Instrumental Intensity Scales for Geohazards

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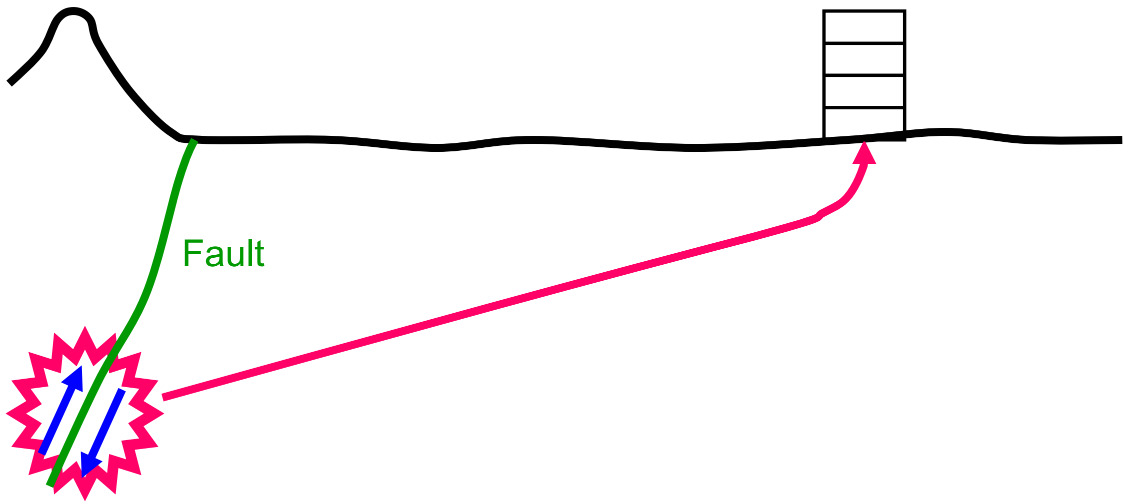
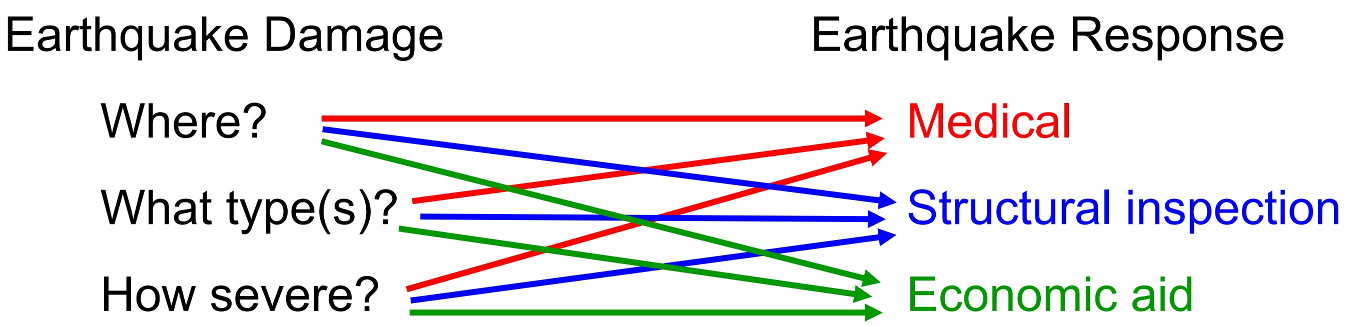
Earthquake Process





Earthquake Intensity & Damage

EARTHQUAKE	GROUND MOTION	RESPONSE OF SYSTEM	DAMAGE TO SYSTEM
Small	Weak	Linear elastic	None

Earthquake Intensity & Damage

EARTHQUAKE	→	GROUND MOTION	→	RESPONSE OF SYSTEM	→	DAMAGE TO SYSTEM
Small		Weak		Linear elastic		None
Large		Strong		Nonlinear, Inelastic		Severe

Earthquake Size

Two common measures:

Magnitude – total energy, one value per earthquake

Intensity – felt motion, many values per earthquake

Observational Intensity

MMI **IV**

During the day felt indoors by many, outdoors by few; at night some awakened; dishes, windows, doors disturbed; walls make cracking sound; sensation like heavy truck striking building; stan… motor cars rocked noticeably

MMI **VII**

Everybody runs outdoors; damage negligible in buildings of good design and construction, slight to moderate in well-built structures, considerable in poorly built or badly designed structures; som…neys broken; noticed by persons driving motor cars

MMI **X**

Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked; rails bent; landslides considerable from river banks and steep slopes; shifted sand and mud; water splashed over banks

Earthquake Size

Two common measures:

Magnitude – total energy, one value per earthquake

Intensity – felt motion, many values per earthquake

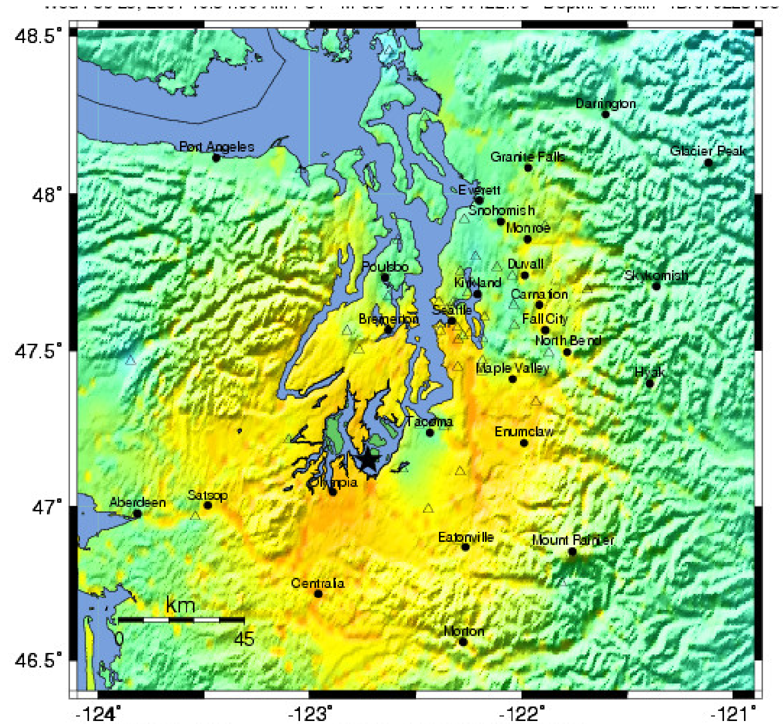
Observational Intensity

Instrumental Intensity

ShakeMap Intensity (*SMI*)

f (*PGA*) for *SMI* < VII

f (*PGV*) for *SMI* > VII

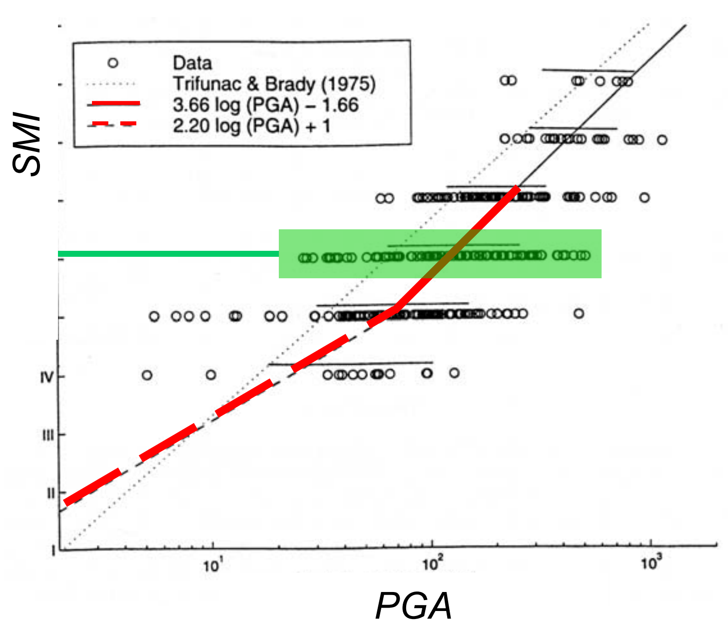


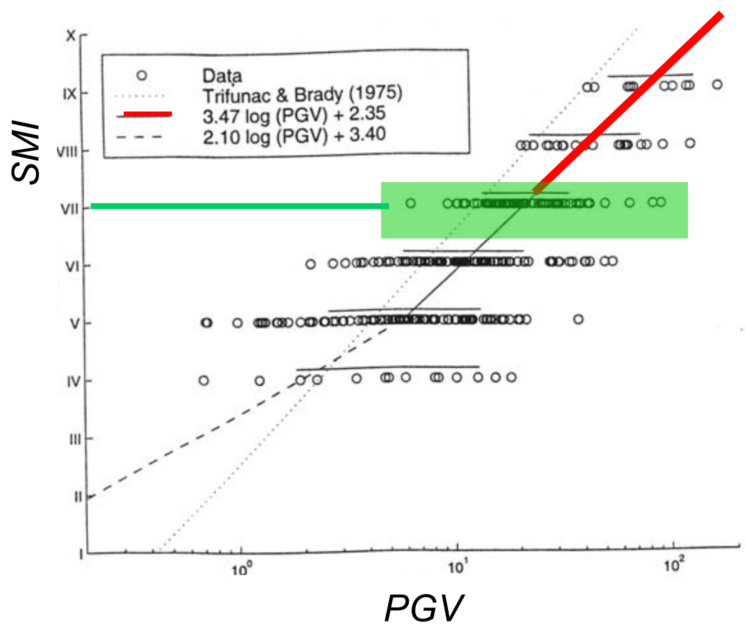
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
[illegible] VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	[illegible]
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

SMI Scale (Wald et al., 1999)

Calibrated against *MMI* (IV ≤ *MMI* ≤ IX)

- **For *MMI* < V: *MMI* = 2.20 log *PGA* + 1.00**
- **For V < *MMI* < VII : *MMI* = 3.66 log *PGA* – 1.66**
- **For *MMI* > VII : *MMI* = 3.47 log *PGV* + 2.35**





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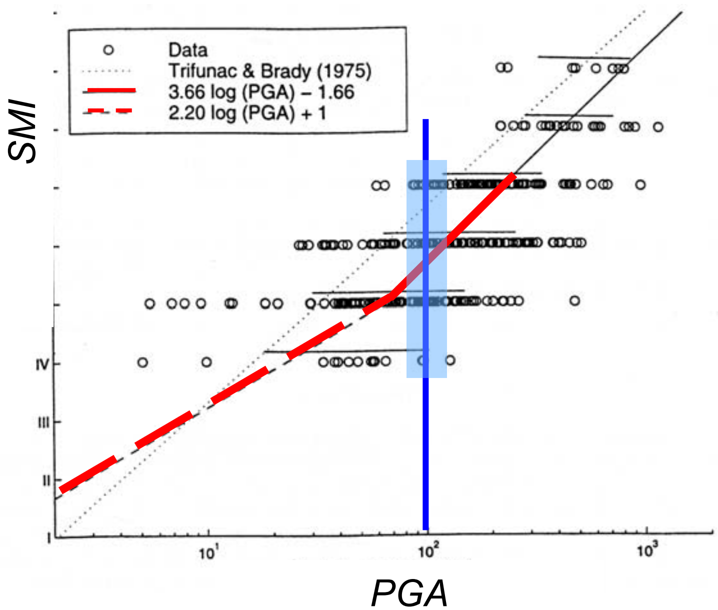

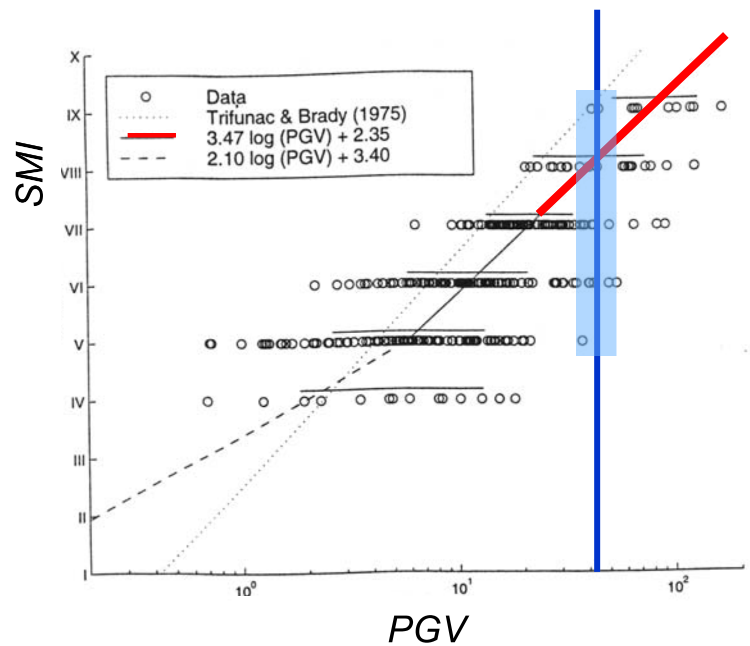

SMI scale is based on an imprecise fit to an imprecise indicator of damage

Objective

To develop an instrumental intensity scale that correlates well to geotechnical damage

- Consider several “components” of damage
- Take advantage of improved computational procedures
- Account for ground motion amplitude, frequency content, duration

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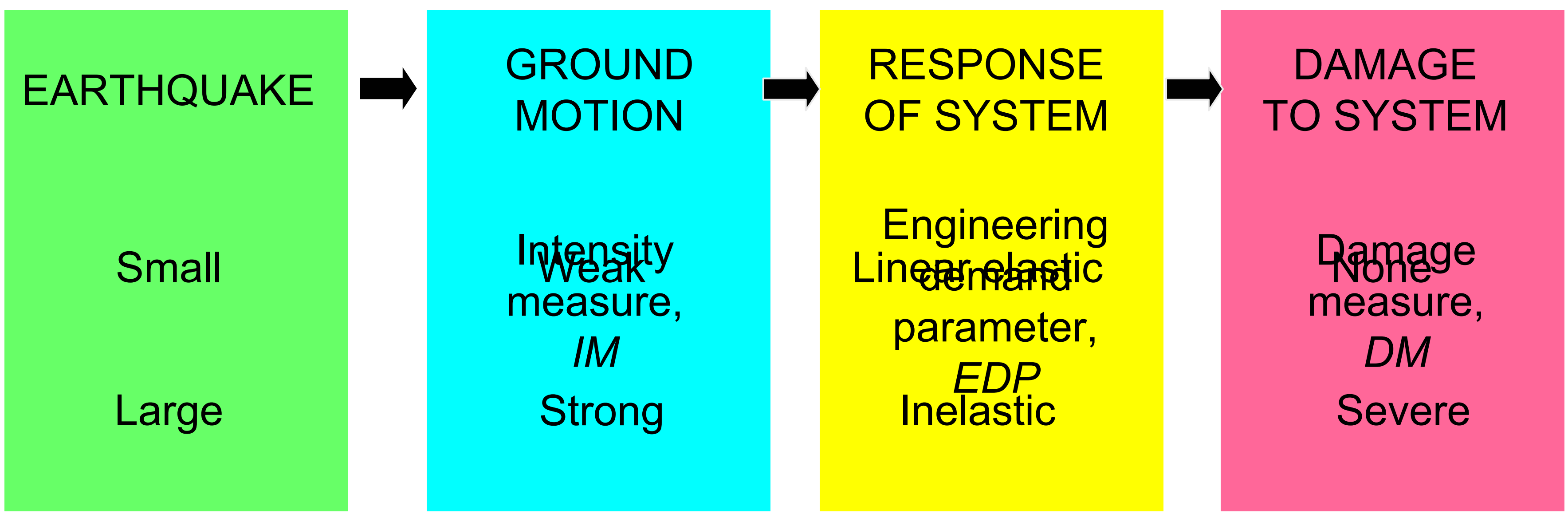
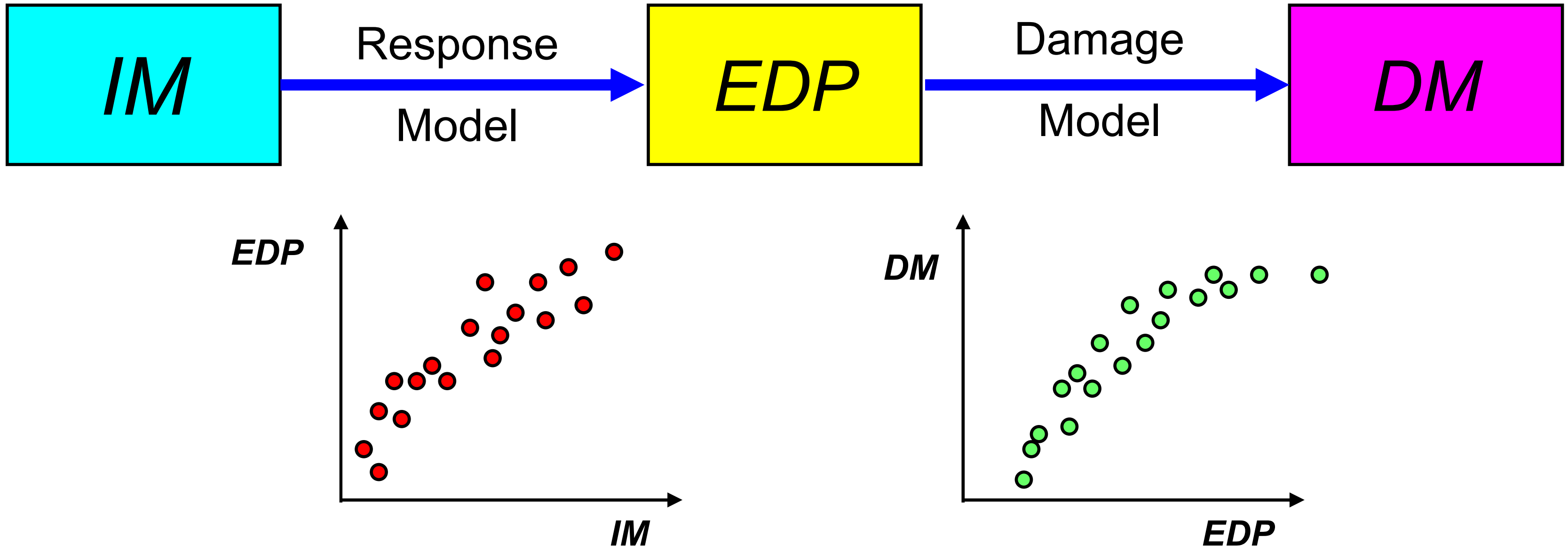
Terminology



Earthquake Intensity & Damage



Identify appropriate response model(s)

Identify appropriate damage model(s)

Identify candidate *IM*s, *EDP*s, *DM*s

Use models to identify efficient and sufficient *IM*s for *DM* prediction

Establish *IM*-*DM* relationship

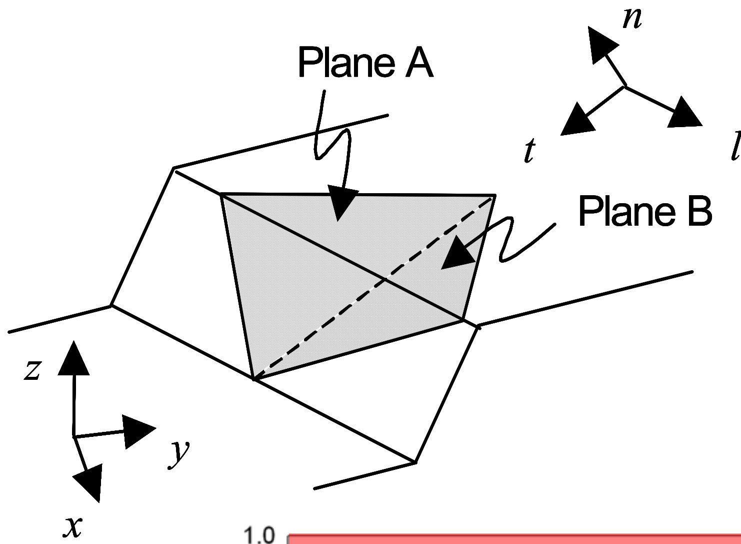
Repeat for each component

Combine to define geohazard instrumental intensity scale

Geohazard Components

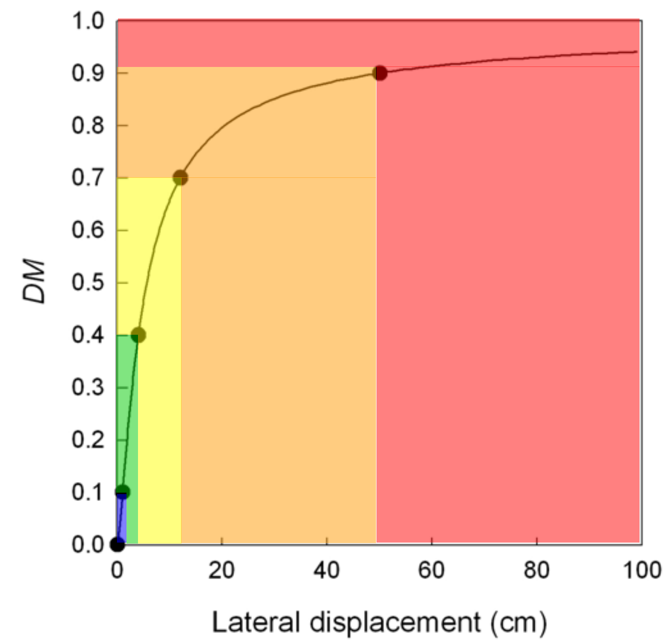
- Slope Instability
- Lateral Spreading
- Post-liquefaction Settlement
- Buried Pipeline Breakage

Response model – 3D Newmark analysis



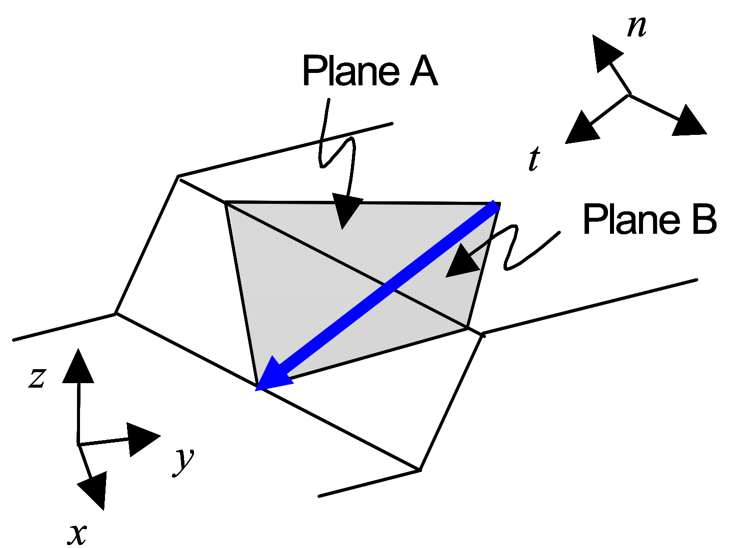
Damage model – subjective poll

Damage State	*DM* range
Negligible	0.0 – 0.1
Minor	0.1 – 0.4
Moderate	0.4 – 0.7
Severe	0.7 – 0.9
Catastrophic	0.9 - 1.0

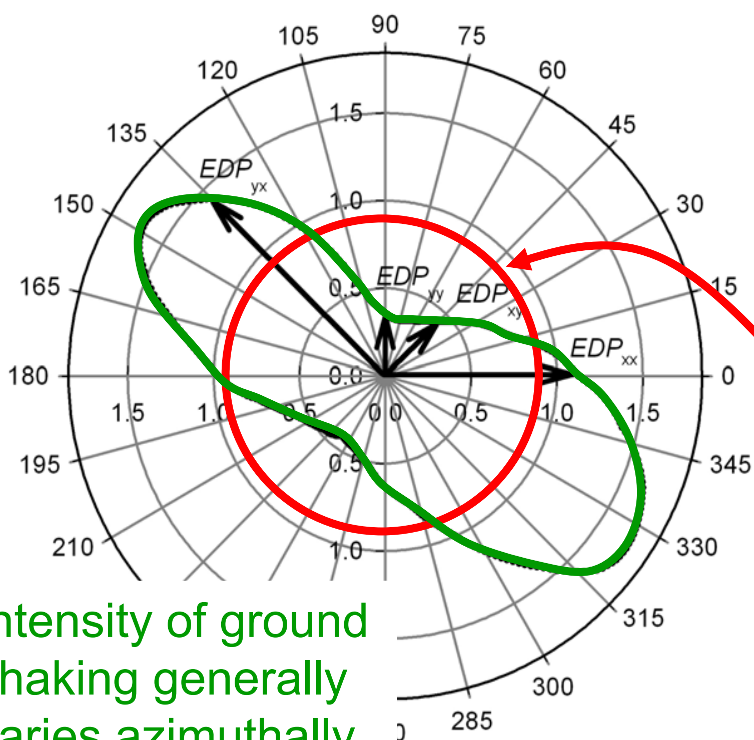


Directionality

Ground moves in three directions during an earthquake



Azimuthal orientation of dip directions generally random



Intensity of ground shaking generally varies azimuthally

Ground motion resolved in 360 azimuthal directions. Average value of *EDP* used to capture azimuthal variability

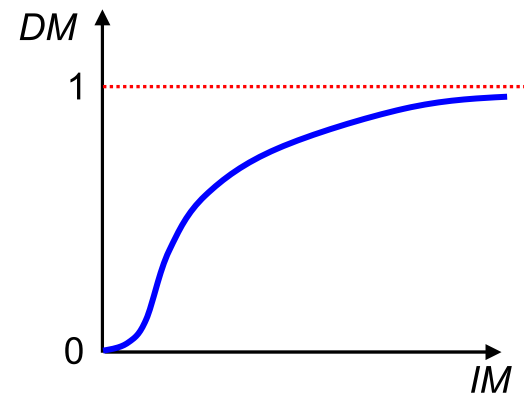
IM – *DM* Relationship

Modified hyperbolic form

DM ranges from 0 to 1 for *IM* = 1, ∞

Allows "threshold" behavior

$$DM = \left[\frac{(aIM_x^e)}{(1 + aIM_x^e)} \right]^b \left[1 + \left(\frac{c}{IM_x} \right)^d \right]^{-0.5}$$



System of engineered slopes analyzed

- 10 slopes with $FS_{initial}$ from 1.05 – 1.95
- Mean $FS_{initial}$ = 1.5, COV = 20%
- Weighting factors were assigned to each slope

455 motions

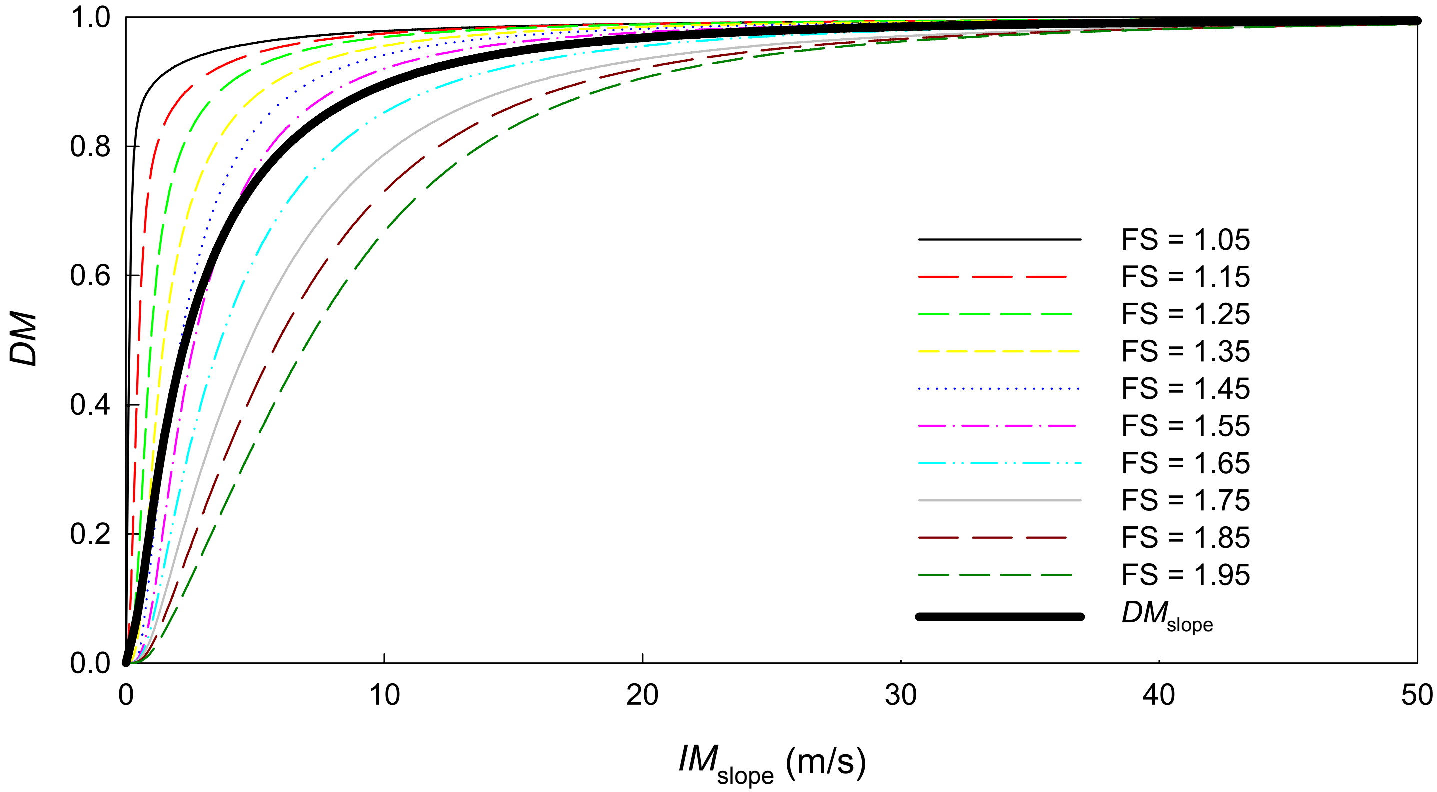
360 components per motion

1,638,000 total Newmark analyses

Optimize to determine *a* – *e* and identify *IM* best correlated with *DM*

IM – *DM* Relationship

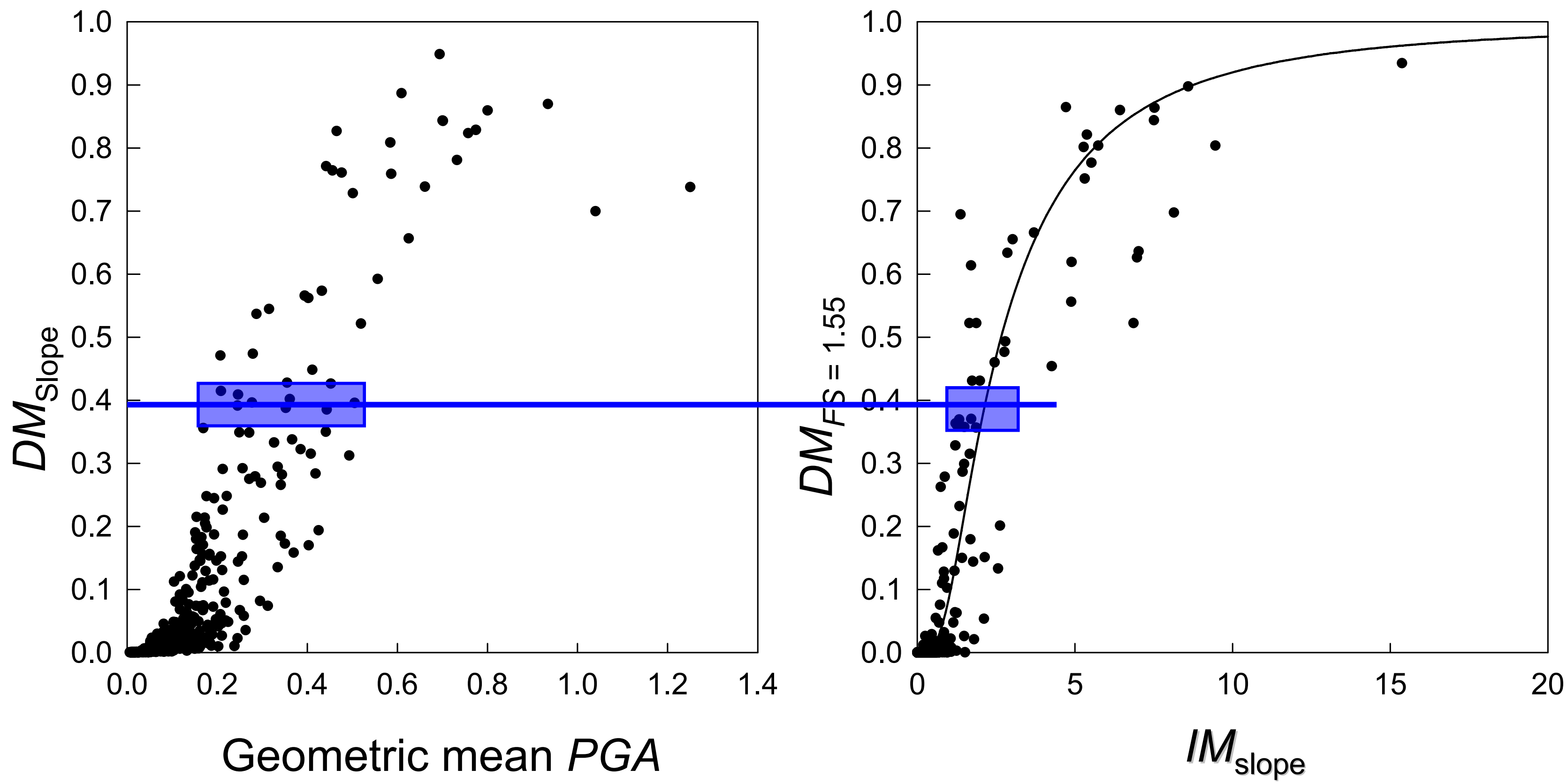
- Arias intensity confirmed as efficient parameter (after Travasarou and Bray, 2003)
- Weighted average of "strong" and "weak" components used to define *IM*: $IM_{slope} = 0.7I_s + 0.3I_w$
- Weighted average of 10 slopes used to establish *IM-DM* relationship



IM – *DM* Relationship

New IM_{slope} parameter provides improved characterization of damage potential of earthquake ground motions

Less scatter in *DM* | *IM*



Other Components

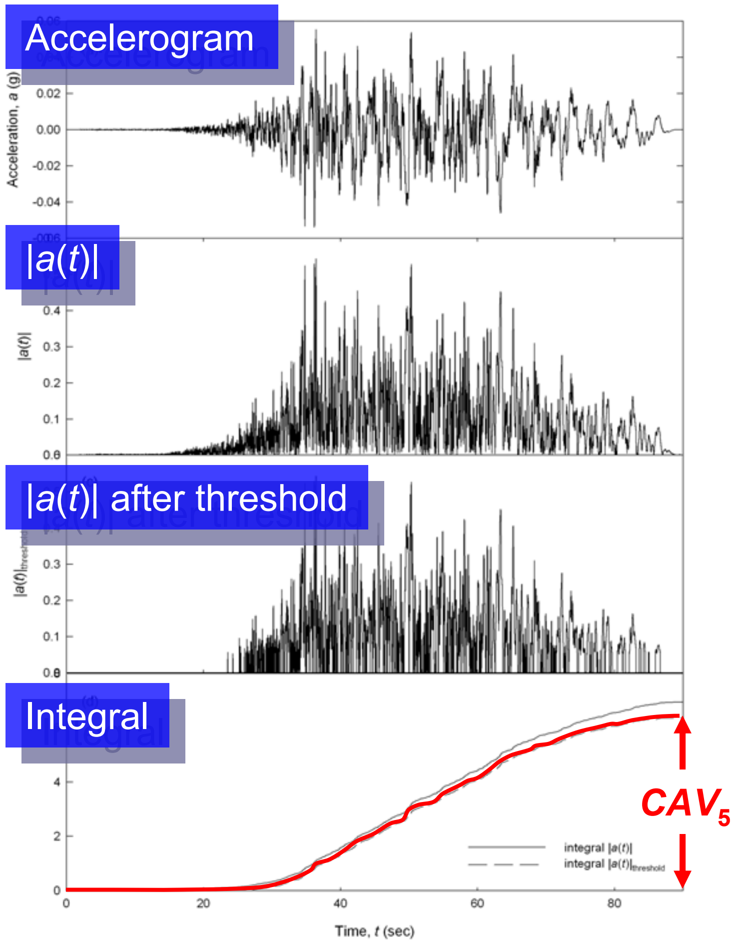
Slope instability $0.7 I_a^S + 0.3 I_a^W$

Lateral spreading $\sqrt{CAV_{5,S}^2 + CAV_{5,W}^2}$

Other Components

CAV_5

Cumulative absolute velocity
5 cm/sec^2 threshold



Other Components

		Weighting factors
Slope instability	$0.7 I_a^S + 0.3 I_a^W$	$w = 0.3$
Lateral spreading	$\sqrt{CAV_{5,S}^2 + CAV_{5,W}^2}$	$w = 0.2$
Post-liquefaction settlement	$\sqrt{CAV_{5,S}^2 + CAV_{5,W}^2}$	$w = 0.2$
Buried pipeline breakage	$\sqrt{PGV_S \, PGV_W}$	$w = 0.3$

Composite Damage Measure: $DM_{geo} = \sum_{i=1}^{4} w_i DM_i$

Note that all *IM*s have units of velocity – geohazards are most strongly affected by intermediate frequencies in spectrum

Instrumental Intensity Scales

Two approaches explored:

Damage Potential Intensity: $DPI_{geo} = 10DM_{geo}$

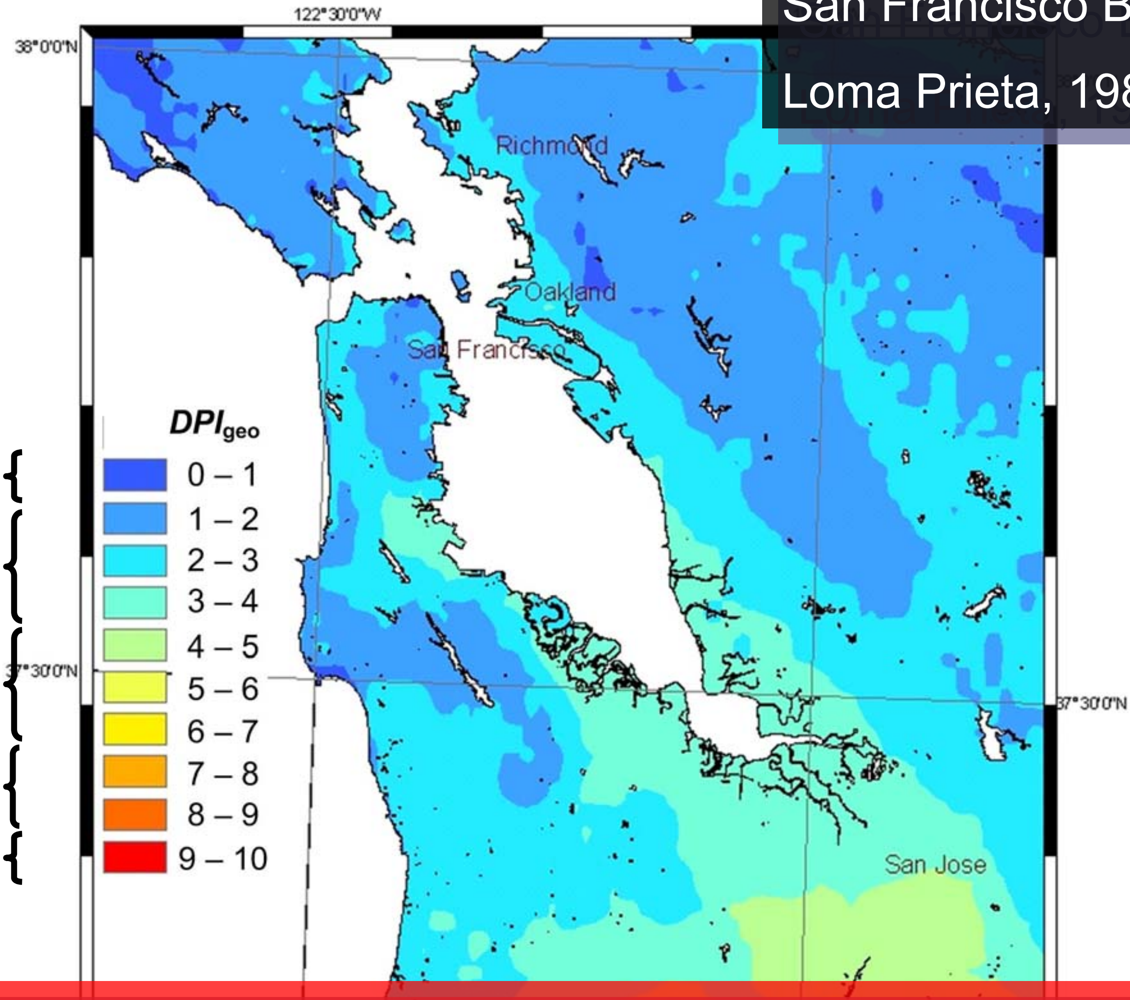
Damage State	DPI_{geo} range
Negligible	0 – 1
Minor	1 – 4
Moderate	4 – 7
Severe	7 – 9
Catastrophic	9 - 10

Application

ShakeMaps created for DPI_{geo} and I_{geo}

San Francisco Bay Area

Loma Prieta, 1989



Negligible (0 – 1)

Minor (1 – 3)

Moderate (3 – 6)

Severe (6 – 8)

Catastrophic (8 – 10)

Note: Actual damage depends on vulnerability

Instrumental Intensity Scales

Two approaches explored:

Apparent Magnitude-Related Intensity: $$I_{geo} = \frac{6.6138}{(-\ln DM_{geo})^{0.10649}}$$

Based on simple attenuation relationship for DM_{geo} on reference site condition (rock)

Solved for M at reference distance (25 km)

I_{geo} interpreted as earthquake magnitude expected to cause equivalent damage at rock site located 25 km from epicenter

Application

ShakeMaps created for DPI_{geo} and I_{geo}

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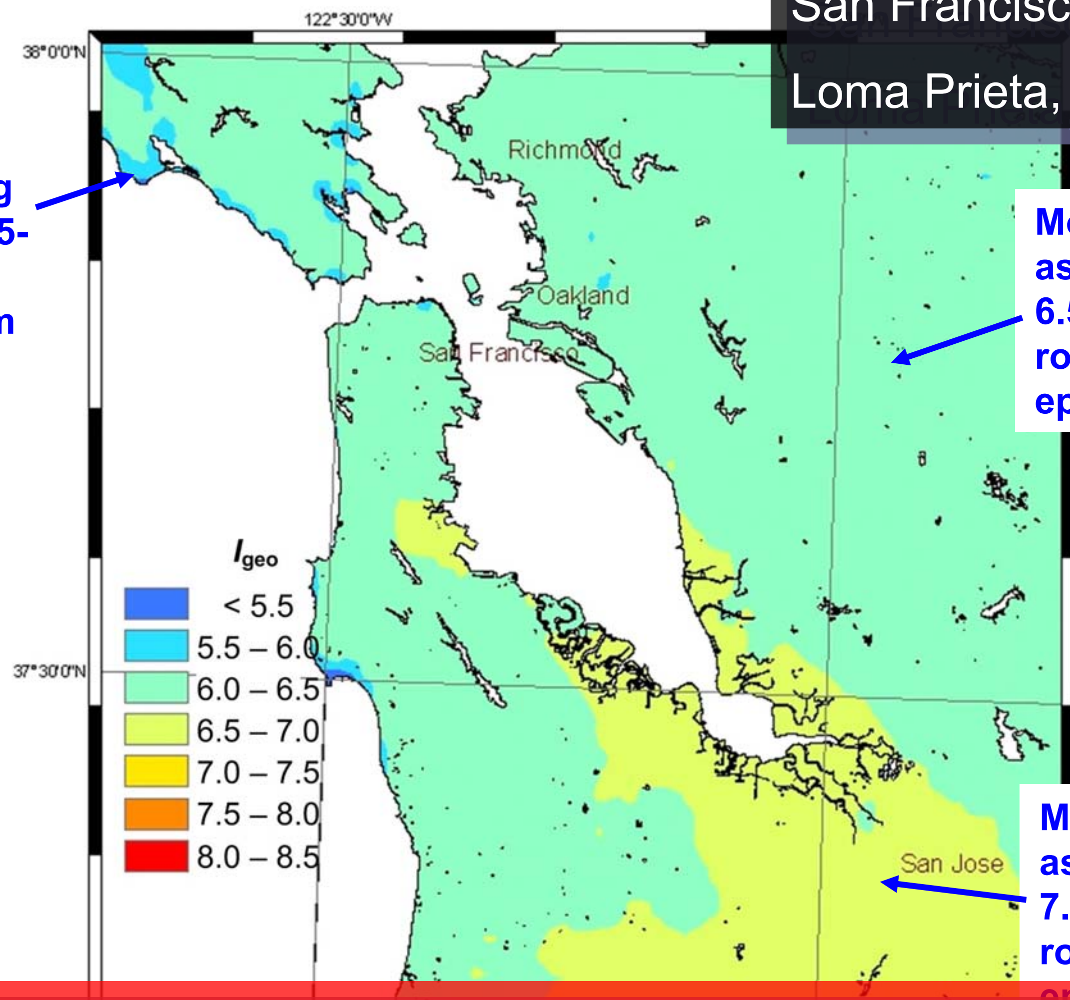


Motion as damaging as motion from M5.5-6.0 earthquake at rock site 25 km from epicenter

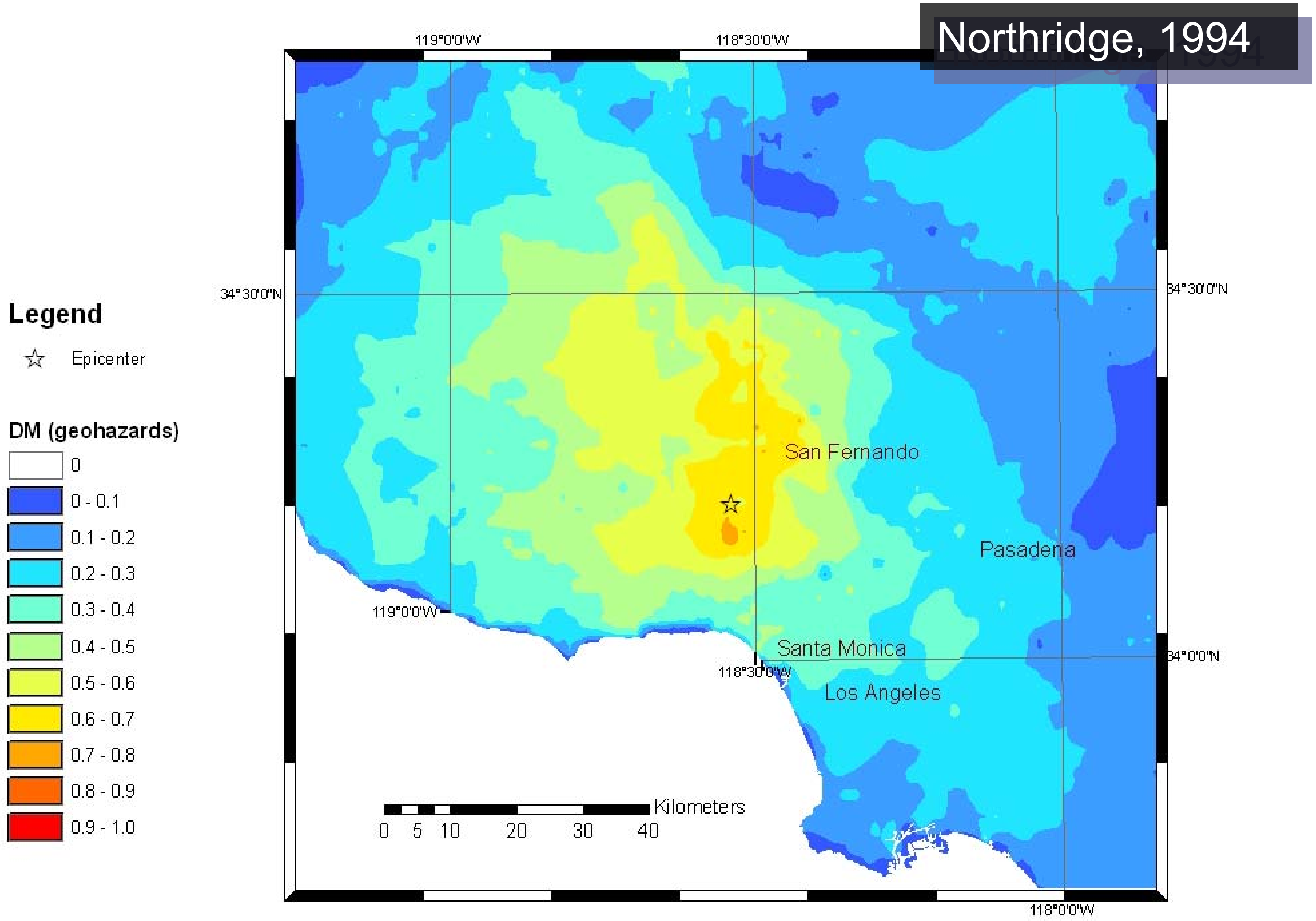
Motion as damaging as motion from M6.0-6.5 earthquake at rock site 25 km from epicenter

Motion as damaging as motion from M6.5-7.0 earthquake at rock site 25 km from epicenter

Note: Actual damage depends on vulnerability

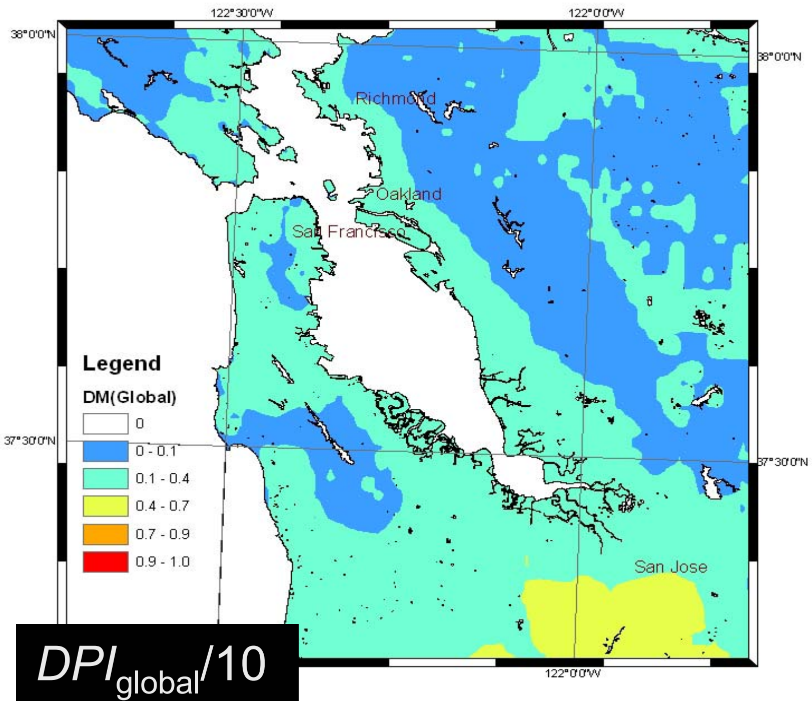
Application

ShakeMaps created for DPI_{geo} and I_{geo}

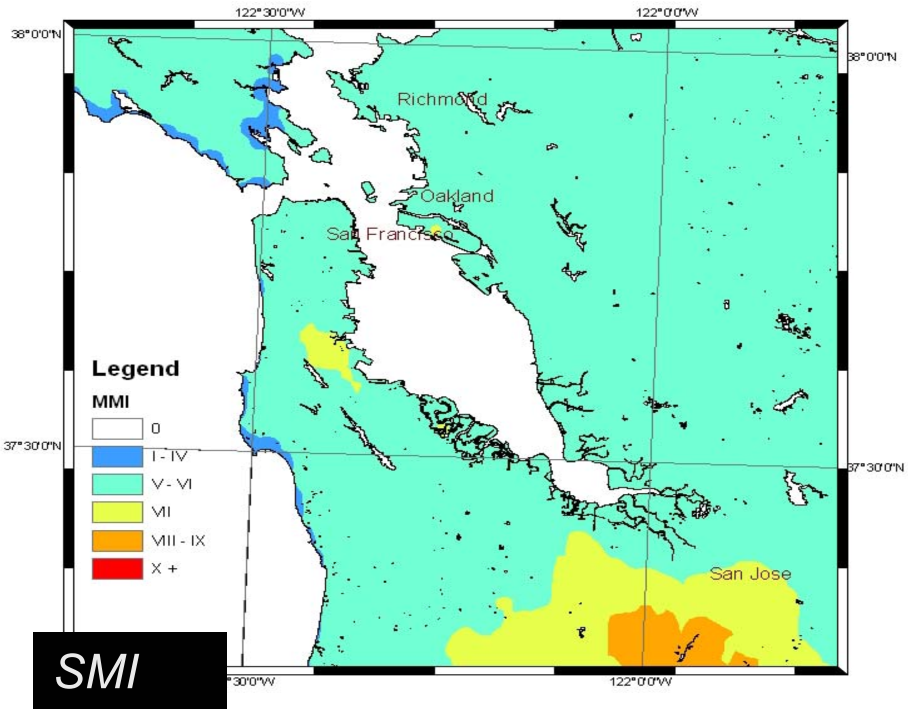


Application

Comparison with SMI



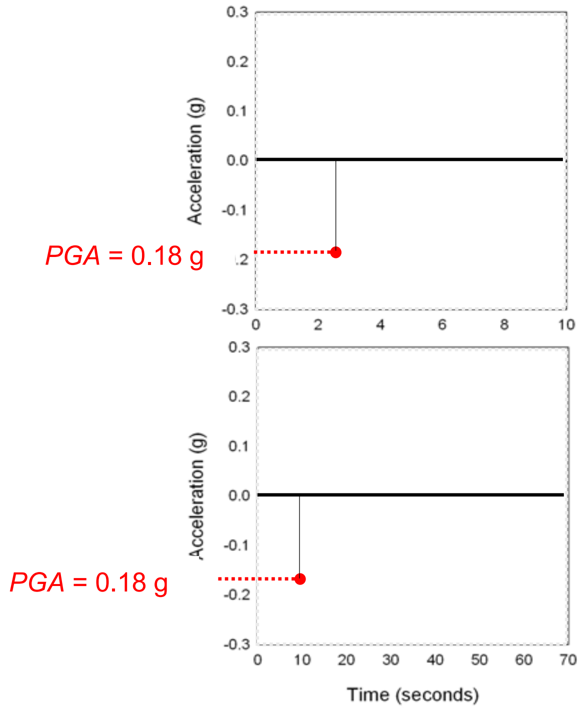
Response of median engineered mechanisms



"Felt" intensities - Response of weaker, more vulnerable elements

Advantages of DPI_{geo} over *SMI*

Comparison with *SMI*



Large difference in duration

Same *PGA* = Same *SMI*

Advantages of DPI_{geo} over *SMI*

Comparison with SMI

***SMI* = 6.5**
(light – moderate damage)

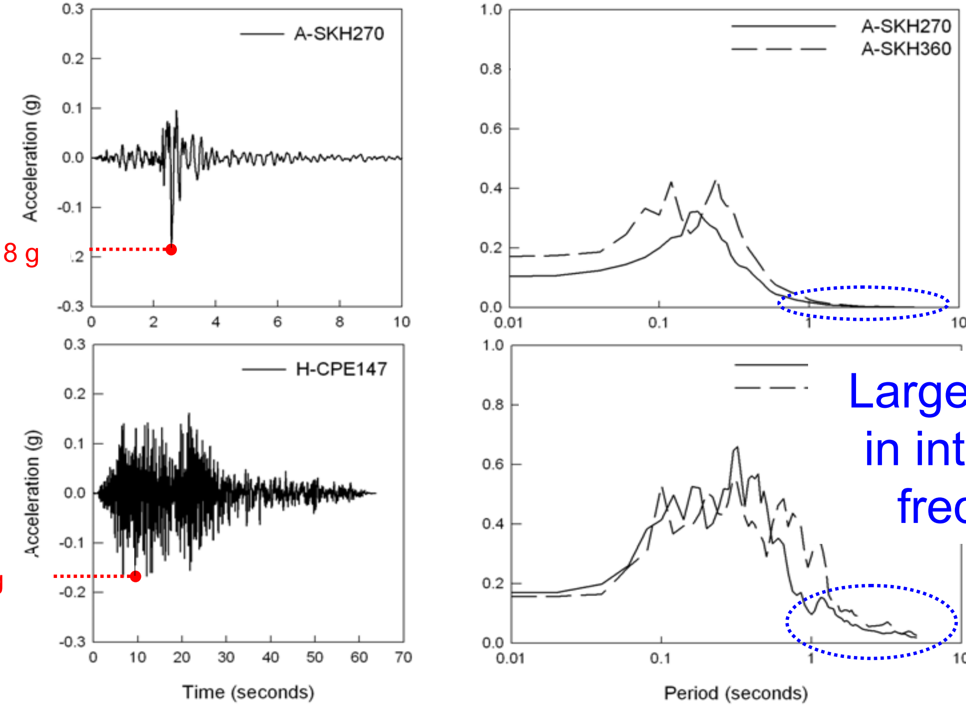
***DPI_{geo}* = 0.1**
(negligible damage)

PGA = 0.18 g

***SMI* = 6.5**
(light – moderate damage)

***DPI_{geo}* = 2.4**
(minor damage)

PGA = 0.18 g



Large difference in intermediate frequencies

Same *PGA* = Same *SMI*

Conclusions

- Different physical mechanisms contribute to geohazard-related damage
- Geohazard-related damage appears to be most closely correlated to velocity-related parameters of intermediate frequencies
- *DPI* scale more accurately reflects ground motion characteristics than currently used methods implemented in ShakeMaps
- Intensity scales can be used to communicate damage potential to technical and non-technical users
- Actual damage depends on the vulnerability of inventory
- Overlaying inventory data on *DPI*-based ShakeMap could produce more accurate short-term estimates of actual damage for emergency response and other applications