Assessing & Mitigating Surface Fault Rupture Deformation

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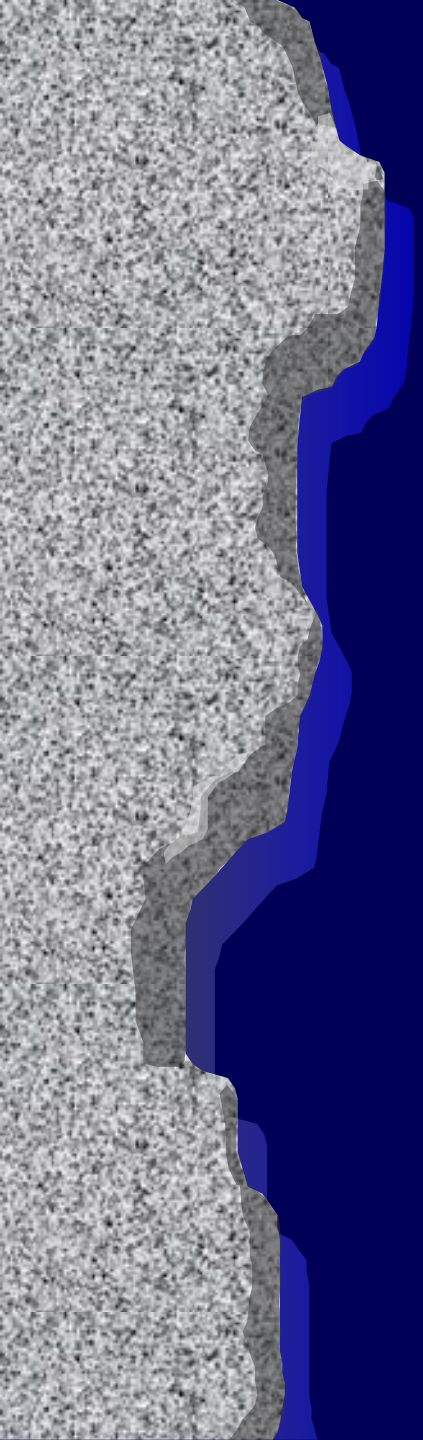


Characteristics and Effects of Surface Rupture Depend on:

- fault type
- inclination of fault plane
- amount of fault displacement
- fault definition
- overlying earth material
- structure and its foundation

Broad Area of Building Damage on Hanging Wall of Reverse Fault

1999 Chi-Chi EQ

Not on footwall

Reverse Fault Experiment (Davies et al. 2007)

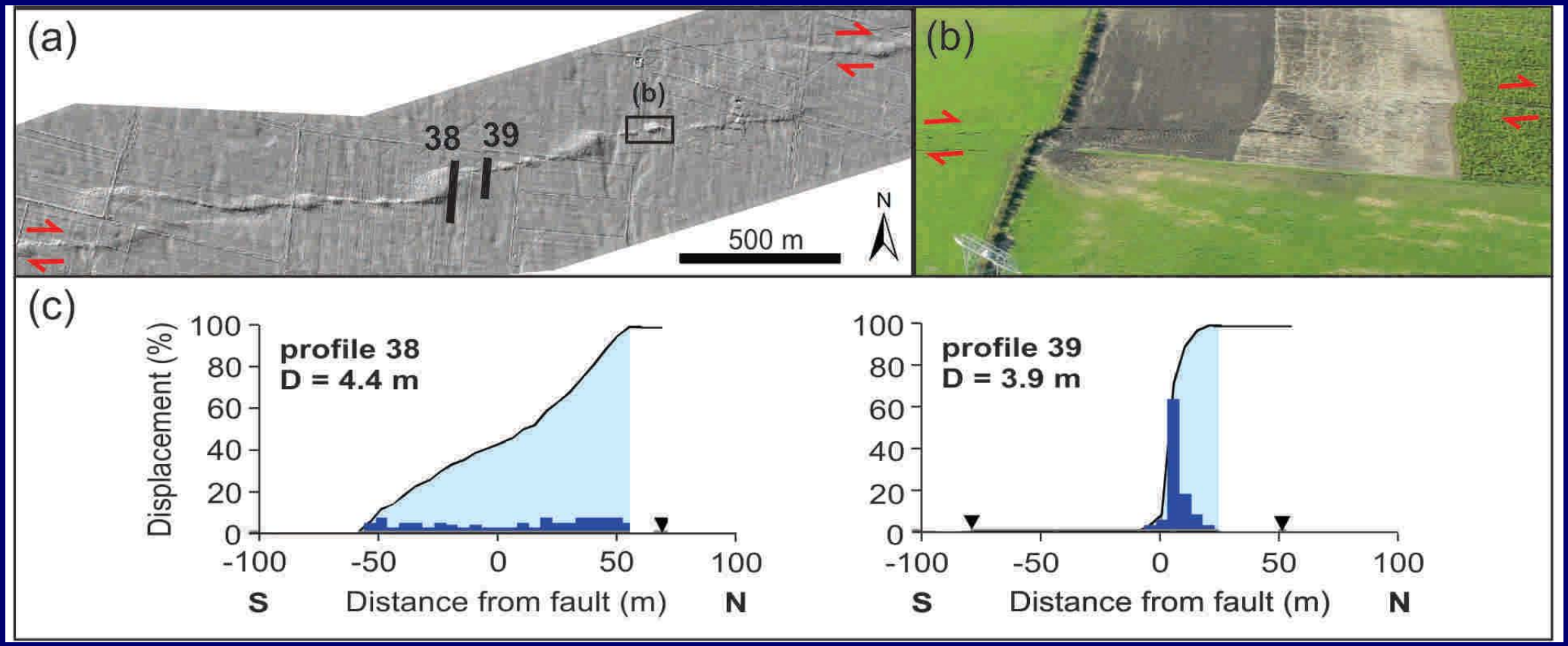
Broad Area of Building Damage on Hanging Wall of Normal Fault

Not on footwall

1999 Kocaeli EQ

Distributed Ground Movement: 2010 Darfield Earthquake

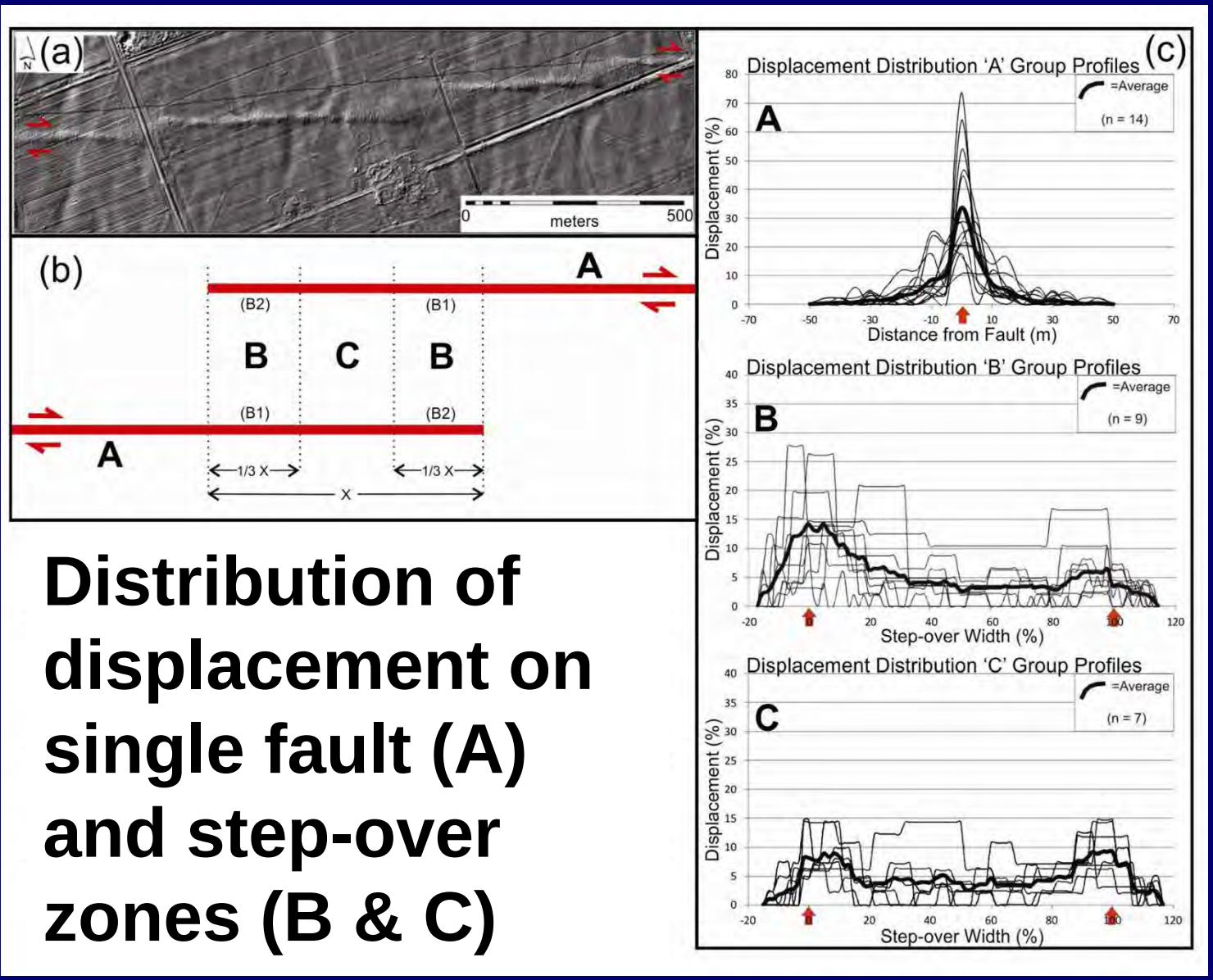
Van Dissen et al. 2013



- **50% of horz. displ. occurred over 40% of width of deformed zone with offset on discrete shears accounting for < 33% of total displ.**
- **Horz. displ. of 1 m required before ground cracks observed**

Distributed Ground Movement: 2010 Darfield Earthquake

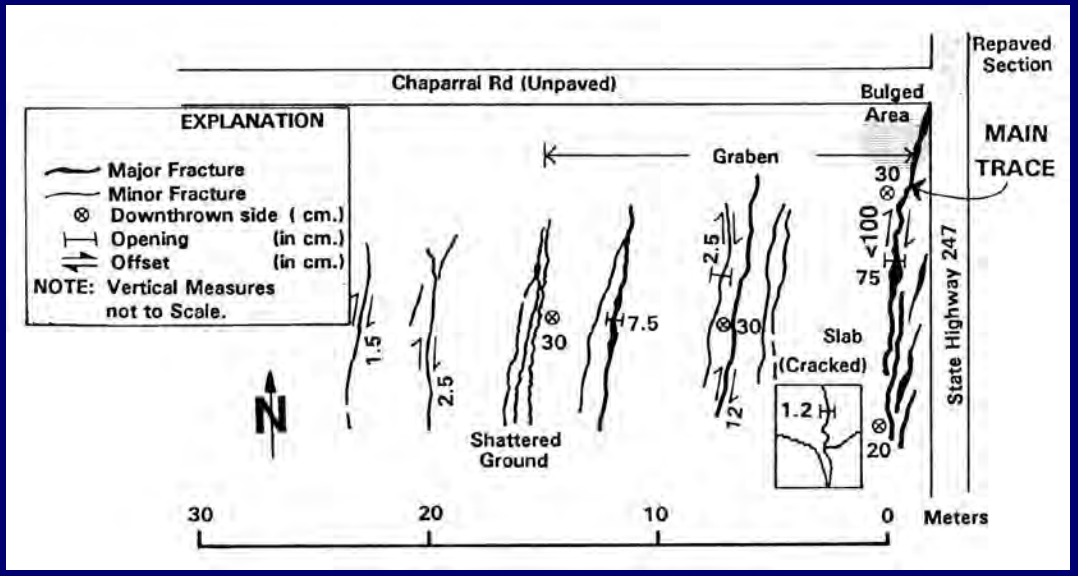
Van Dissen et al. 2013

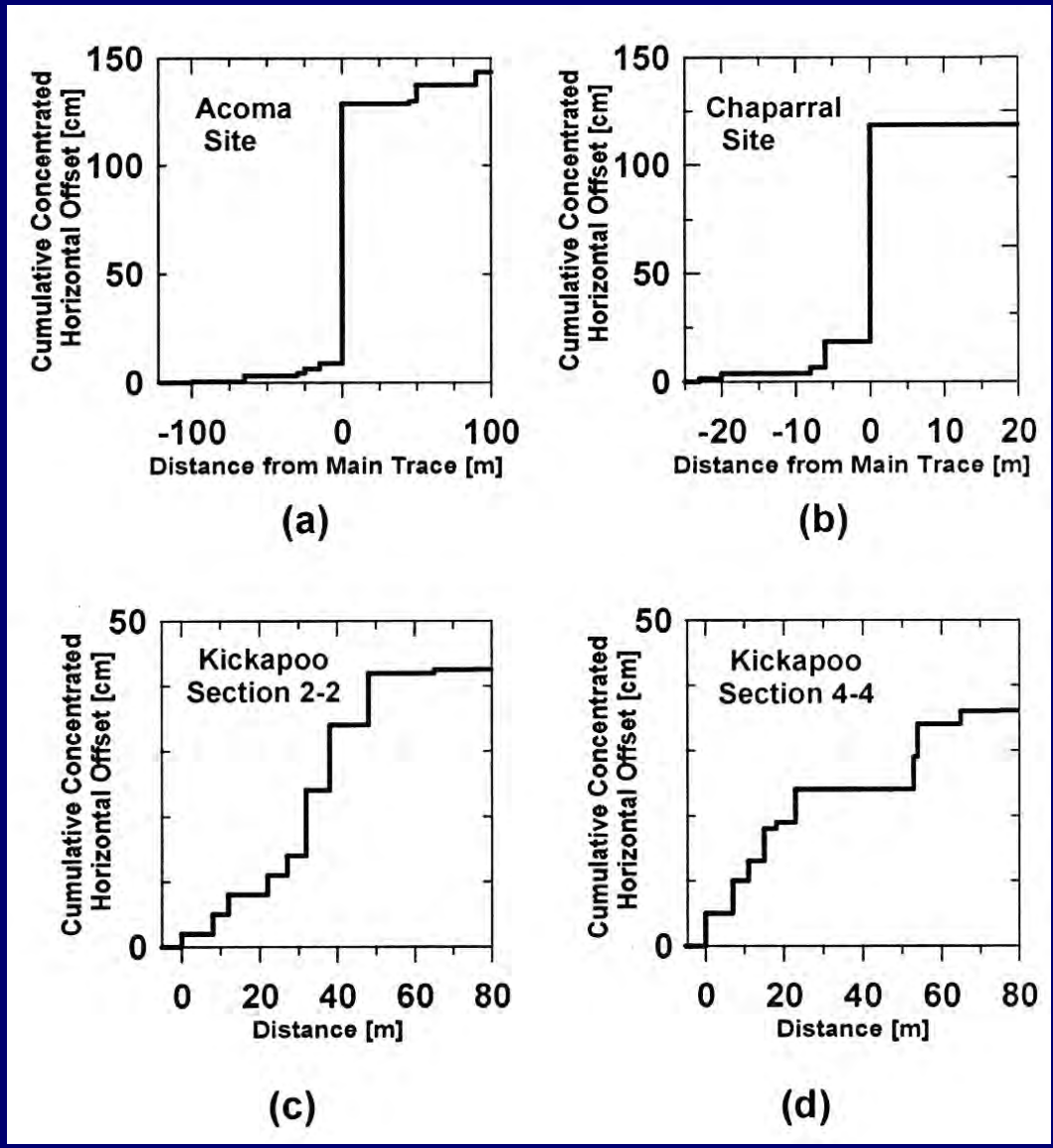


Distribution of displacement on single fault (A) and step-over zones (B & C)

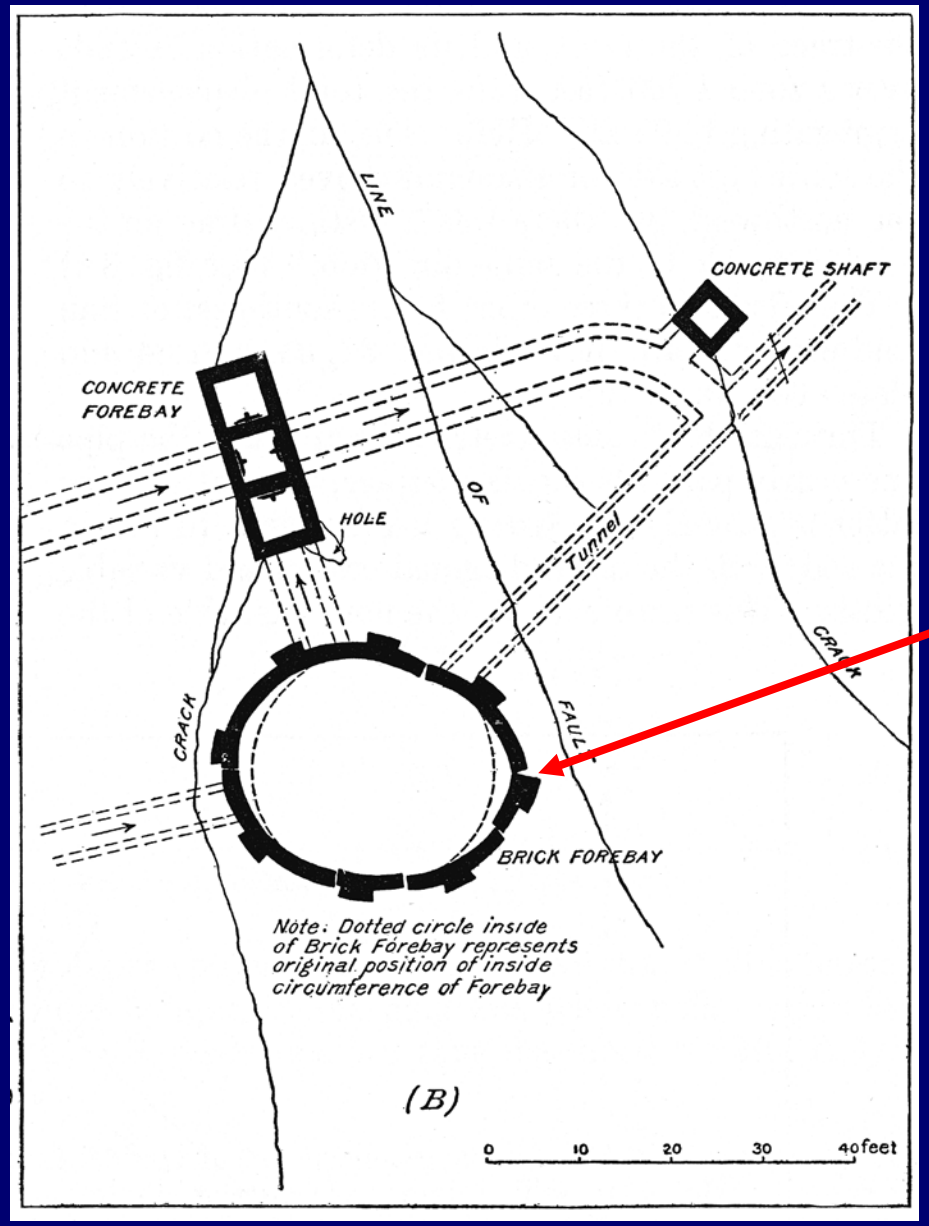
1992 Landers Earthquake Ground Deformation

Lazarte, Bray & Johnson (1994)

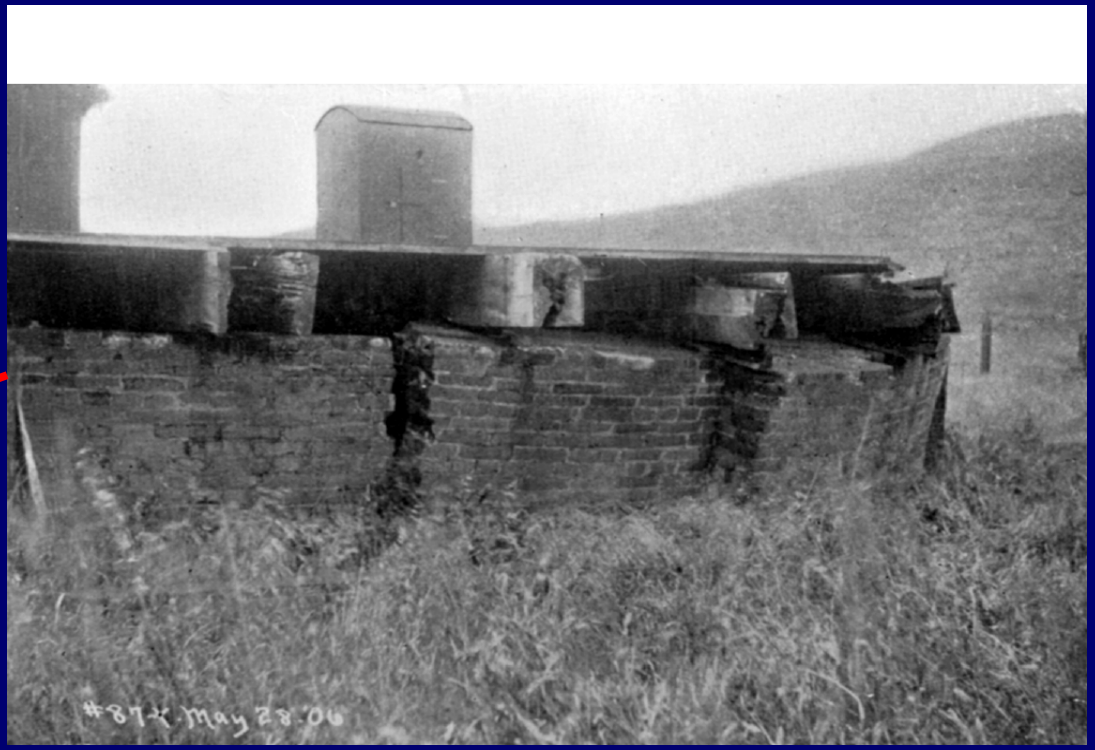




Soil Deformation between Shear Ruptures



1906 San Francisco EQ
(Lawson 1908 & Schussler 1906)

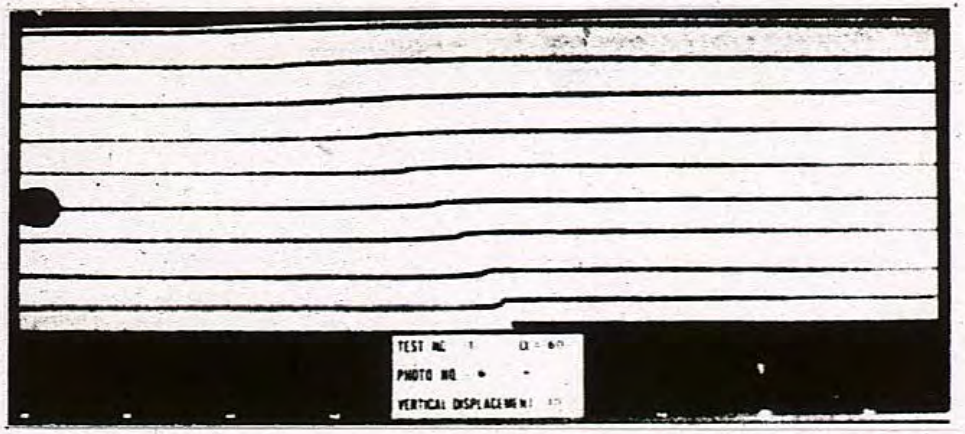


Soil Effects

1906 San Francisco EQ

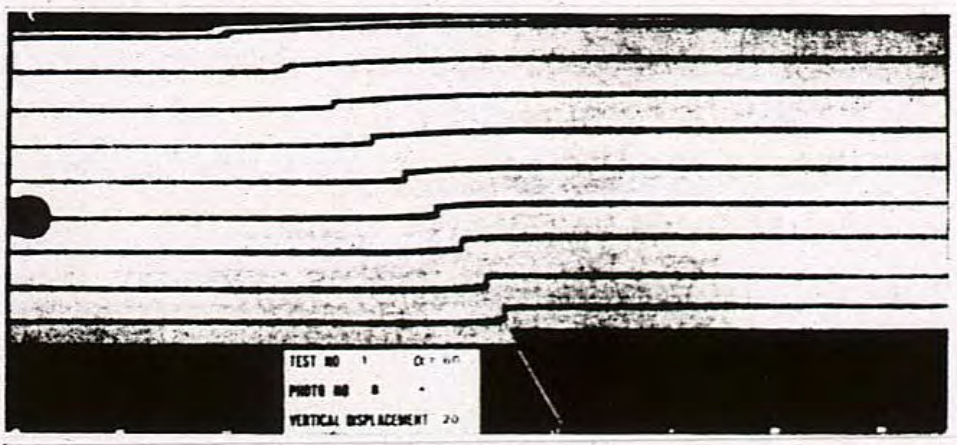
"It could be traced as a multitude of small cracks in the swampy land … then as a well-defined fissure up … to where it disappeared in the sand dunes." **(Lawson 1908)**

Earthquake Fault Rupture Propagation through Soil



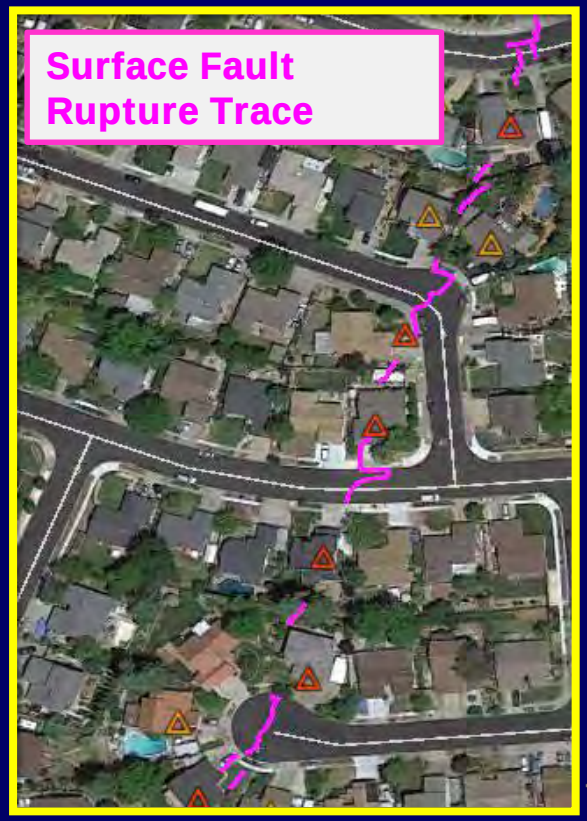
(B) Initiation Of Failure Surface At Bedrock Fault

(Lade and Cole 1984)



(C) Fully Developed Failure Surface

Surface Fault Rupture Damage to Homes in M6 South Napa EQ



Documented 27 homes affected by surface rupture

Average observed deformation: 100 to 125 mm

Key Observations:

- No life safety issue resulted from surface faulting
- Unreinforced concrete slabs cracked
- Reinforced slabs slid uniformly or tilted
- Structures on pier foundations more heavily damaged
- Seismically retrofit homes/new construction performed best

GEER Report-037 Bray et al. 2014

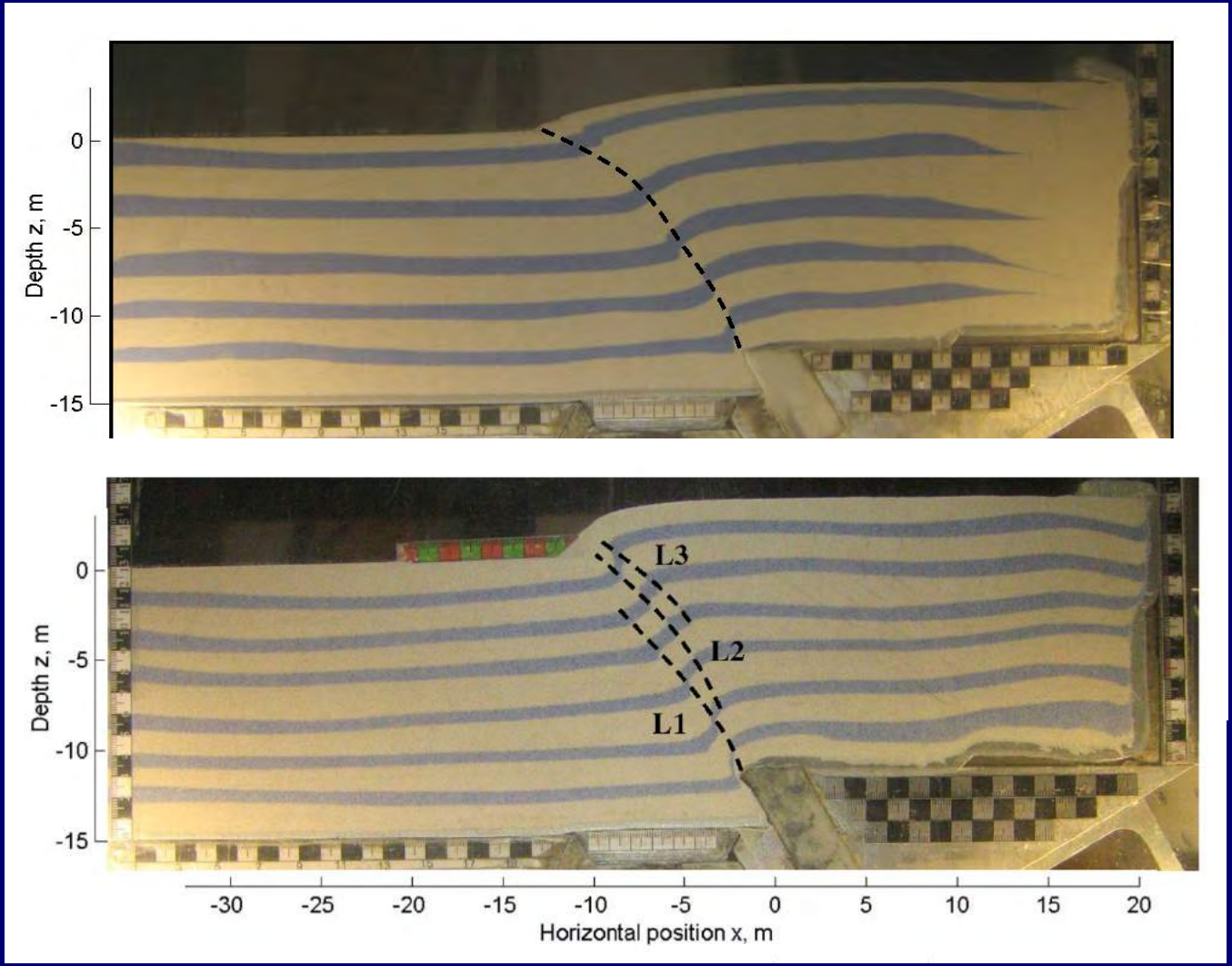
Cracked garage slab

Pushed off foundation

Rupture through piers

Damage to structure

Stiff Mat Foundation Affects Characteristics of Surface Fault Rupture

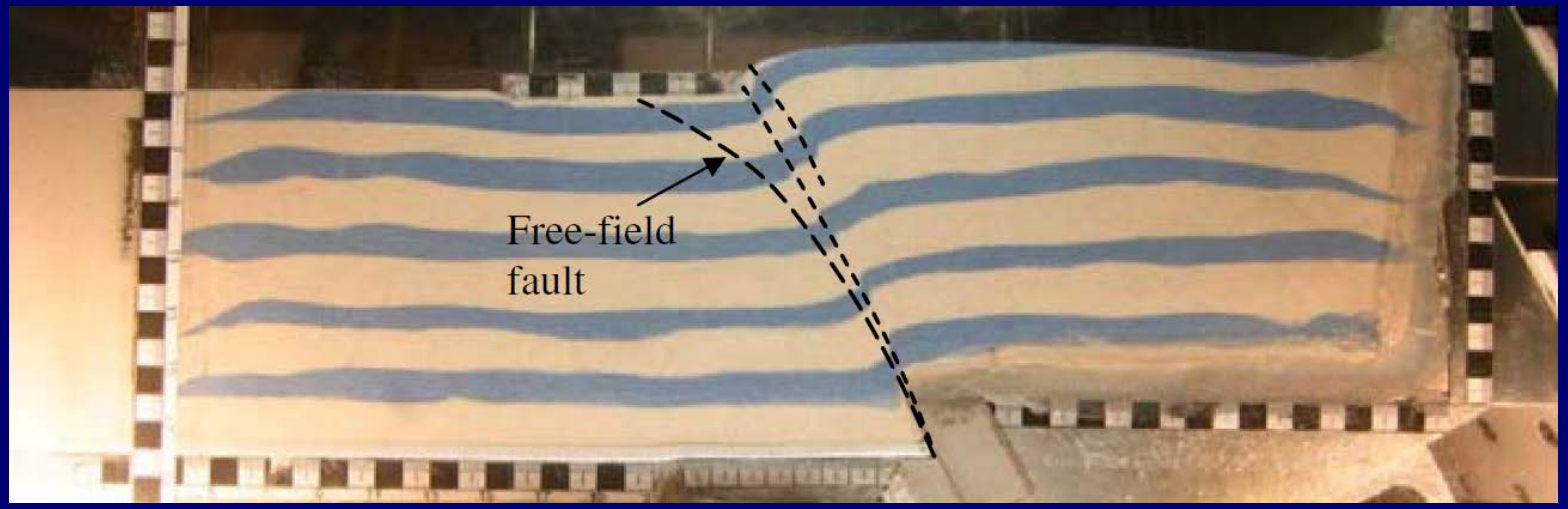


Davies et al. 2007; provided by Anastapolous & Gazetas

WEIGHT OF MAT FOUNDATION EFFECTS

Light Load:
q = 37 kPa

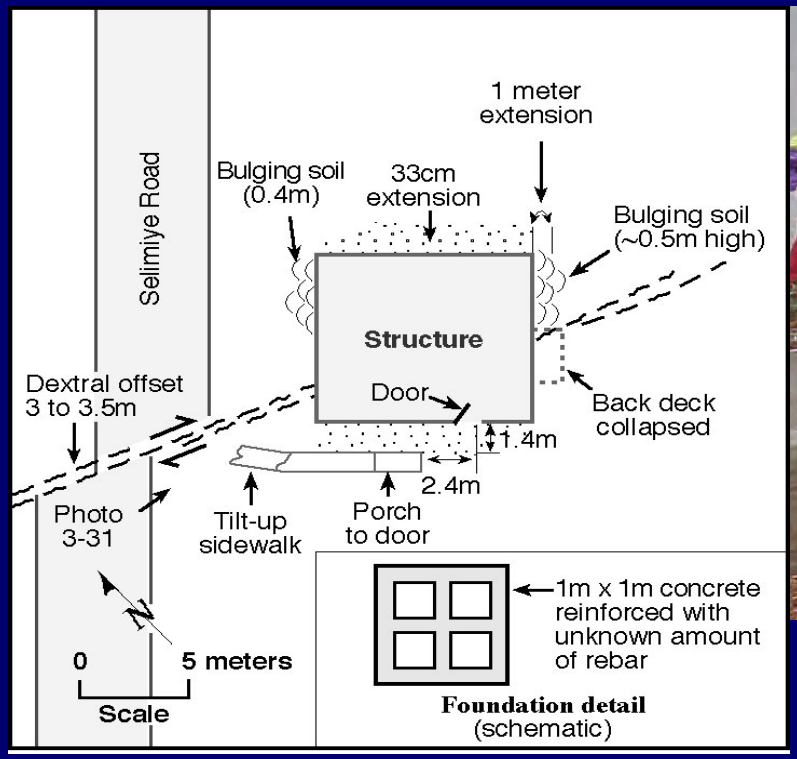
Heavy Load:
q = 91 kPa

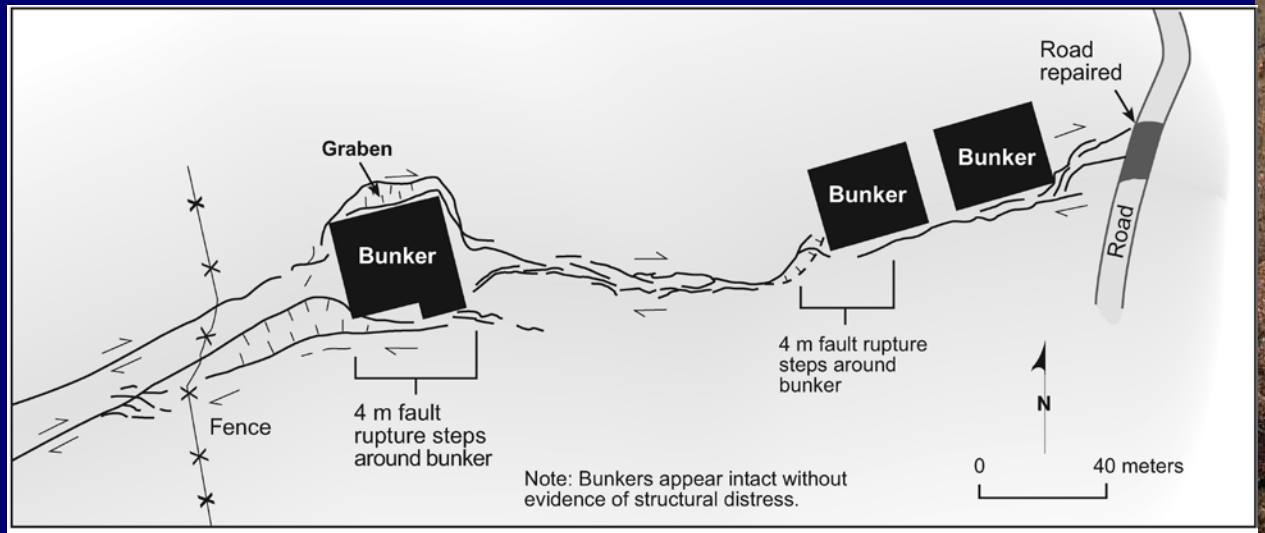


Davies et al. 2007 provided by Anastapolous & Gazetas

Systems (Tied to the Ground) Damaged by Faulting

Systems (Not Tied to Ground) Not Damaged by Faulting - Decoupling





Mapped by : J. Bachhuber and W. Lettis

An Analogy

ROOTED TREE DAMAGED

POLE UNDAMAGED

Photographs from Prof. R. Ulusay, Turkey

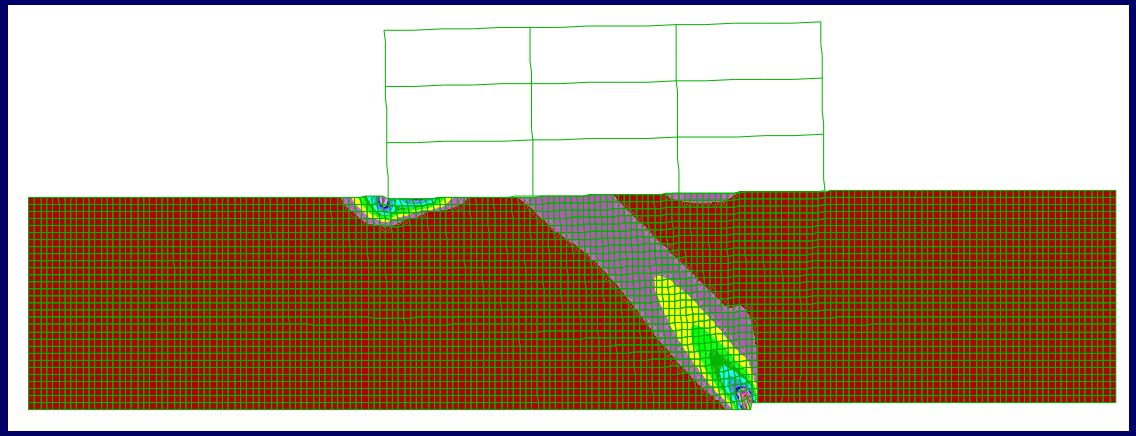
Mitigation Strategies

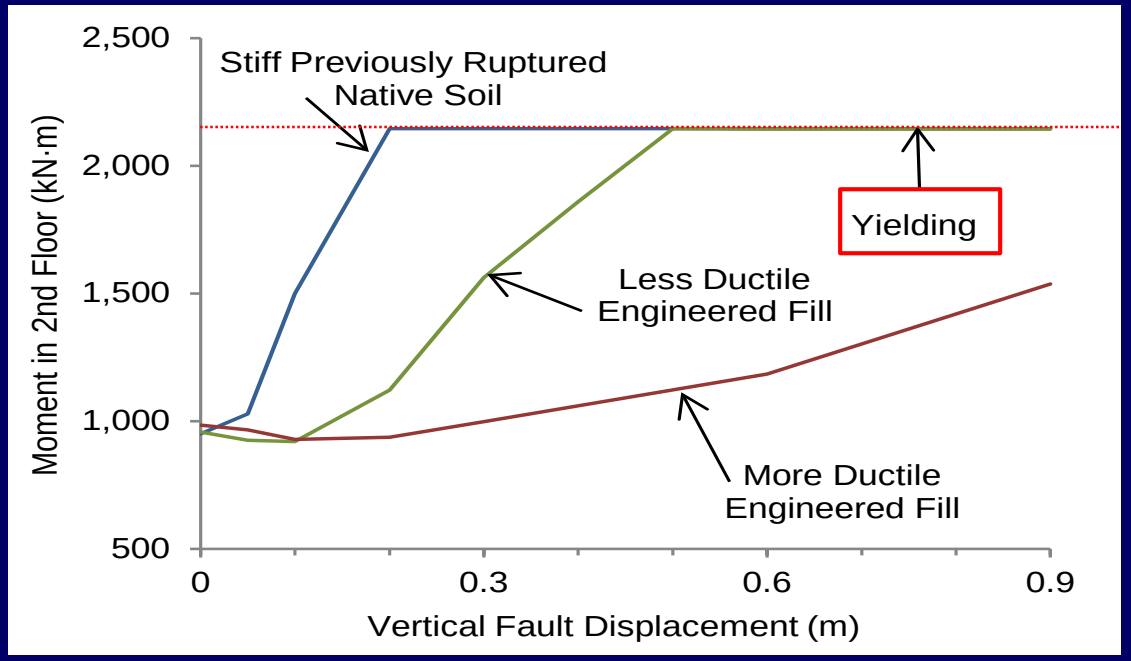
A. Diffuse fault offset

B. Accommodate fault offset

C. Divert fault offset

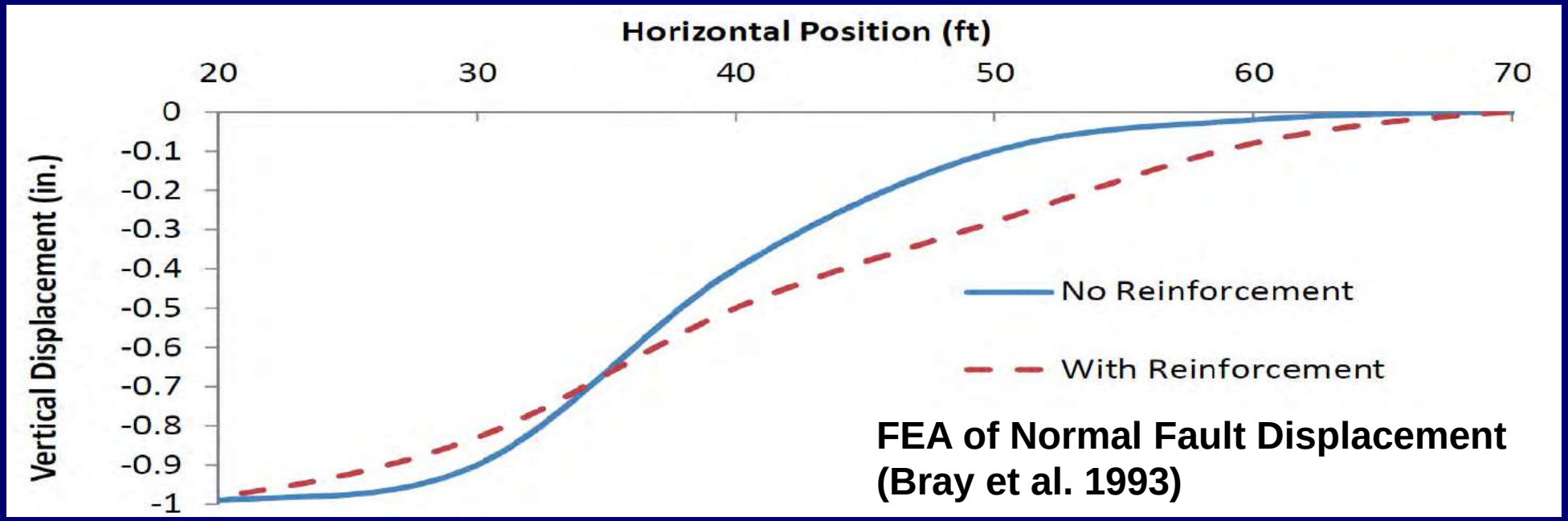
Diffuse Underlying Fault Movement with Engineered Fill





Oettle and Bray (2013)

Reinforcement Improves Fill Ductility and Diffuses Ground Movement

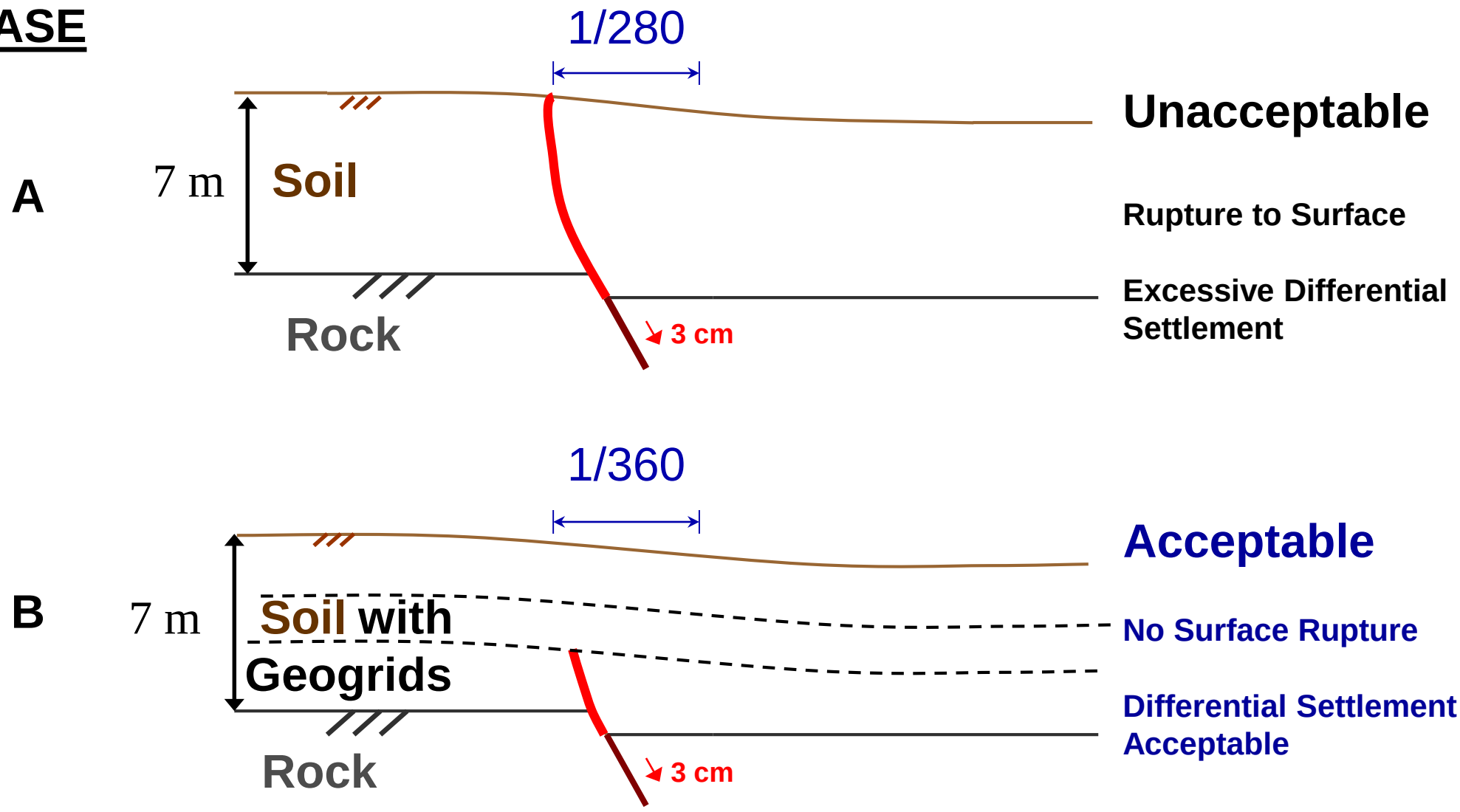


FEA of Normal Fault Displacement (Bray et al. 1993)

(Shewbridge and Sitar 1993)

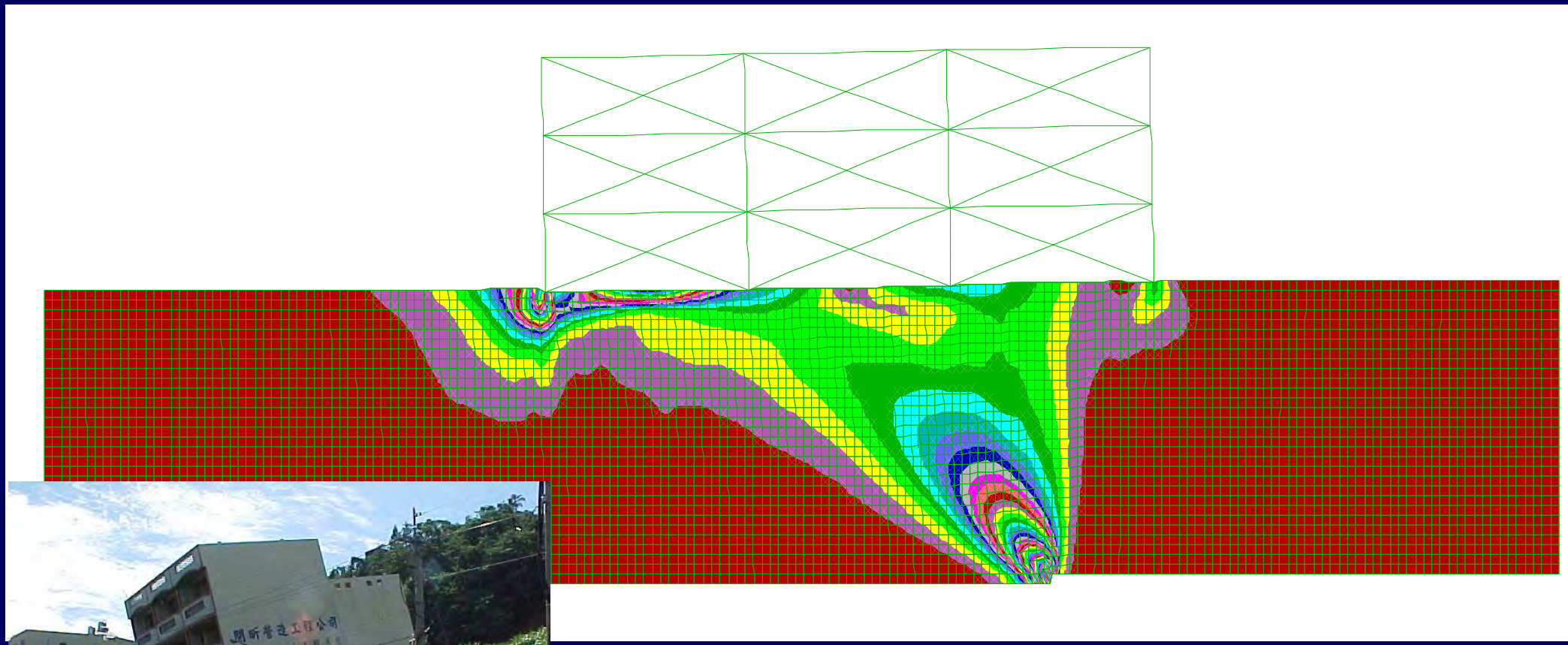
RESULTS OF NUMERICAL SIMULATIONS (Bray 2001)

CASE



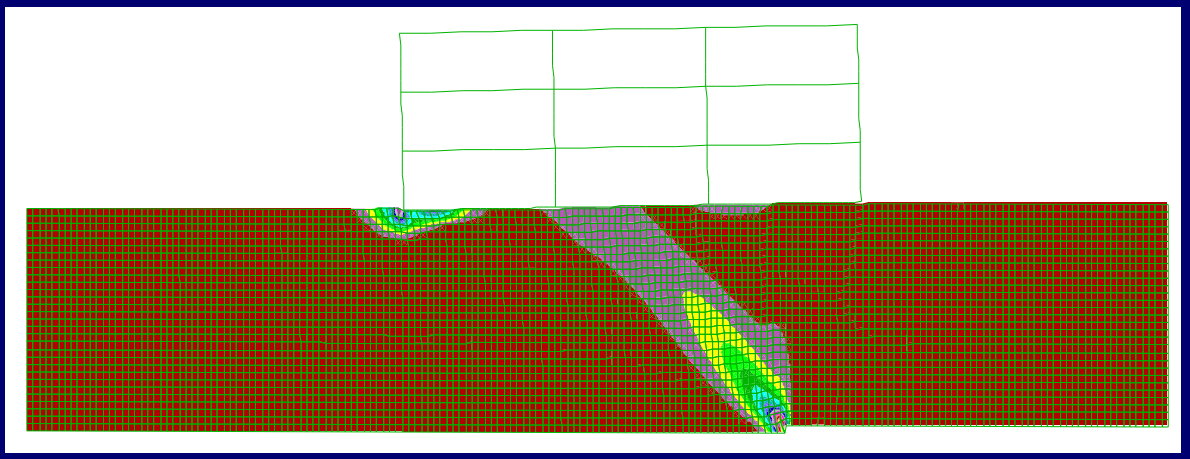
Accommodation with Strong Structure

Stronger building modifies the structural response



(Oettle & Bray 2013)

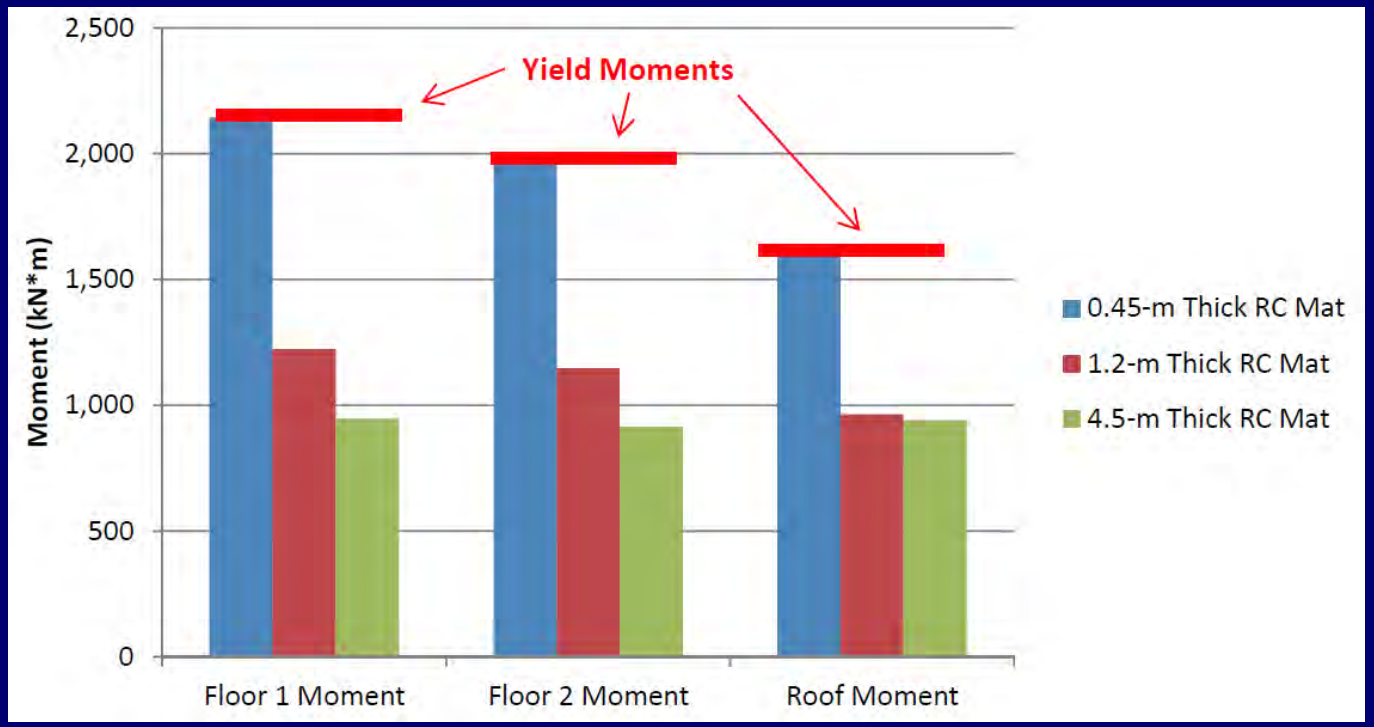
Effects of Foundation Strength & Stiffness



15 m deep sand deposit

70 cm reverse fault displ.

(Oettle & Bray 2013)

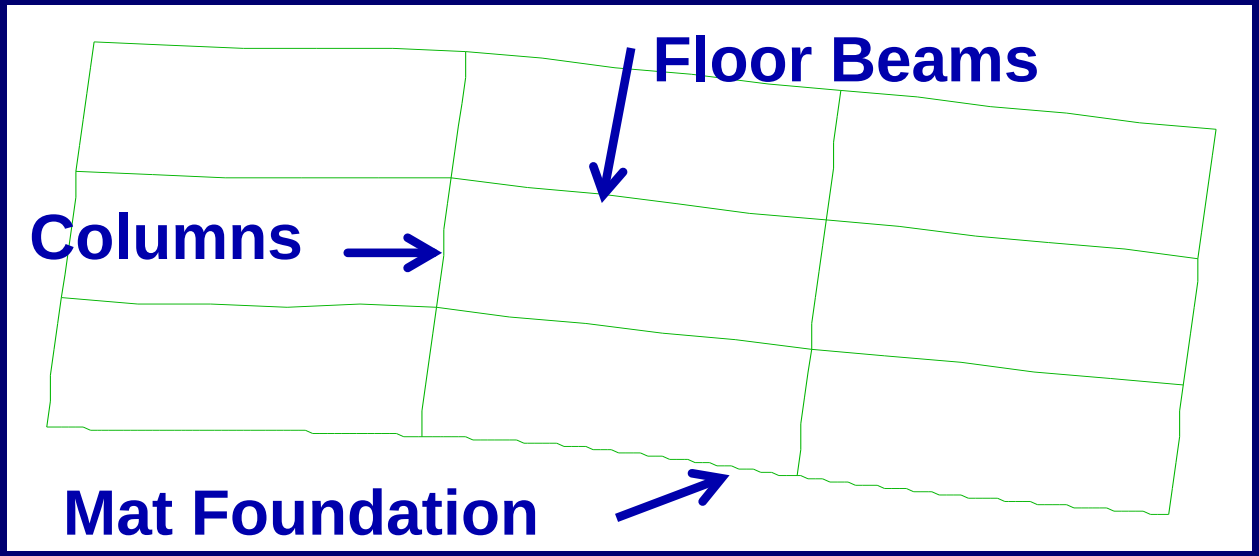


Thicker mat foundation significantly reduces building damage

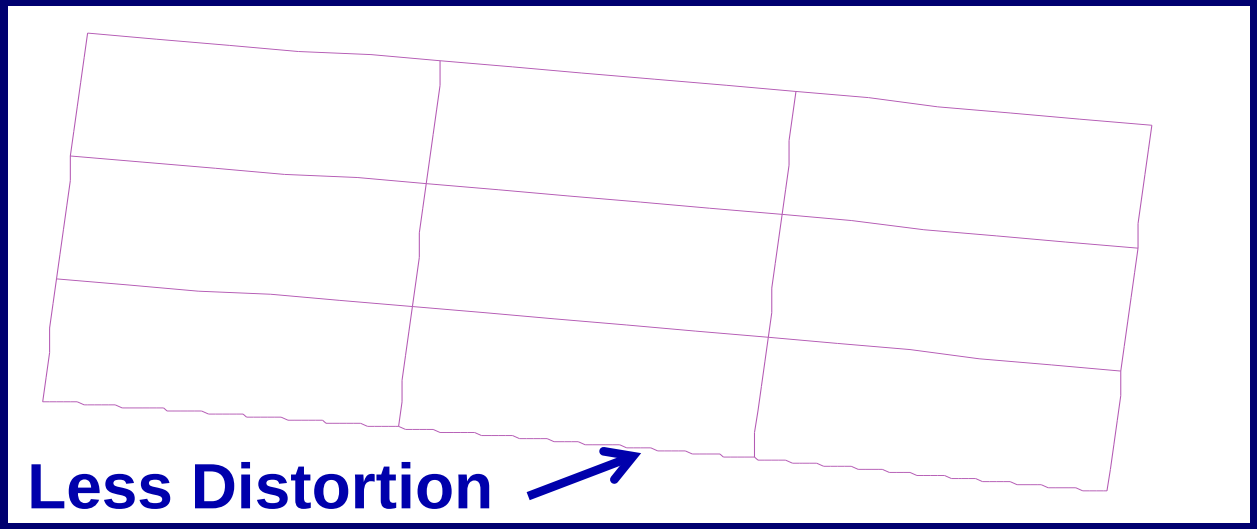
Accommodation with Thick Mat Foundation

Thicker mat foundation "shields" structure from ground deformation

Mat Thickness
= 0.45 m



Mat Thickness
= 1.2 m



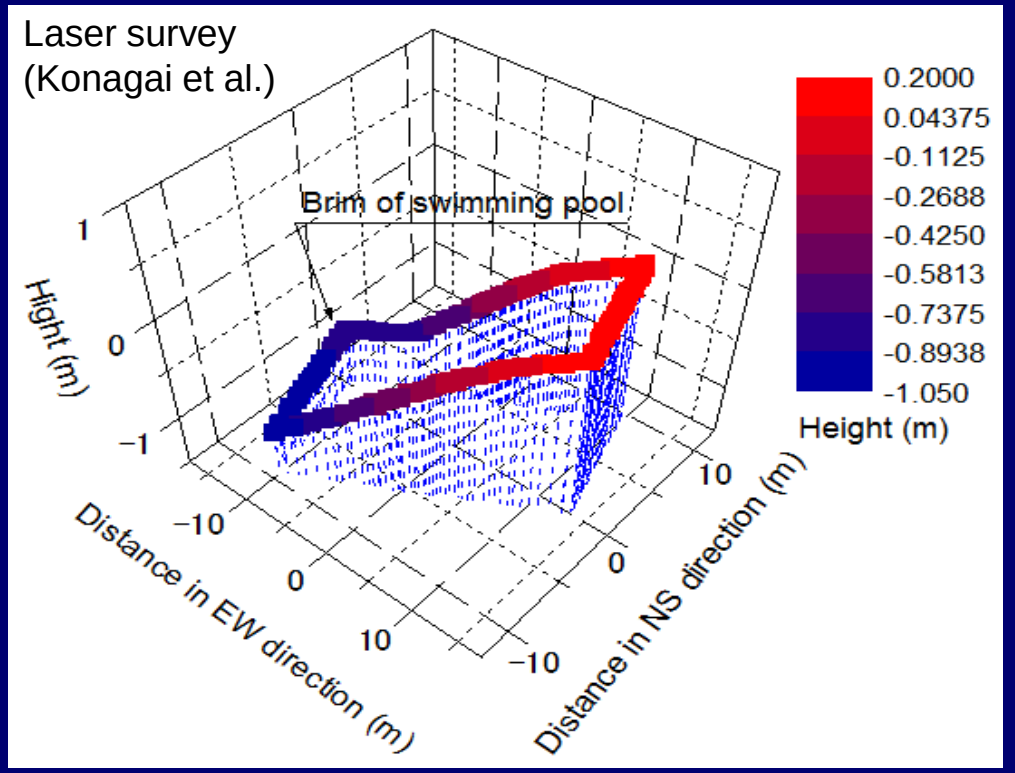
Oettle and Bray (2013)

Accommodate Ground Movement with Stiff Foundation

M_w 6.6 Hamadoori Aftershock of 4/11/11:
Shionohira Fault Displacement at Tabito Middle School

2-3^o tilt of building without loss of functionality

Accommodate Ground Movement with Ductile Structure



M_w 6.6 Hamadoori Aftershock of 4/11/11:
Shionohira Fault Displacement at Tabito Middle School

1.25 m vertical displacement of pool without cracking

Anchorage Courthouse

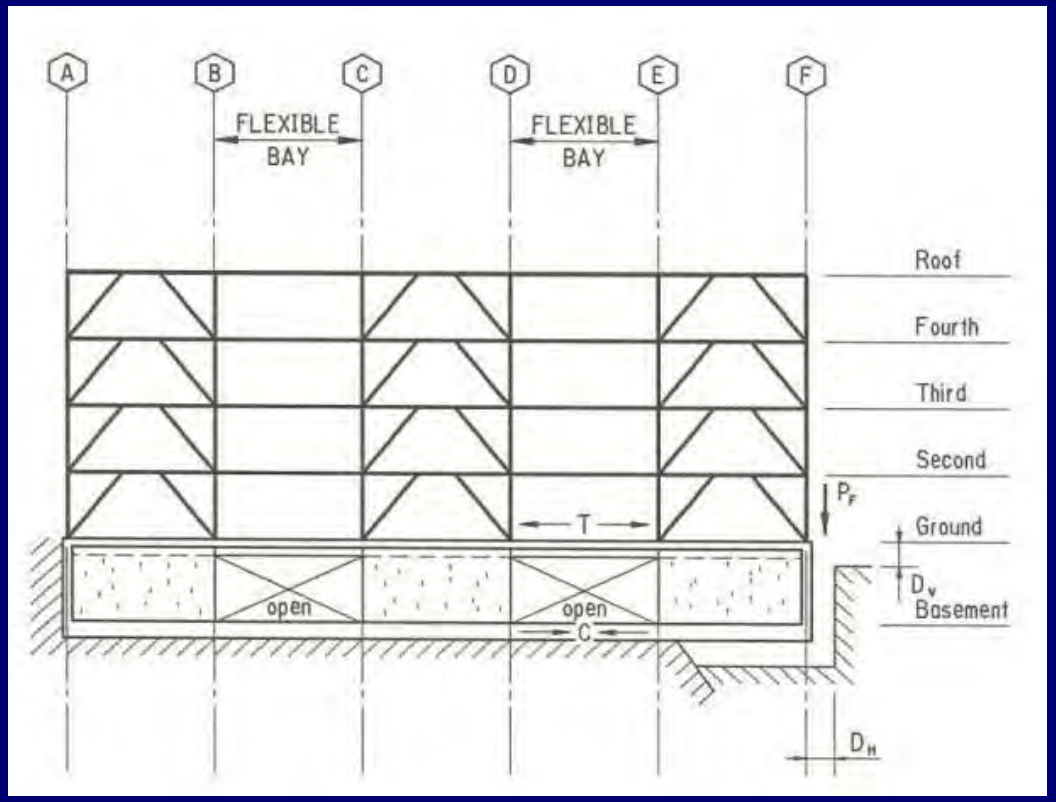
Translatory Block Slide

(Modified after Hansen, Ref. 7)

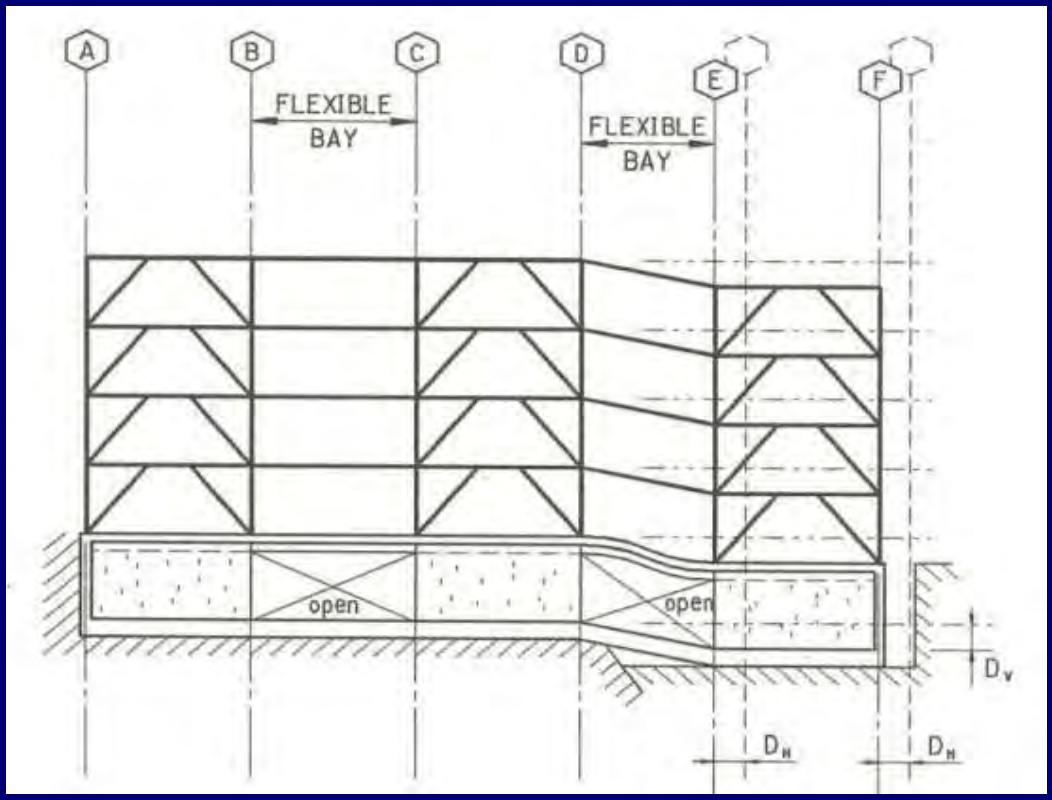
Craig Comartin, SE, with Idriss, Moriwaki, Shah et al.

Anchorage Courthouse: Structural System

Stiff Bay's "Cantilever" Response



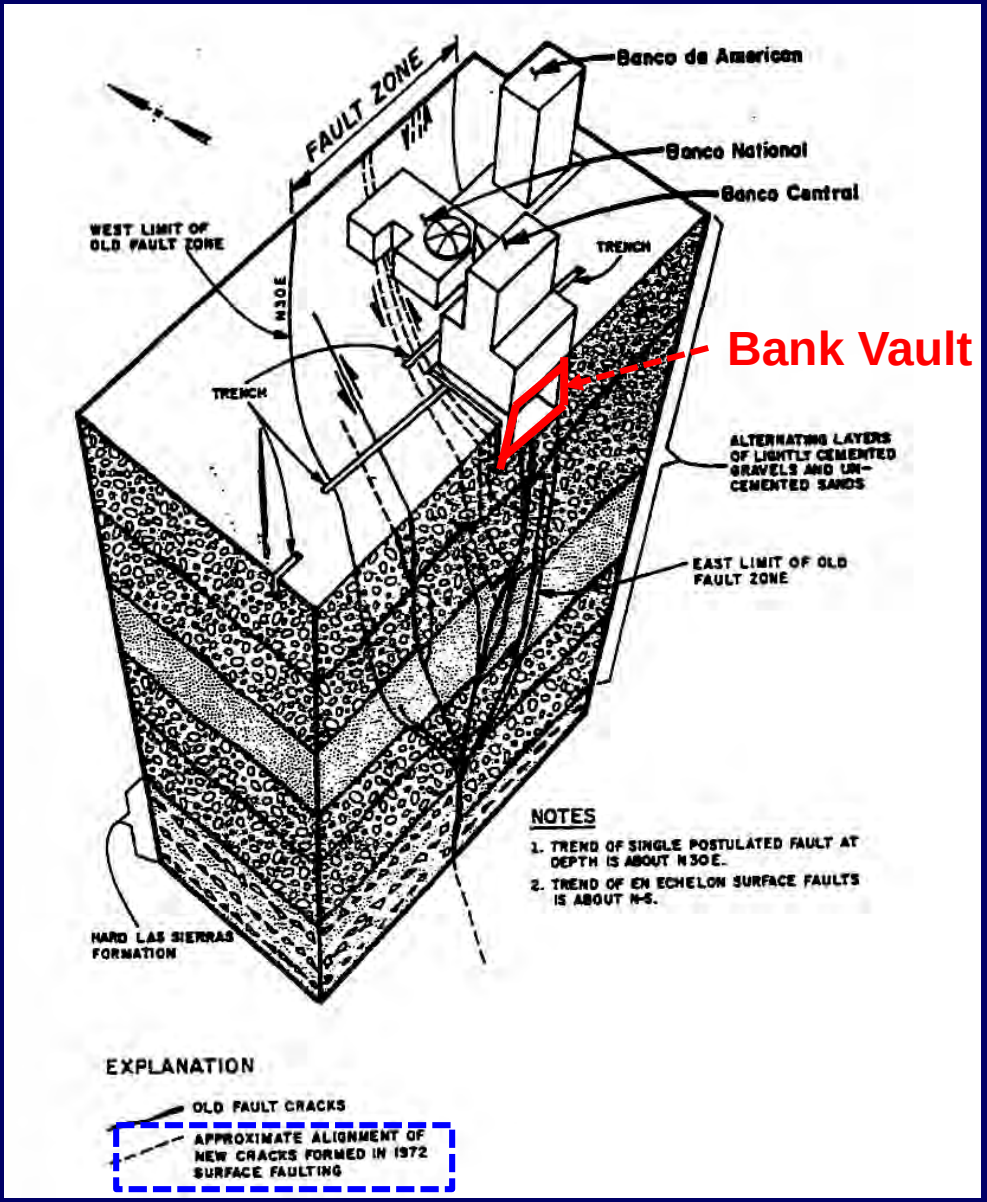
Flexible Bay's "Deformed" Response



D_H = 1.2 m D_V = 0.8 m

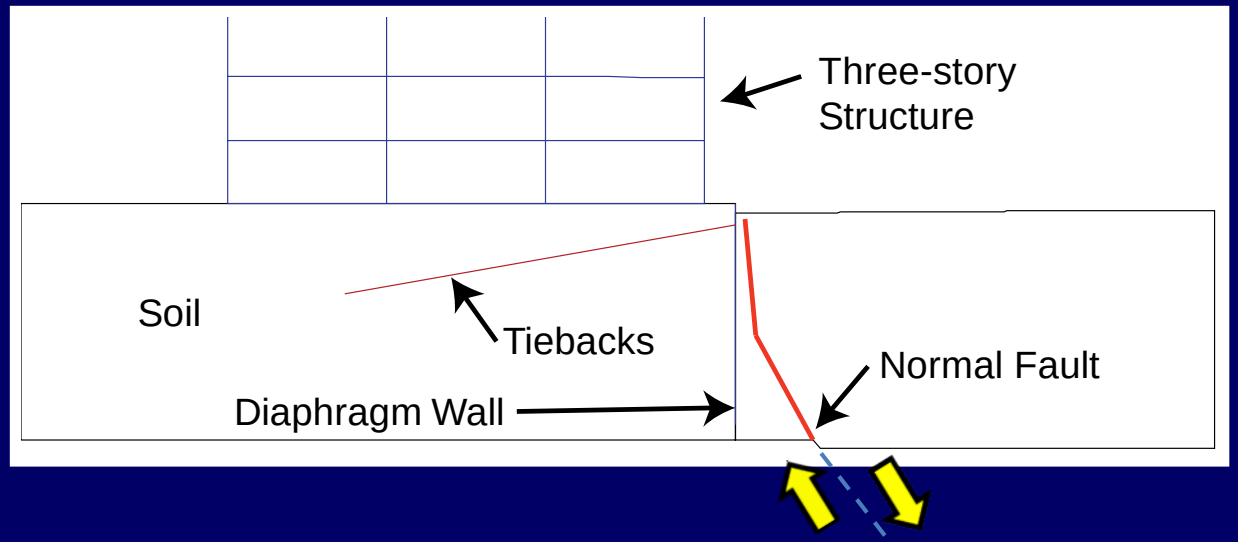
Craig Comartin, SE, CDComartin, Inc.

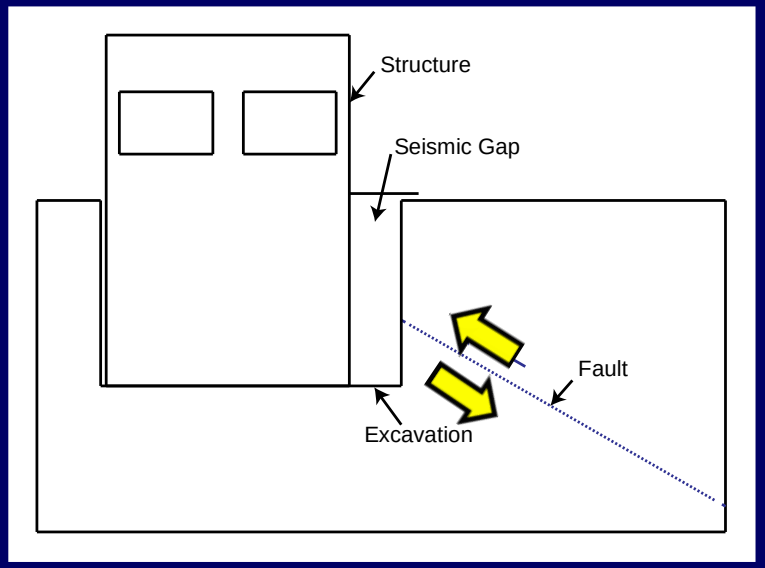
Diverting Fault Offset



Banco Central after 1972 Managua EQ (Niccum et al. 1976)

Diverting Fault Offset (Shield / Protect Structure)





Oettle and Bray (2013)

Decoupling Structure from Underlying Ground Movements

Denali Fault-Crossing

(Lloyd Cluff and others; Woodward-Clyde)

November 3, 2002 rupture

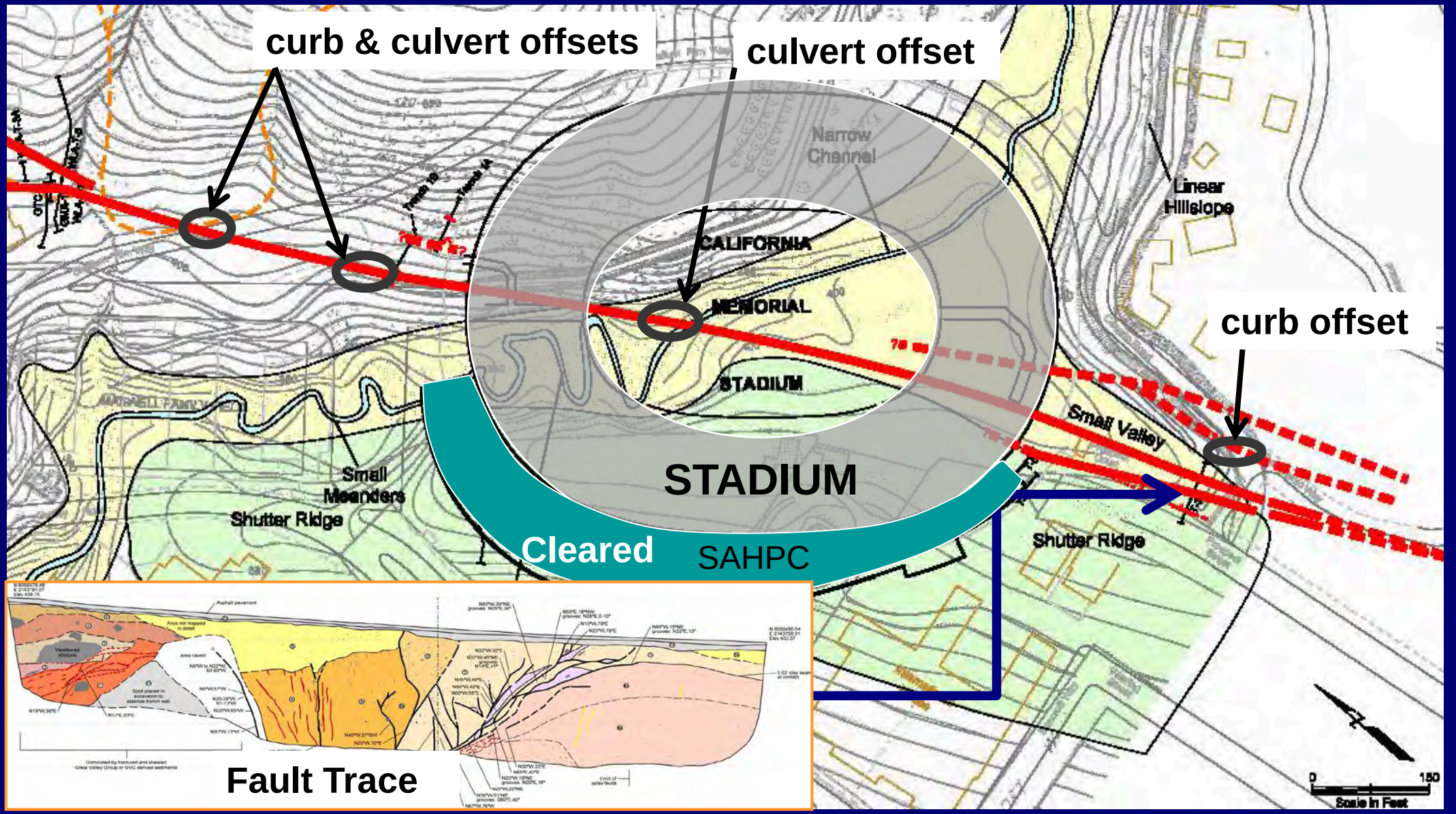
- Horizontal: 5.5 m
- Vertical: 1.1 m, N side up
- Axial compression: 3.3 m

"Pipeline performed as designed; and not a drop of oil was spilled"
– L. Cluff

Sorensen et al. (2003)

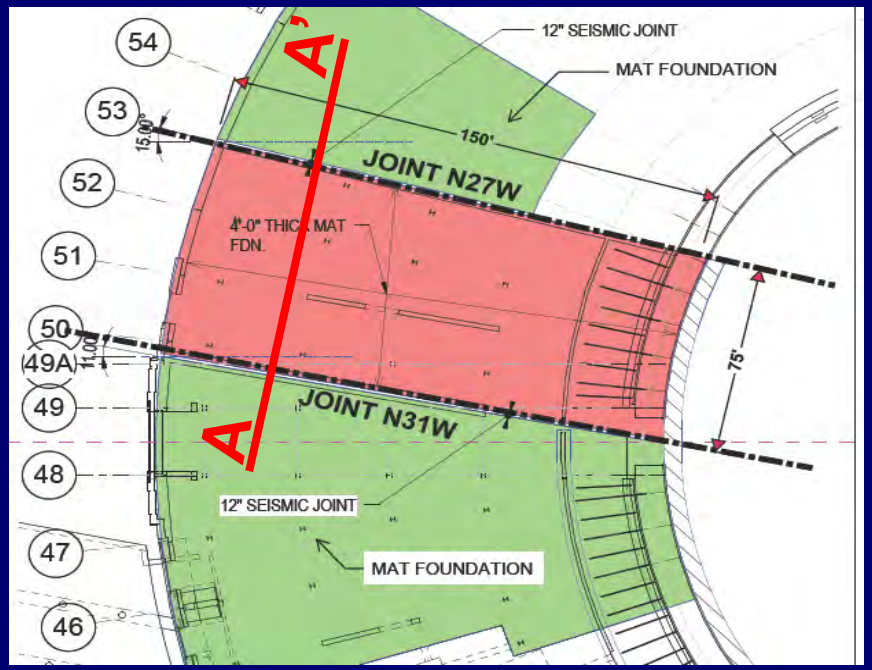
California Memorial Stadium Fault Characterization

AMEC Geomatrix (Wells , Swan, et al.)

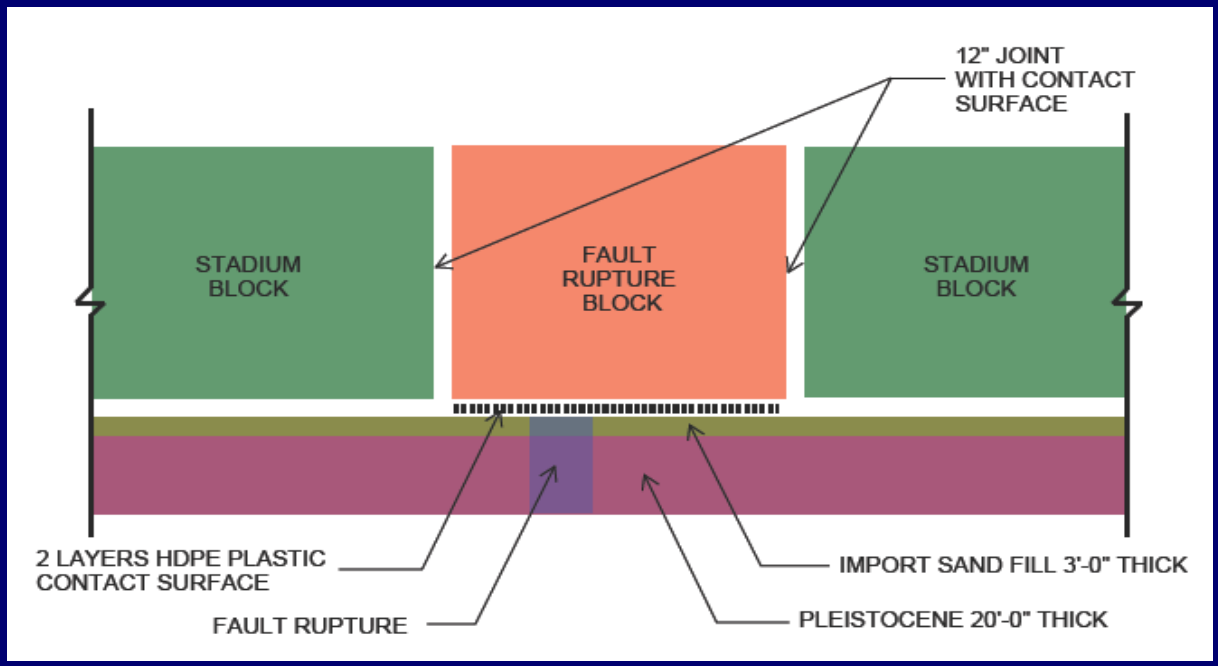


UCB Seismic Review Committee (Bray, Sitar, Comartin, Moehle, et al.) Forell/Elsesser Engineers, Inc. (Friedman, Vignos, et al.)

Design Concept



PLAN VIEW



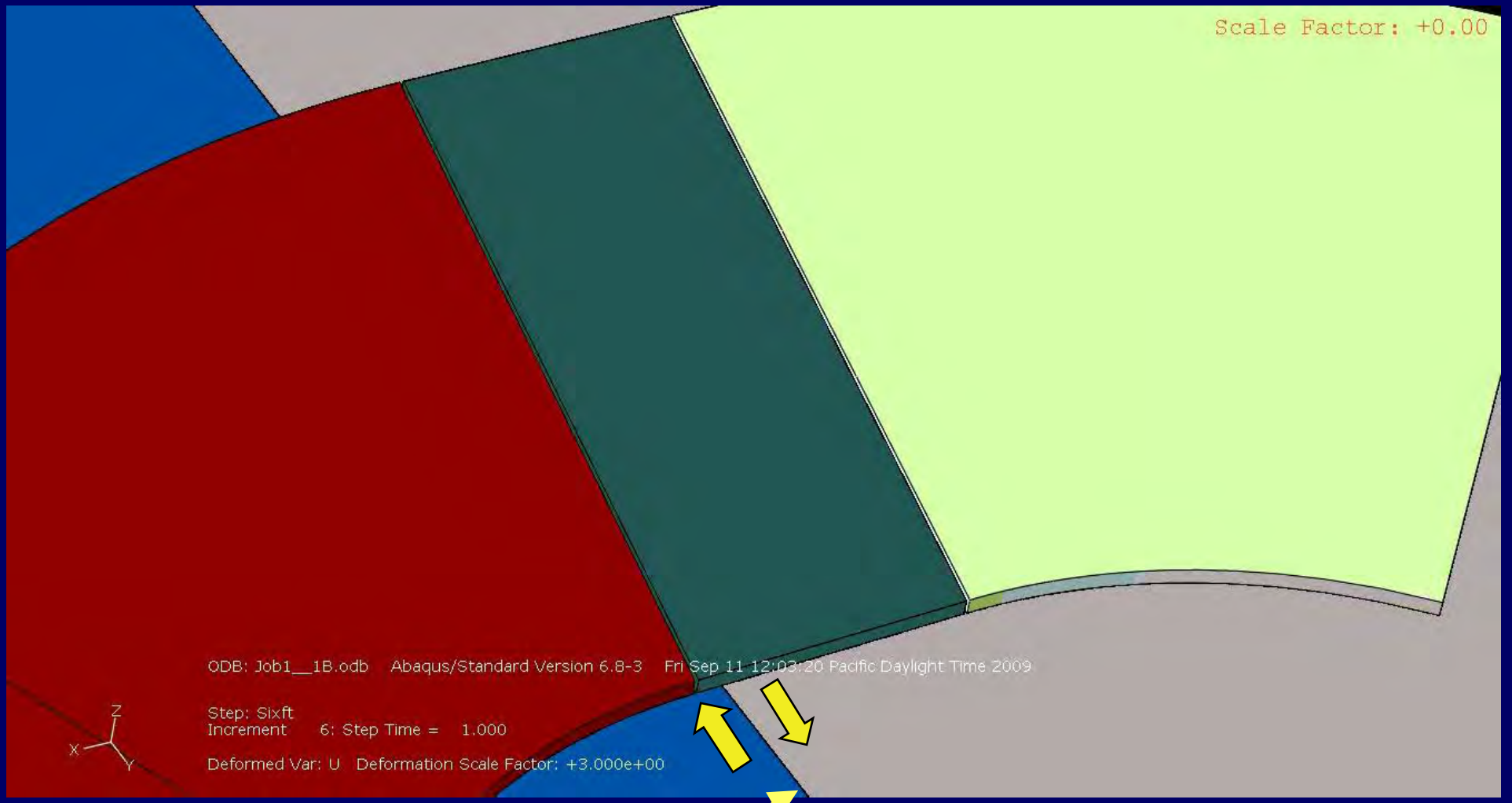
Cross Section A-A'

UCB Seismic Review Committee
(Bray, Sitar, Comartin, Moehle, et al.)

AMEC Geomatrix
(French et al.)

Forell/Elsesser Engineers, Inc.
(Friedman, Vignos, et al.)

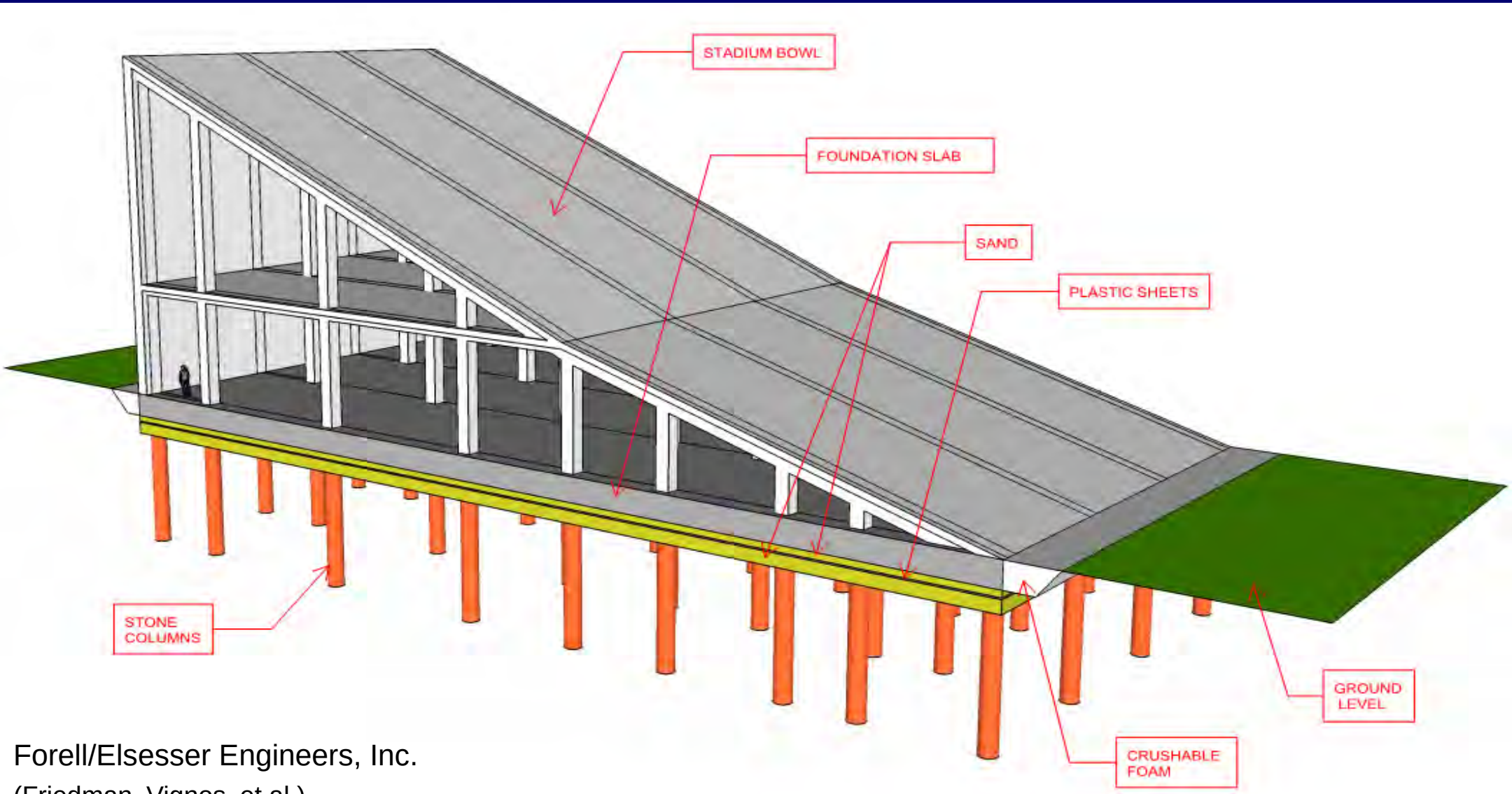
Modeling of the Effects of Surface Faulting



Fault

Forell/Elsesser Engineers, Inc.
(Friedman, Vignos, et al.)

CMS Fault Rupture Block



Forell/Elsesser Engineers, Inc.

(Friedman, Vignos, et al.)

CONCLUSIONS

- **Surface faulting is affected by:**
  - **fault characteristics**
  - **overlying soil**
  - **foundation & structure**

- **Surface fault rupture can be mitigated by:**
  - **diffusing fault offset**
  - **accommodating fault offset**
  - **diverting fault offset**