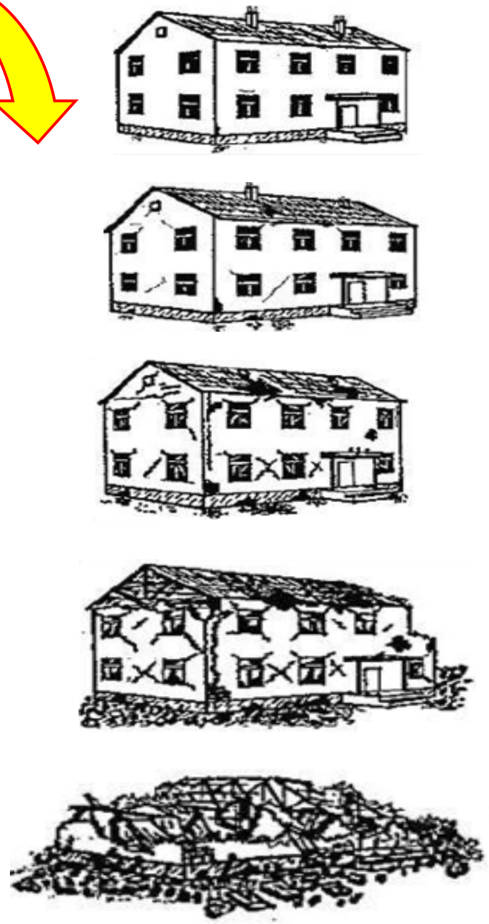
Seismic Damage Grades: Defined according to the European Macroseismic scale EMS-98

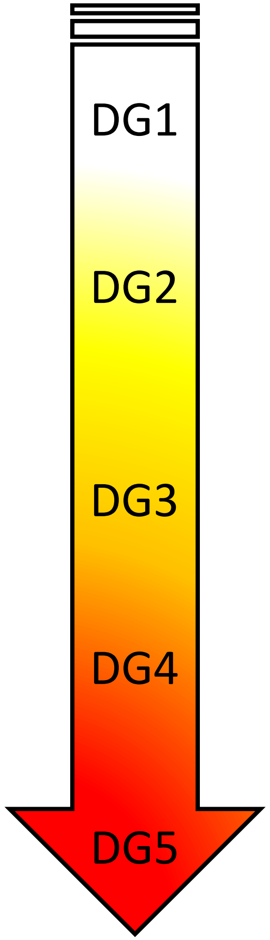
The AeDES form (Baggio et al. 2008)



D4-D5 Gravissimo	D3-D2 Medio-Grave	D1 Leggero	Danno nullo	Livello danno
			✓	0
			✓	0
		<1/3		1
		1/3-2/3		1
		>2/3		1
	<1/3			2
	<1/3	<1/3		2
	<1/3	1/3-2/3		2
	<1/3	>2/3		2
	1/3-2/3	<1/3		3
	1/3-2/3			3
	>2/3			3
<1/3				3
<1/3		<1/3		3
<1/3		1/3-2/3		3
<1/3	<1/3			3
<1/3	<1/3	<1/3		3
<1/3	1/3-2/3			4
<1/3	>2/3			4
1/3-2/3				4
1/3-2/3		1/3-2/3		4
1/3-2/3	<1/3			4
1/3-2/3	1/3-2/3			5
>2/3				5
>2/3		<1/3		5
>2/3	<1/3			5

Conversion Matrix
AeDES damage EMS damage grade





Dolce et al. 2017

➢ **...for each building it is possible to associate a damage grade from the empirical damage**

DAMAGE ANALYSIS – PROBABILITY OF DAMAGE

III. LIQUEFACTION FRAGILITY CURVES

PGA and relevant potential liquefaction of ground?

Iwasaki et al., 1984

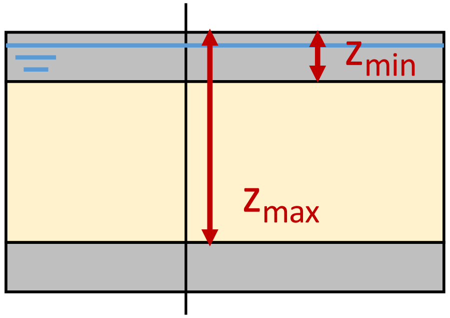
$$I_{AM} = \frac{1}{1 + z_{min}} \int_{z_{min}}^{z_{max}} r_u^{\,2} dz$$

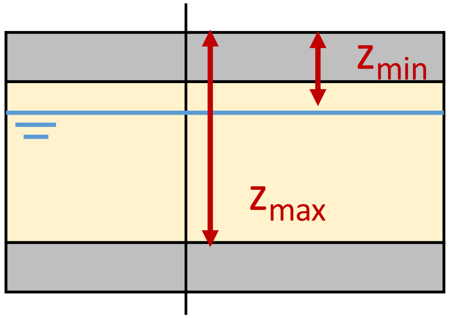
$$r_u = \frac{\Delta u}{\sigma'_{v0}} = f\left(F_s = \frac{CRR}{CSR}\right)$$

se $F_S \leq 1 \rightarrow r_u = 1$

se $F_S > 1 \rightarrow r_u = (F_S)^{1/b}$

The exponent b is a function of the cyclic resistance of the soil (defined in laboratory tests)





- It has a clear physical meaning (**depends on the most superficial liquefiable material layer and its equivalent thickness**)
- It takes into account the increase in interstitial pressure even in the layers in which the liquefaction is not carried out (r_u <1)
- Directly correlated with the post-cyclic consolidation settlement in free-field conditions (as a consequence of the structural damage)
- **It can be easily determined by simplified assessment of susceptibility to liquefaction** (estimation of ru as a function of a safety factor, FS) and from the results of dynamic analyzes in effective tensions (rigorous calculation of ru).
- Finally, assuming the liquefaction for the entire potentially liquefiable layer, the index can be calculated **on the basis of stratigraphic knowledge**

Damage Analysis – Probability of Damage

III. LIQUEFACTION FRAGILITY CURVES

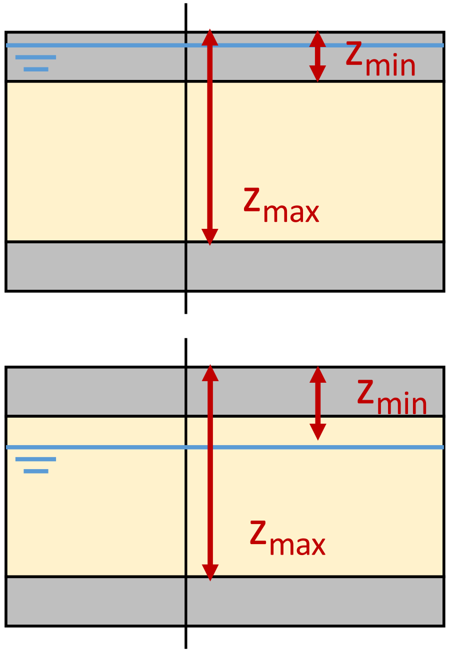
PGA and relevant potential liquefaction of ground?

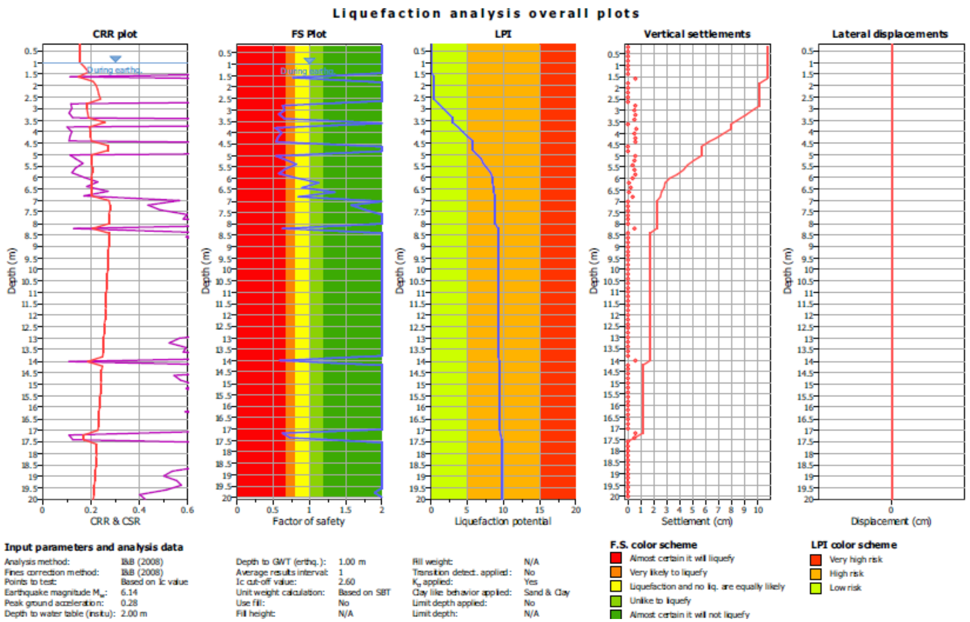
$$I_{AM} = \frac{1}{1 + z_{min}} \int_{z_{min}}^{z_{max}} r_u^{\,2}\, dz$$

It has been assumed

$r_u = 1$

$$I_{AM} = \frac{z_{max} - z_{min}}{1 + z_{min}}$$





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Iwasaki et al., 1984

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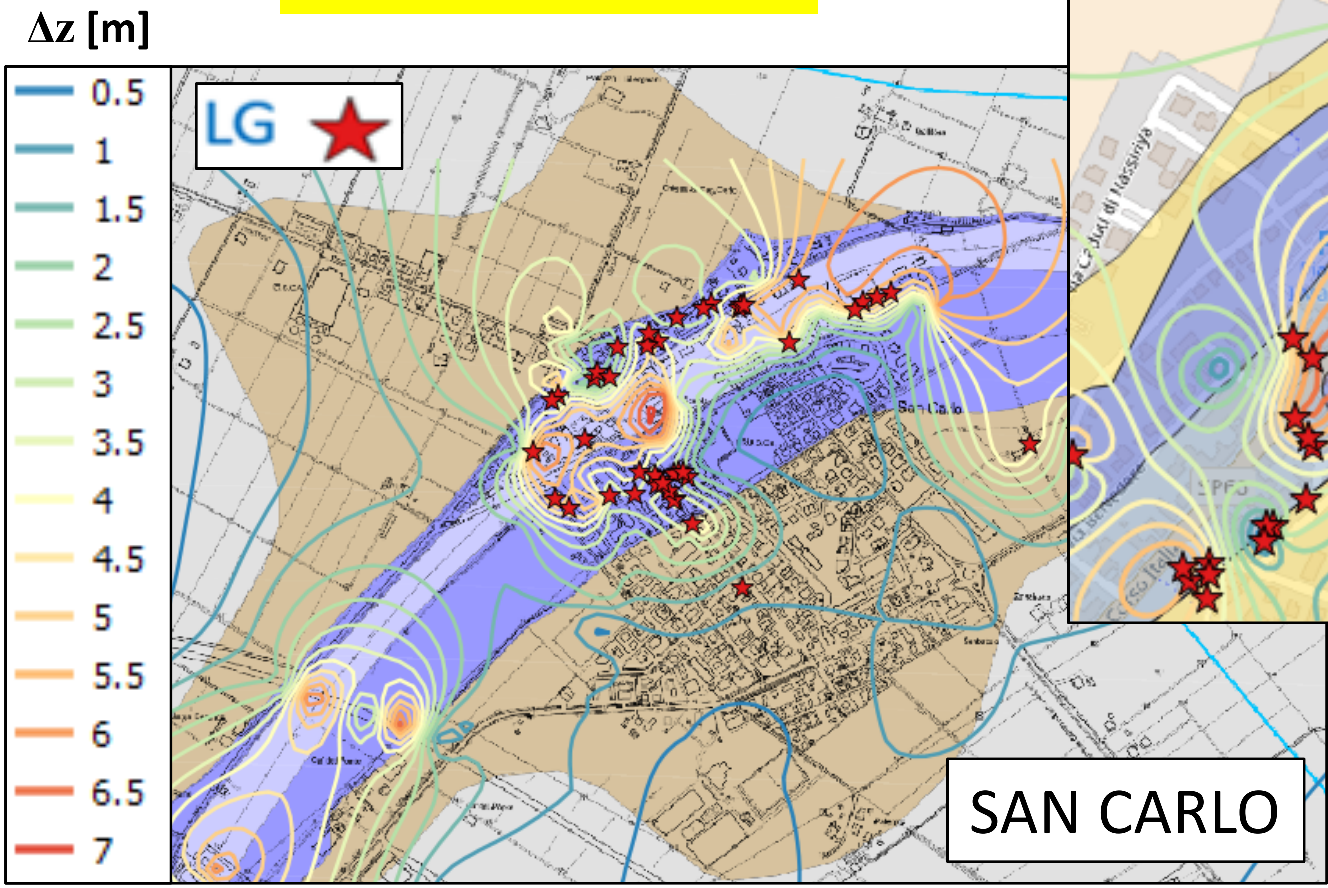
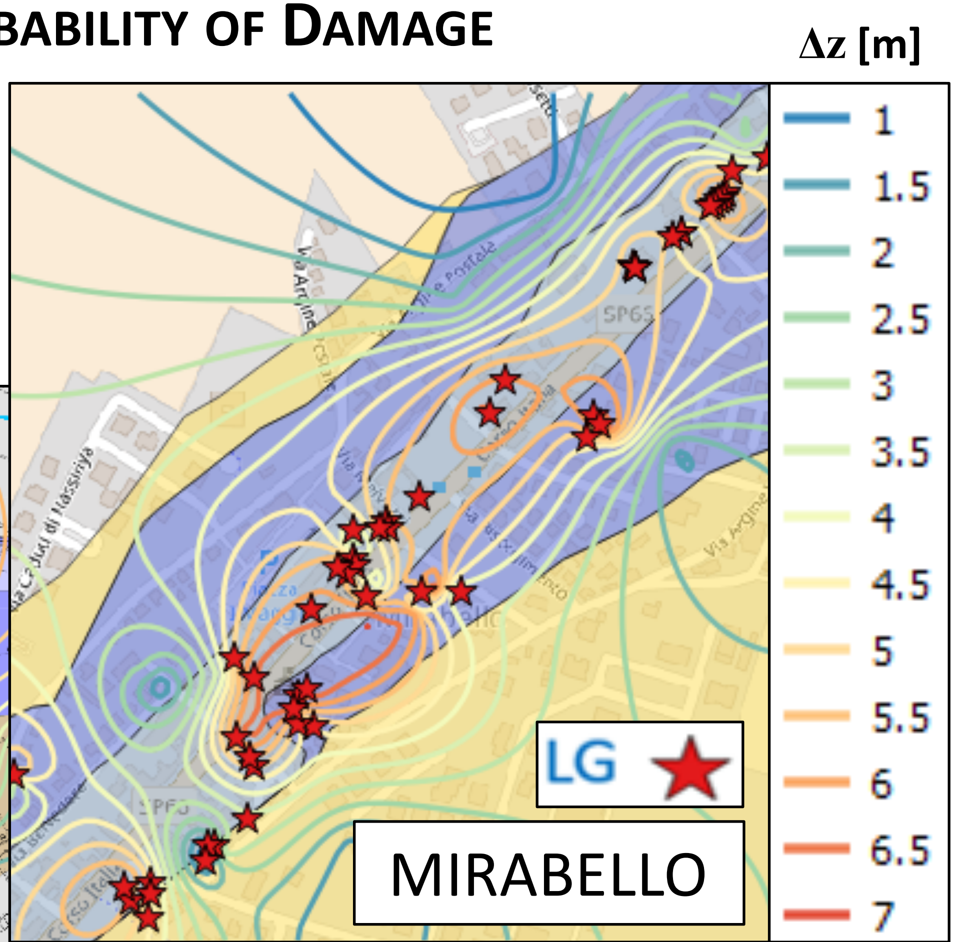
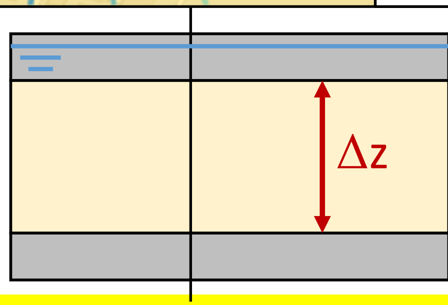
DAMAGE ANALYSIS – PROBABILITY OF DAMAGE

III. LIQUEFACTION FRAGILITY CURVES

Δz MAP OF LAYER POTENTIAL LIQUEFACT







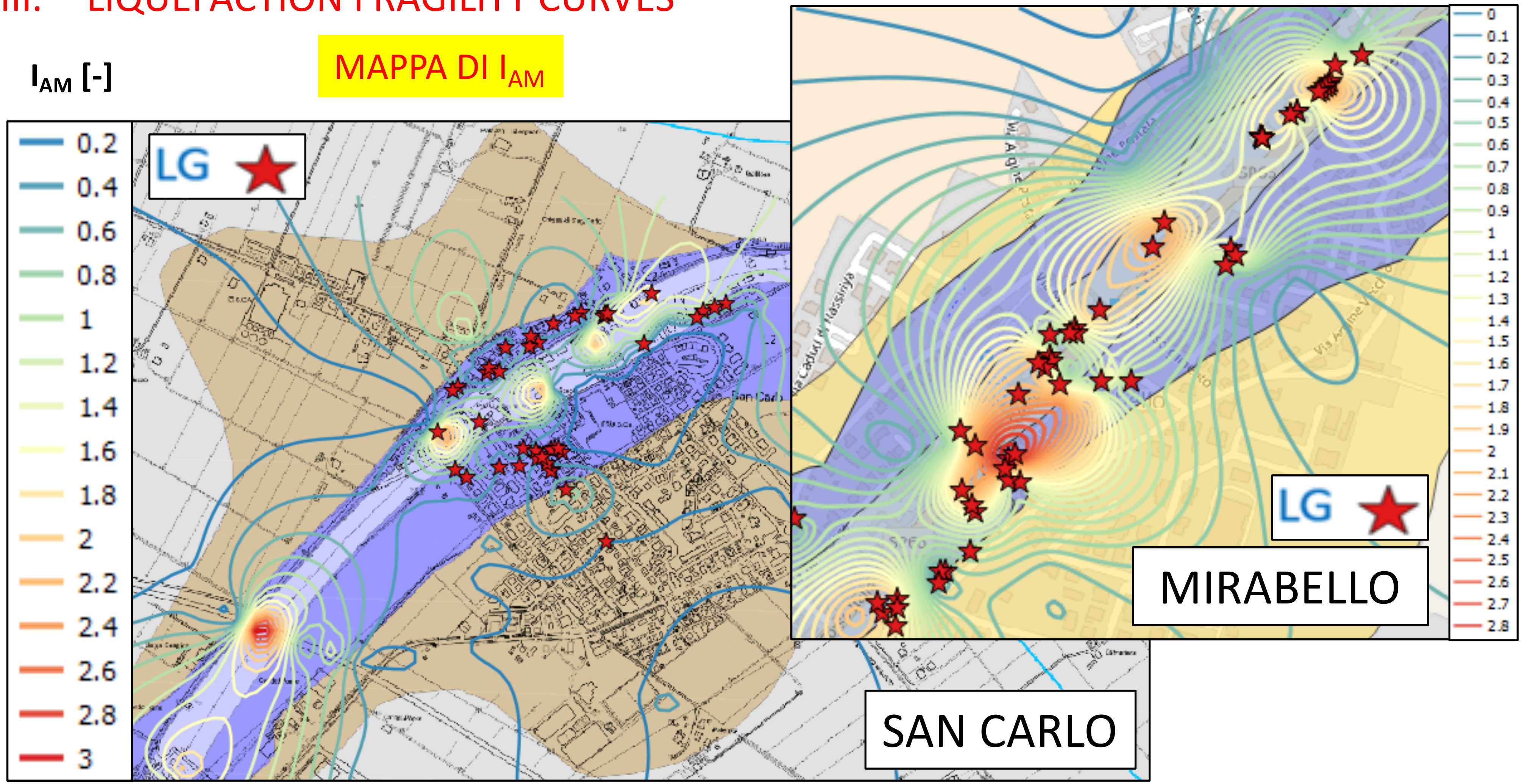
The spatial distribution of the thickness of potentially liquefiable material appears to be well correlated with the damage to the structures induced by liquefaction

DAMAGE ANALYSIS – PROBABILITY OF DAMAGE

III. LIQUEFACTION FRAGILITY CURVES

MAPPA DI I_{AM}

I_{AM} [-]

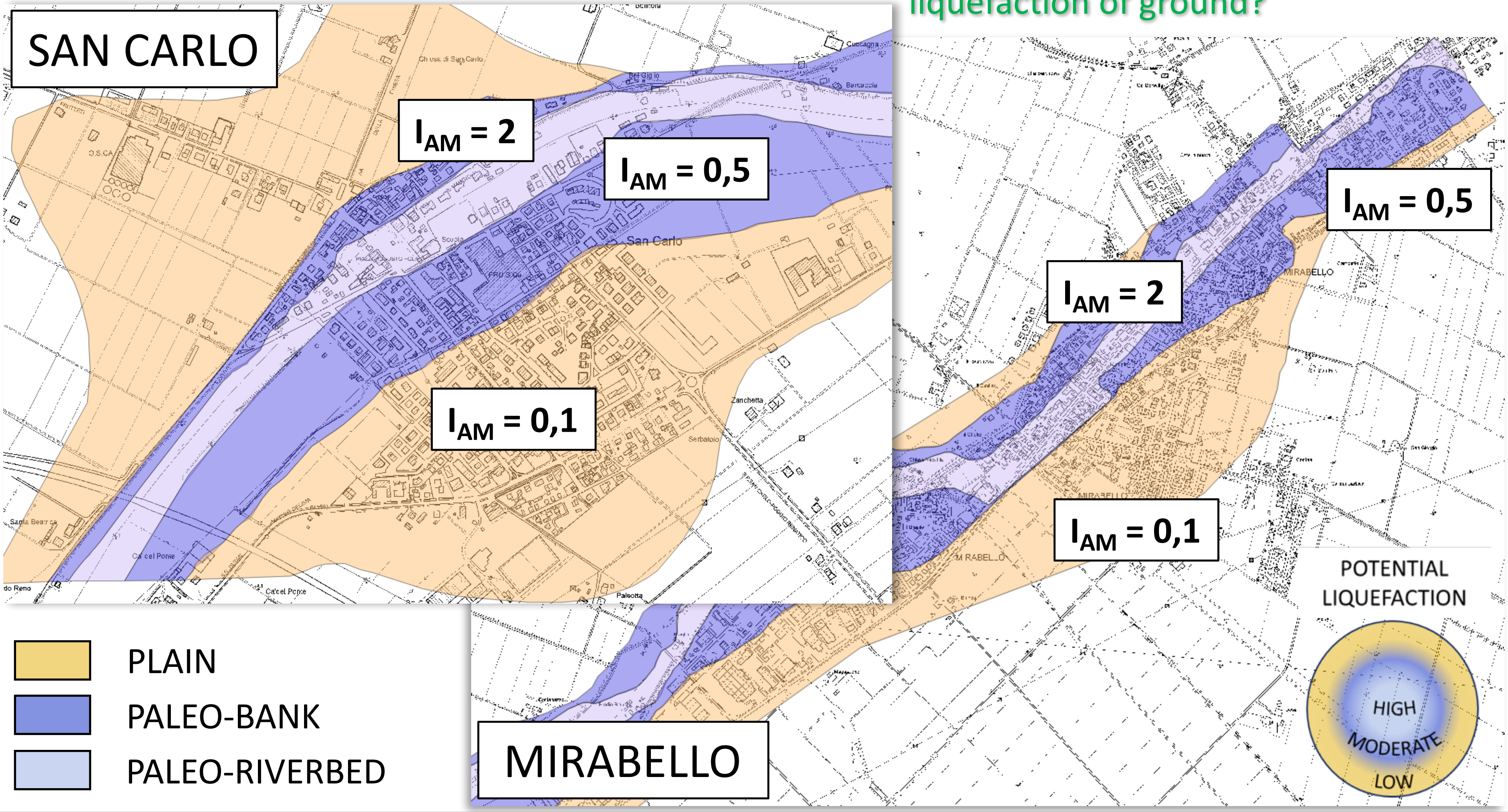


... I_{AM} is weel correlated to the liquefaction induced damage

DAMAGE ANALYSIS – PROBABILITY OF DAMAGE

III. LIQUEFACTION FRAGILITY CURVES

PGA and relevant potential liquefaction of ground?



DAMAGE ANALYSIS – PROBABILITY OF DAMAGE

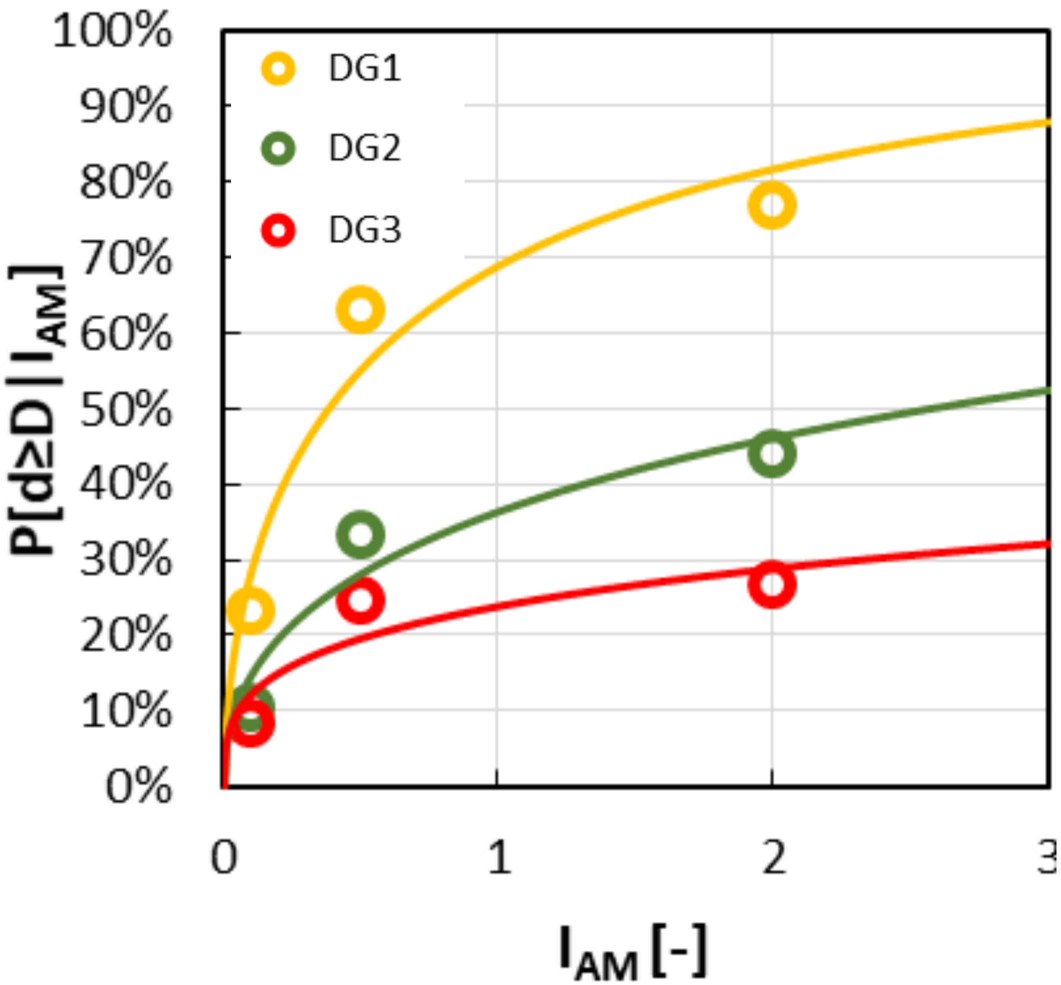
III. LIQUEFACTION FRAGILITY CURVES

MODELLO DI PREVISIONE ESPONENZIALE
(Amiri et al. 2007;
Rossetto e Elnashai 2003;)

$$P[DG \geq dg|I_{AM}] = 1 - e^{-\alpha I_{AM}^{\beta}}$$

EXPONENTIAL PREVISION MODEL

nonlinear Least Squares Estimation (LSE) fitting



- **Insufficient data for DG4 and DG5 curves; more I_{AM} values needed**
- **Damage grades are based on seismic convention**
- **These curves are related to a given PGA range and it has been assumed ru = 1**

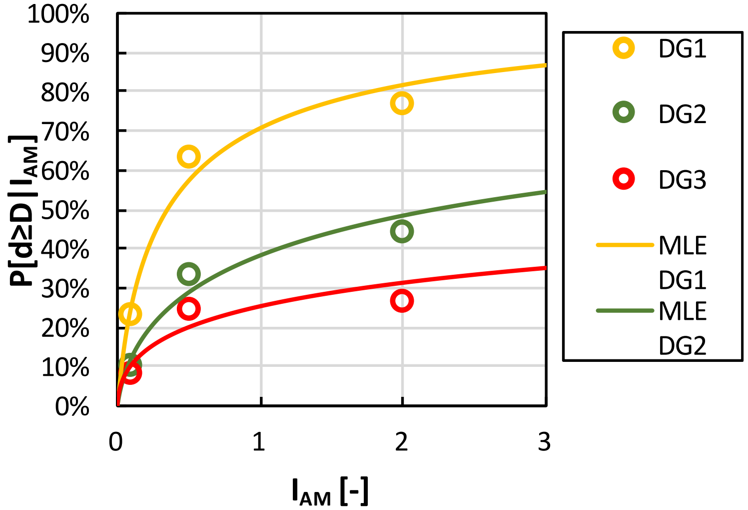
Damage Analysis – Probability of Damage

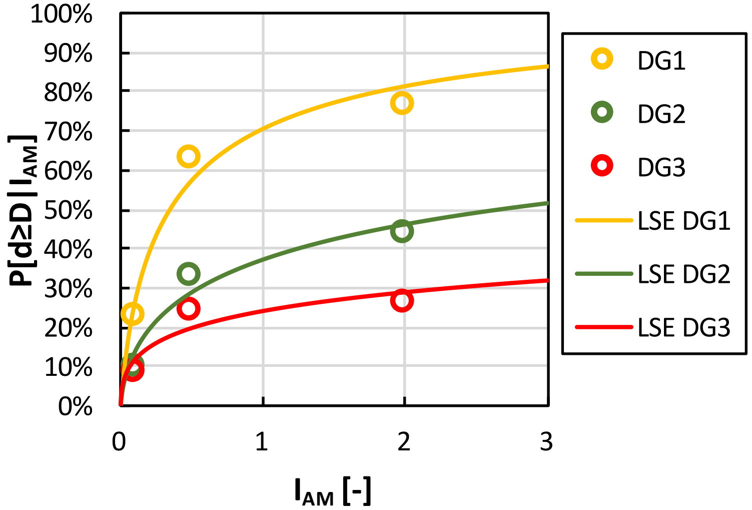
III. LIQUEFACTION FRAGILITY CURVES

LOGNORMAL PREVISION MODEL

$$\Phi\left(\frac{\ln(x)-\mu}{\sigma}\right)$$

Shinozuka et al, 2000; Rota et al, 2008

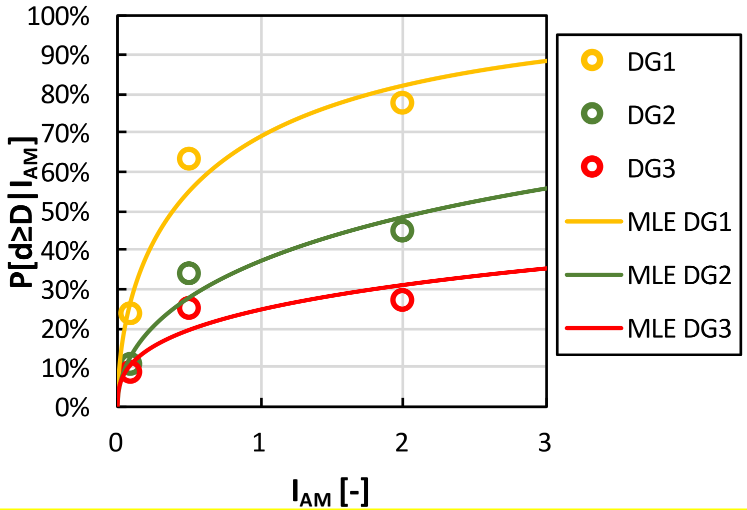


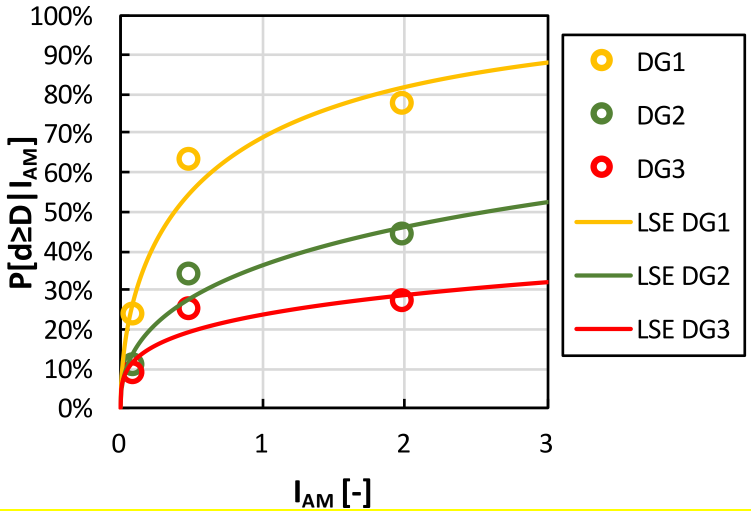


EXPONENTIAL PREVISION MODEL

$$1-\exp\left(-\alpha x^{\beta}\right)$$

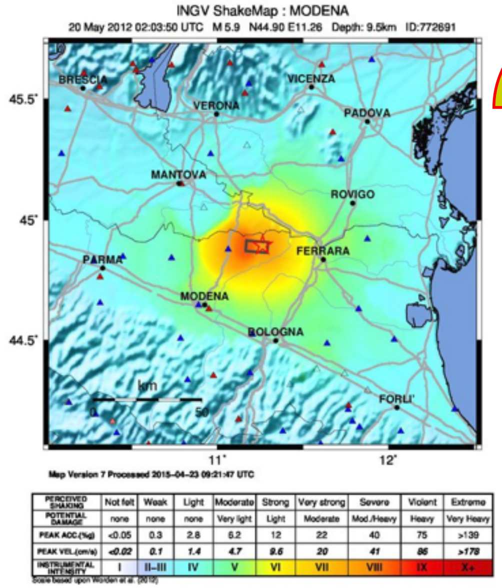
Rossetto e Elnashai, 2003; Amiri et al, 2007



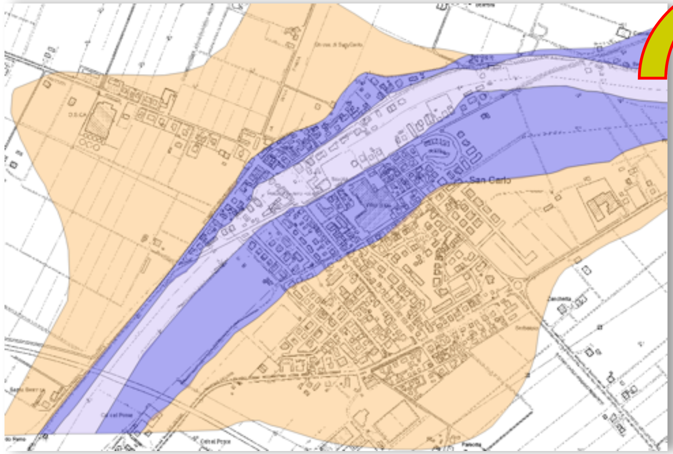


- **Insufficient data for DG3 and DG4 curves; more I_{AM} values needed**
- **Damage grades are based on seismic convention**
- **These curves are related to a given PGA range and it has been assumed ru = 1**

FUTURE DEVELOPMENTS



- PGA Scenario



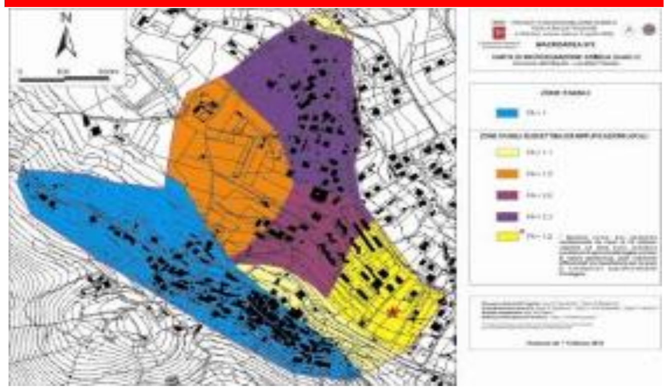
- ....different I_{AM} values

- I_{AM} Scenario

- ....damage grades accounting for liquefaction induced damage
- (amplification factor?)

Losses Scenario

✓ Seismic Micronazionation



✓ Actual repair costs