2012 WILLIAM B. JOYNER MEMORIAL LECTURE:

SEISMOLOGICAL SOCIETY OF AMERICA &
EARTHQUAKE ENGINEERING RESEARCH INSTITUTE

BUILDING NEAR FAULTS

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Sponsored in part by the National Science Foundation: CMMI-0926473

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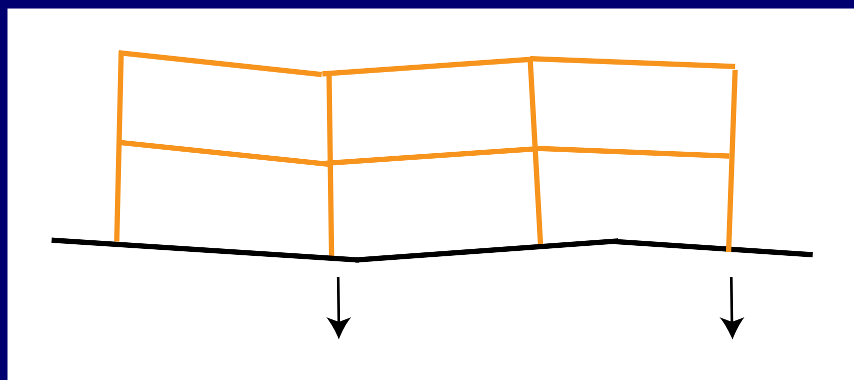
University of California, Berkeley

Ground Moves Beneath Structure



Hazards of Ground Movements

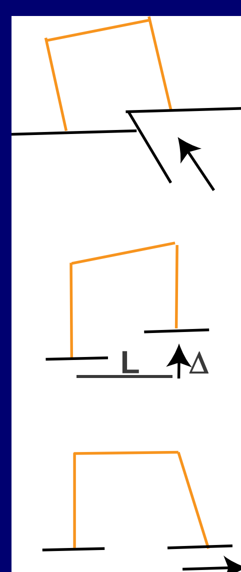
A. Shear Rupture

B. Angular Distortion

C. Extensional Strain

D. Tilt

E. Tectonic Subsidence



$\beta = \Delta / L$

$\varepsilon_h = \Delta_h / L$

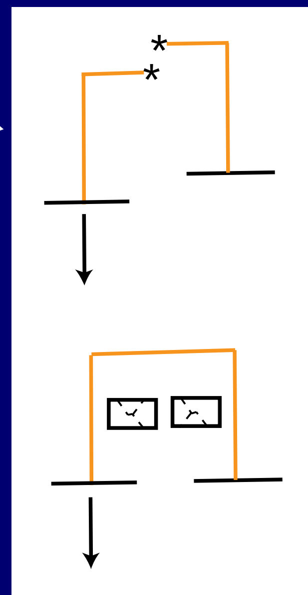
Consequences of Ground Movements

A. Structural Damage

B. Loss of Function

C. Architectural Damage

D. Excessive Tilt



Potential Causes of Ground Movements

A. Expansive Soils

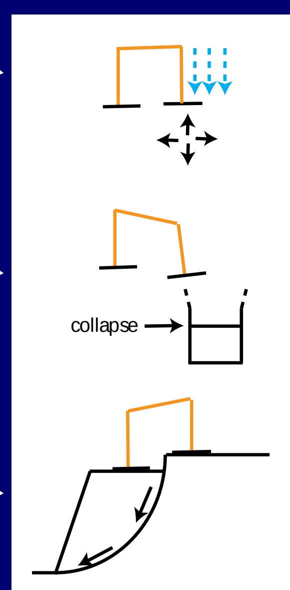
B. Static & Seismic Settlement

C. Mining Subsidence

D. Surface Faulting

E. Landslide

F. Lateral Spreading



Tolerable Levels of Ground Movements

A. **Conventional Construction:** $\beta = 1/500$, $\Delta_t = 1$ inch

B. **Post-Tensioned Slab Residential:** $\beta = 1/360$, $\Delta_t = 1.5$ inch

C. **Liquefaction-Induced Settlement:** $\Delta_t = 4$ inch

(with "structural mitigation" CGS SP-117A, Youd 1989)

D. **Liquefaction-Induced Horz. Movement:** $\Delta_t = 12$ inch

(with "structural mitigation" CGS SP-117A, Youd 1989)

Tolerable Levels of Ground Movements

A. Conventional Construction: $\beta = 1/500$, $\Delta_t = 1$ inch

B. Post-Tensioned Slab Residential: $\beta = 1/360$, $\Delta_t = 1.5$ inch

NOT $\Delta_t = 0$ inch

C. Liquefaction-Induced Settlement: $\Delta_t = 4$ inch

(with "structural mitigation" CGS SP-117A, Youd 1989)

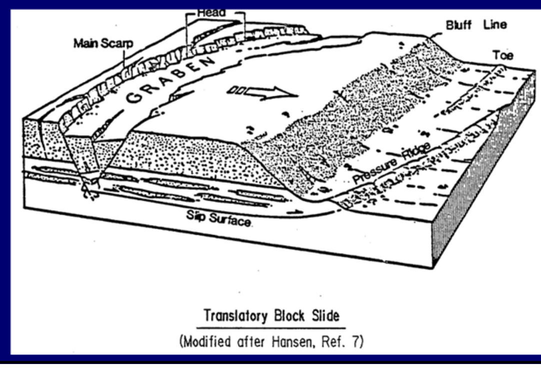
D. Liquefaction-Induced Horz. Mvmt: $\Delta_t = 12$ inch

(with "structural mitigation" CGS SP-117A, Youd 1989)

Anchorage Courthouse

Craig Comartin, SE, Coffman Engineers
(now with CDComartin, Inc.)

Also:
Idriss & Moriwaki, Woodward-Clyde
H. Shah, Stanford Univ.



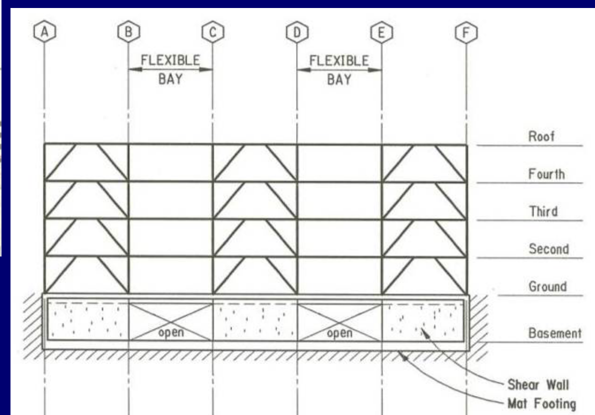
Translatory Block Slide
(Modified after Hansen, Ref. 7)

Anchorage Courthouse:
Performance Objectives & Design Displacements

Seismic Event	Return Period	Displacement Horizontal	Displacement Vertical
EQD-I (moderate level)	500 years	0.40 ft	0.27 ft
(minimize damage; repairable)		**(5 in)**	**(3 in)**
EQD-II (major level)	5,000 years	4.00 ft	2.70 ft
(maximize life safety; avoid collapse)		**(48 in)**	**(32 in)**

Craig Comartin, SE, CDComartin, Inc.

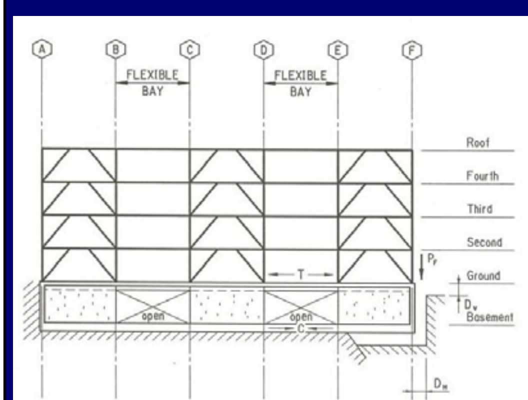
Anchorage Courthouse: Structural System



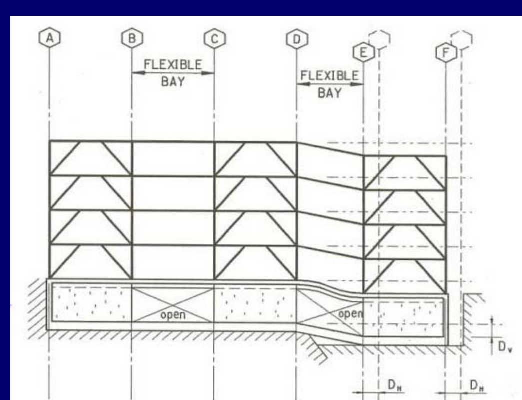
Craig Comartin, SE, CDComartin, Inc.

Anchorage Courthouse: Structural System

Stiff Bay's "Cantilever" Response



Flexible Bay's "Deformed" Response



D_H = 48 in. D_V = 32 in.

Craig Comartin, SE, CDComartin, Inc.

Denali Fault-Crossing

(Lloyd Cluff and others; Woodward-Clyde)

DESIGN PARAMETERS:

- Horizontal: 20 feet
- Vertical: 5 feet, North side up
- Right-slip will cause axial compression

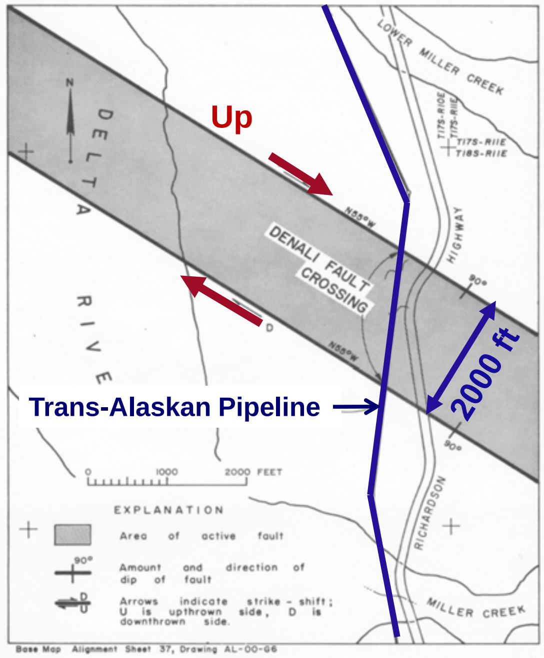


Figure 48. Map showing the location of the Denali fault crossing along the TAPS route.

Denali Fault-Crossing

(Lloyd Cluff and others; Woodward-Clyde)

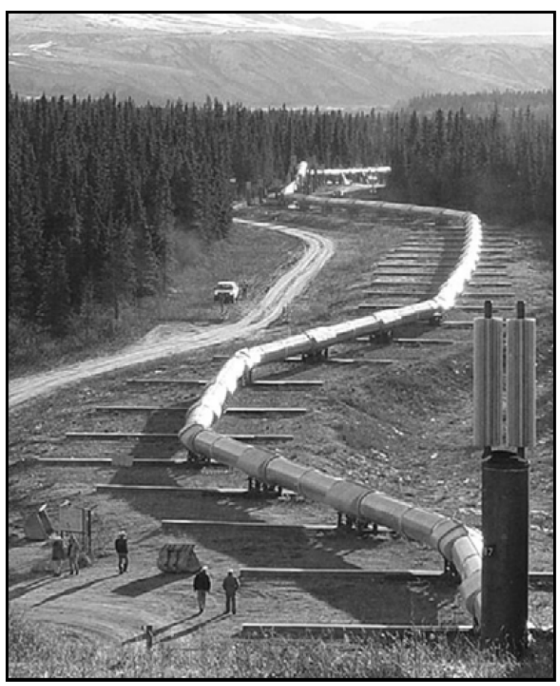
DESIGN PARAMETERS:

- Horizontal: 20 feet
- Vertical: 5 feet, North side up
- Right-slip will cause axial compression

November 3, 2002 rupture

- Horizontal: 18 feet
- Vertical: 3.5 feet, N side up
- Axial compression: 11 feet

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



Sorensen et al. (2003)

1972 Alquist-Priolo Geologic Hazard Zones Act

Sect. 2621.5:
"… to provide for the public safety in hazardous fault zones."

Sect. 2622:
… active traces of the San Andreas, Calaveras, Hayward, and San Jacinto Faults, and such other faults … sufficiently active and well-defined as to constitute a potential hazard to structures …"

Sect. 2623:
"… not approve … structure … if an undue hazard would be created…

If … no undue hazard exists … structure may be approved."

1972 Alquist-Priolo Geologic Hazard Zones Act
ORIGINAL FOCUS

- **Public Safety**
  - **If undue hazard would be created**
  - **If not, structure may be approved**
- **Hazardous Fault Zones**
  - **San Andreas, Calaveras, Hayward, & San Jacinto faults**
  - **Other faults that are a potential hazard to structures**

1972 Alquist-Priolo Geologic Hazard Zones Act

IMPLEMENTATION:

"site … shall be approved … in accordance with policies and criteria established by the State Mining and Geology Board …"

1973 Policies and Criteria of the State Mining and Geology Board

"No structure for human occupancy …. shall be permitted to be placed across the trace of an active fault."

Avoidance of active fault traces becomes norm

21st Century Approach

- **Cannot always avoid active faults**
- **Not all active faults are hazardous:**

  low slip-rate fault with < 2 inch offset vs.
  high-slip rate fault with > 10 foot offset
- **Unintended consequences**
- **"Unless proven otherwise" is too stringent**
- **If we can design for mining subsidence, landslides, & lateral spreading, why not minor fault-induced ground movements?**

21st Century Approach

- Cannot always avoid active faults
- Unintended consequences

low slip rate fault with < 2 inch offset vs.

- "Unless proven otherwise" is too stringent
- If we can design for mining subsidence, landslides, & lateral spreading, why not minor fault-induced ground movements?

Does the structure care why the ground moved?

California State Mining and Geology Board

Alquist-Priolo Technical Advisory Committee

DRAFT RECOMMENDATIONS:

Focus on active faults that could produce significant differential ground movement that would constitute a hazard to structures

Significant differential ground movement could produce a significant risk to a structure during a single rupture event:

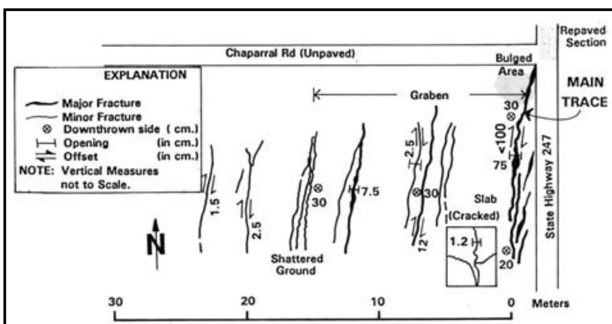
Vert. Δ_t = 4 in. or Horz. Δ_t = 12 in. over 10 ft-wide zone, OR

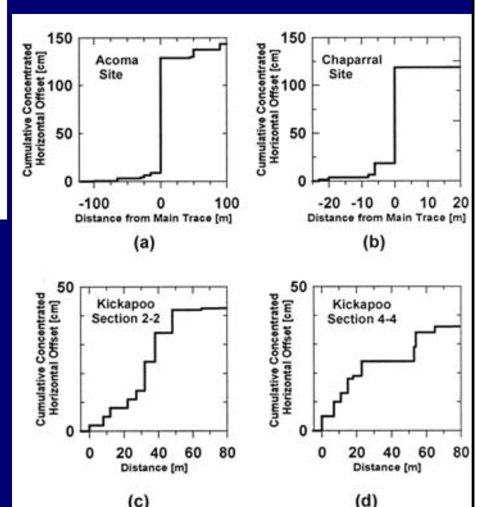
Vert. Δ_t = 8 in. or Horz. Δ_t = 24 in. across the structure

Surface Fault Rupture Mitigation

1992 Landers Earthquake

1992 Landers Earthquake





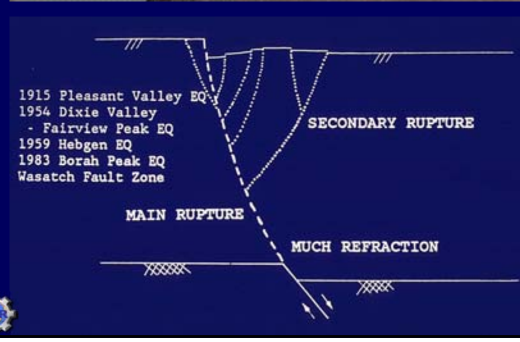
Lazarte, Bray & Johnson (1994)

Broad Area of Building Damage on Hanging Wall of Reverse Fault

Not on footwall

1999 Chi-Chi EQ

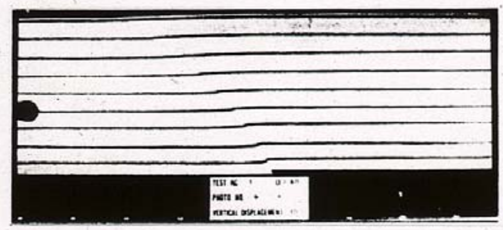
1999 KOCAELI EQ



Soil Effects

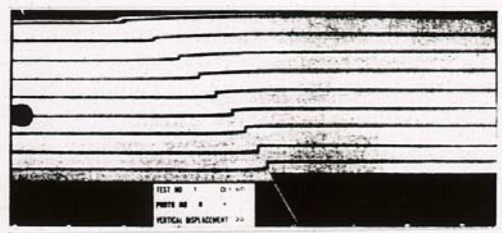
1992 Landers EQ

"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)



(B) Initiation Of Failure Surface At Bedrock Fault

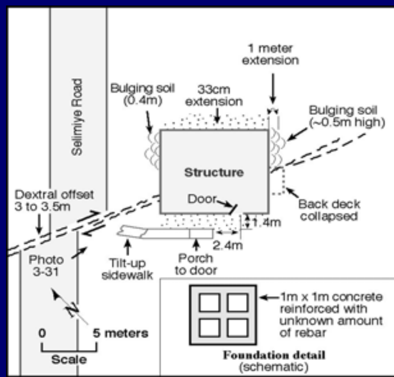
(Lade and Cole 1984)

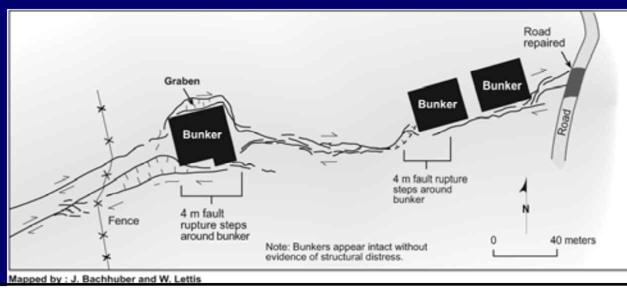


(C) Fully Developed Failure Surface

Systems (Tied to the Ground) Damaged by Faulting

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





An Analogy

ROOTED TREE DAMAGED

POLE UNDAMAGED

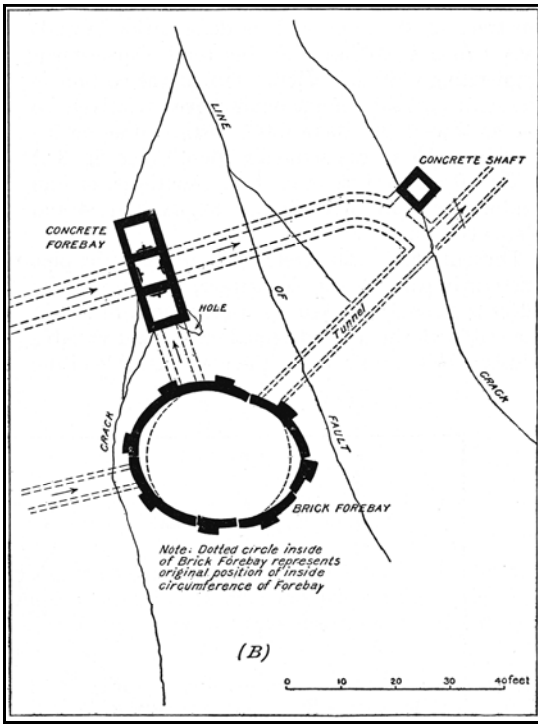
Photographs from Prof. R. Ulusay, Turkey

FLEXIBILITY vs. RIGIDITY

Photographs from Dr. C. Roblee, Caltrans, 1999 Chi-Chi EQ

Photo by K. Kelson

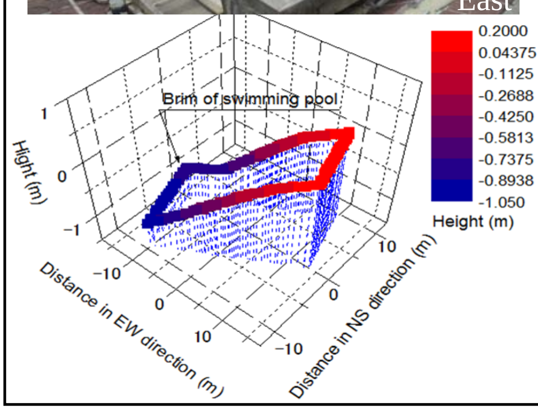
Building Response to Chi-Chi Fault Rupture



Response of Buried Systems

max. possible pressure is the passive earth pressure

1906 San Francisco EQ
(Lawson 1908 & Schussler 1906)



TABITO MIDDLE SCHOOL

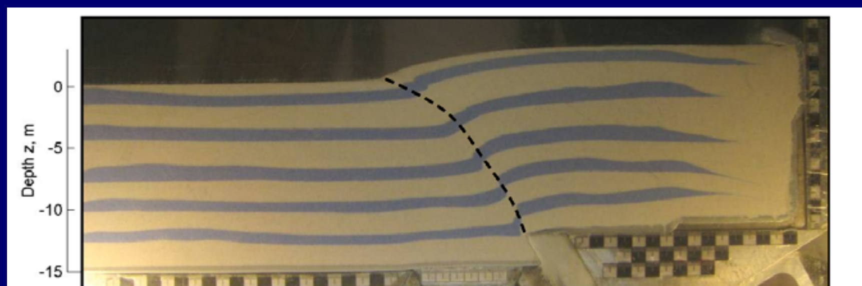
M_w 6.6 Hamadoori Aftershock of 4/11/11: Shionohira Fault Displacement

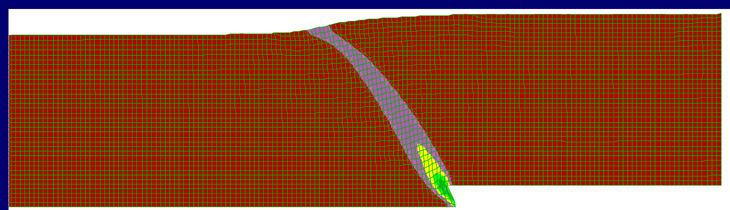
Laser survey of the brim of the pool (Konagai, Bray, Streig, & others)

1.25 m vertical displacement between ends of pool

MODELING OF FAULT RUPTURE

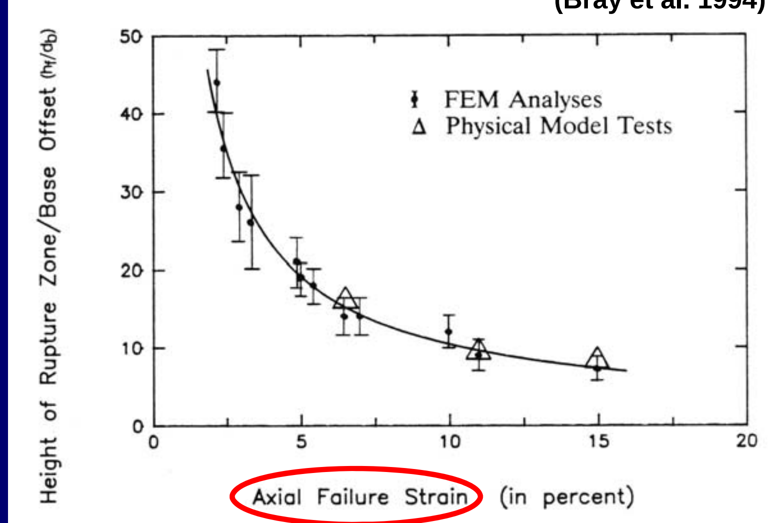
Centrifuge Test: 60º Reverse Fault Uplift in Sand (Davies et al. 2007; Prototype Scale)



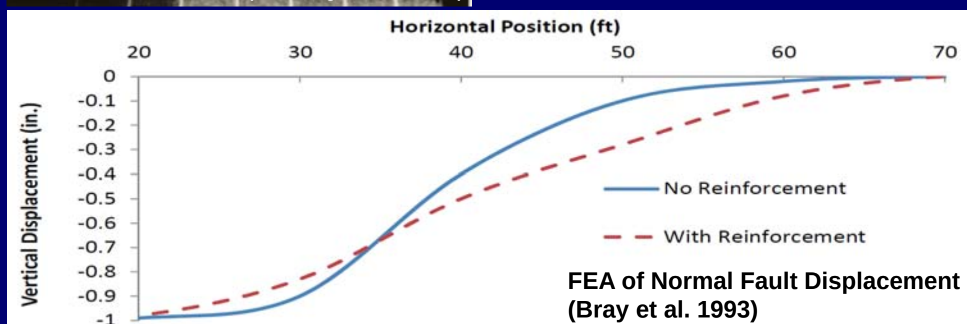


FLAC-2D/UBCsand Analysis: 60º Reverse Fault Uplift in Sand (Oettle & Bray)

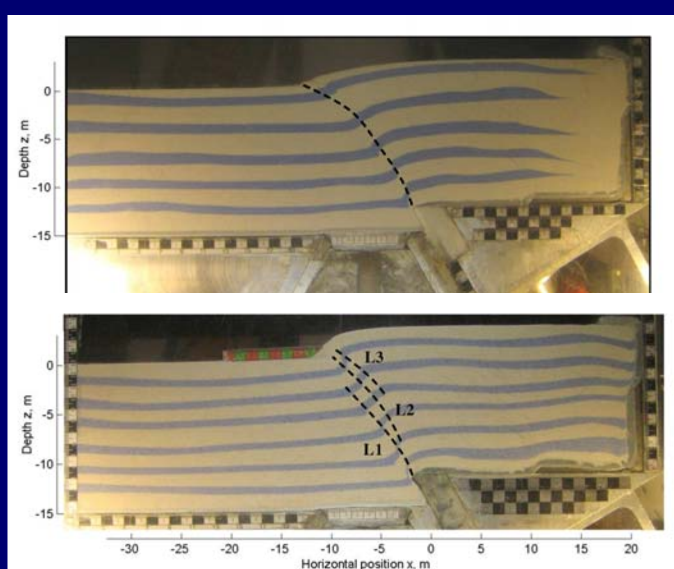
Failure Strain



REINFORCEMENT IMPROVES DUCTILITY



CENTRIFUGE TEST OF FAULT RUPTURE WITH AND WITHOUT MAT FOUNDATION (Davies et al. 2007)

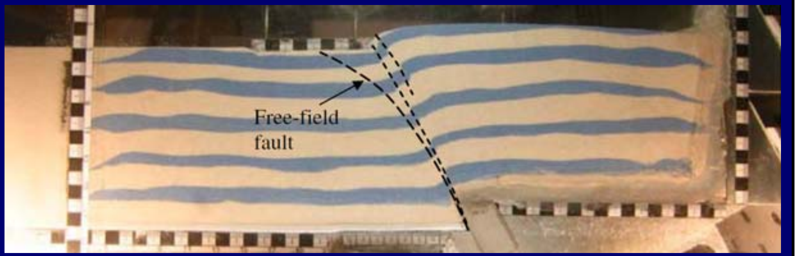


provided by Anastapolous & Gazetas

WEIGHT OF MAT FOUNDATION EFFECTS (Davies et al. 2007)

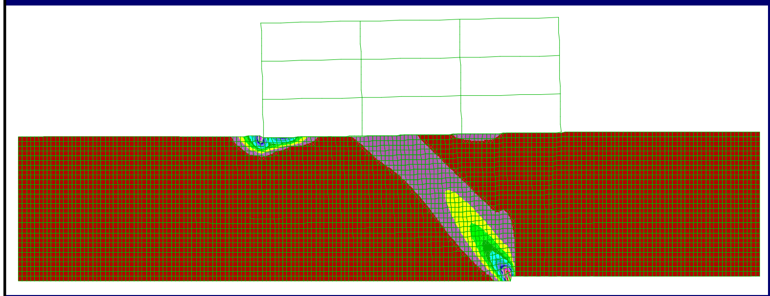
Light Load:
q = 37 kPa

Heavy Load:
q = 91 kPa

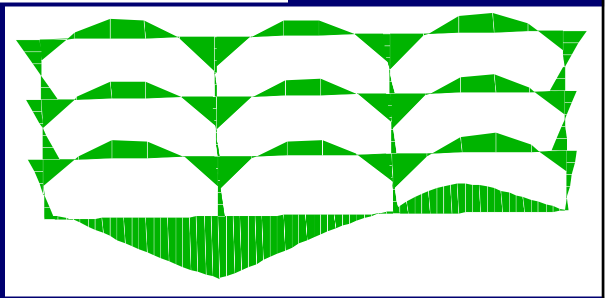


provided by Anastapolous & Gazetas

Fault-Structure Interaction Analyses



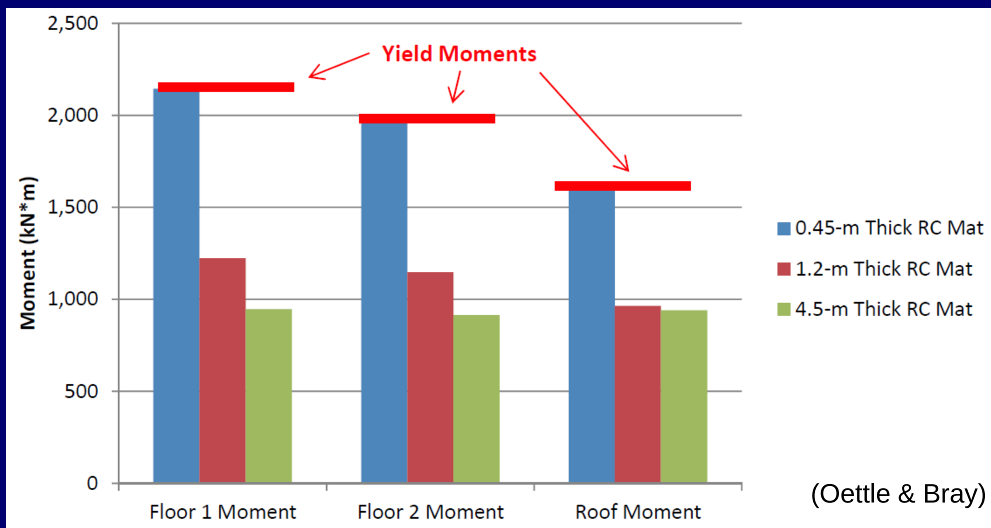
(Oettle & Bray)



Max. bending moments develop near beam-column joints

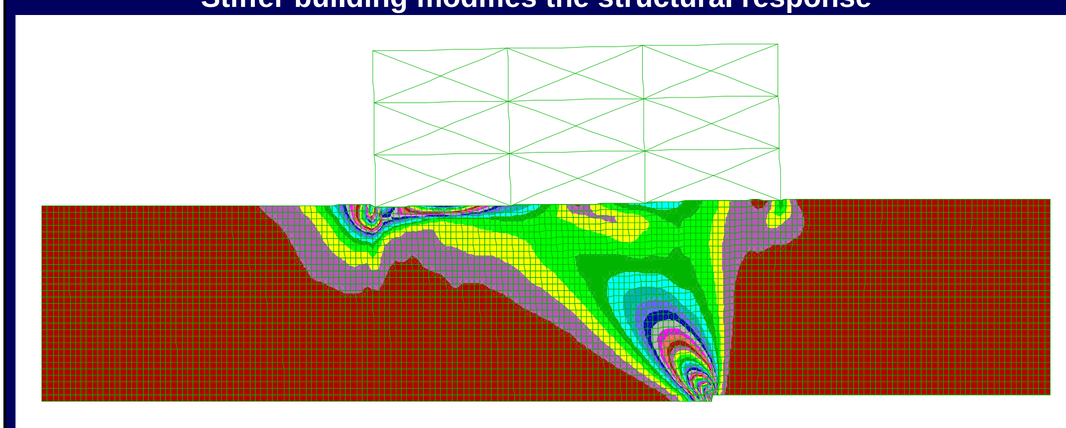
Mitigation with Thick Mat Foundation

Thicker mat foundation significantly reduces building damage



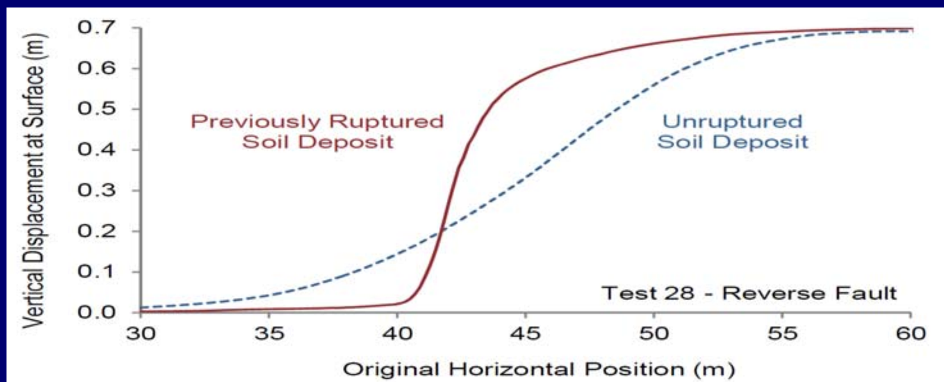
Mitigation with Superstructure Strength & Stiffness

Stiffer building modifies the structural response



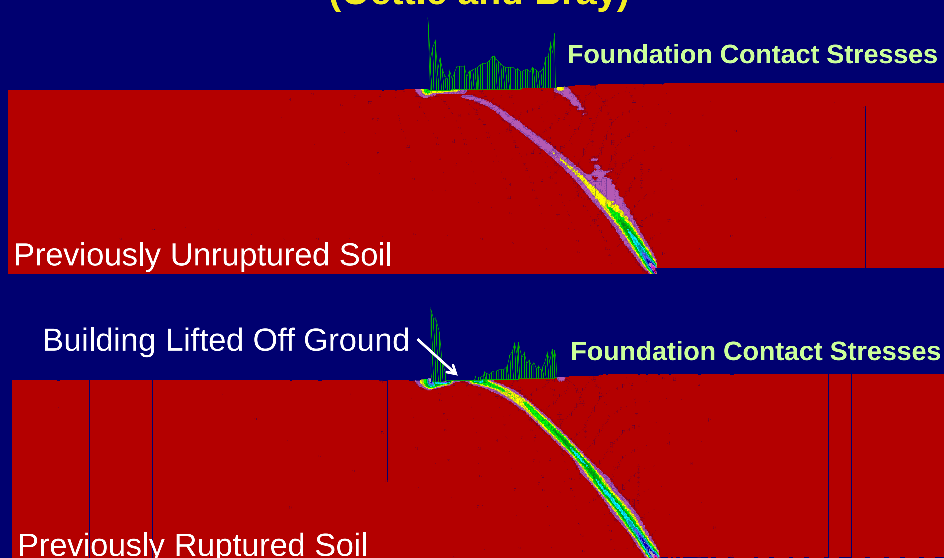
(Oettle & Bray)

Response of Previously Ruptured Soil
(Oettle and Bray)



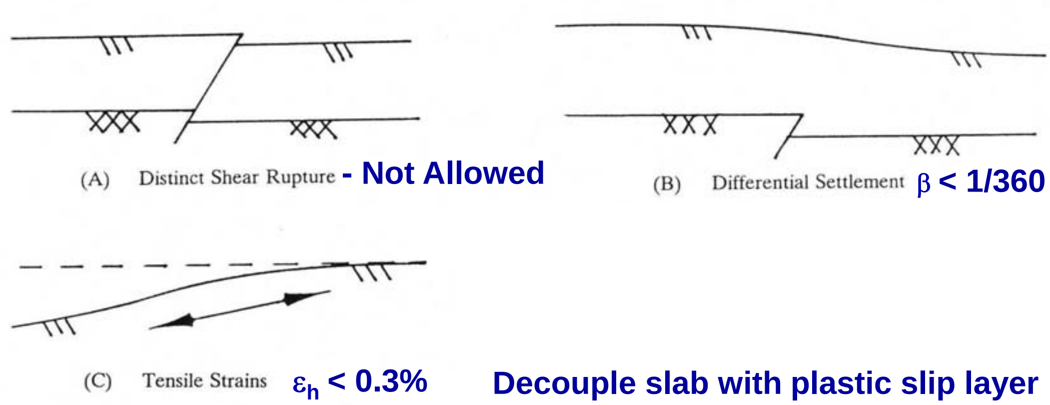
More localized deformation with previously ruptured soil

Effects of Previously Ruptured Soil
(Oettle and Bray)



APPLICATION 1:

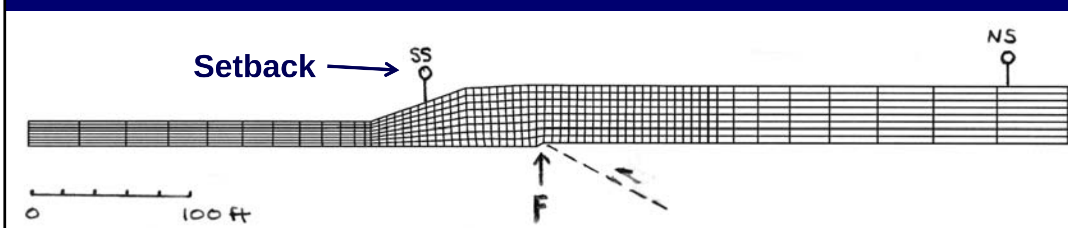
Moorpark Development Project, Southern California



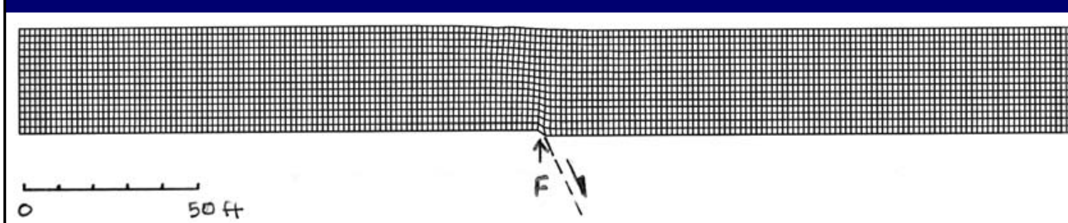
GROUND DEFORMATION DESIGN CRITERIA FOR BUILDING AREAS

Moorpark Development – Surface Fault Rupture Evaluation

(Bray 2001)

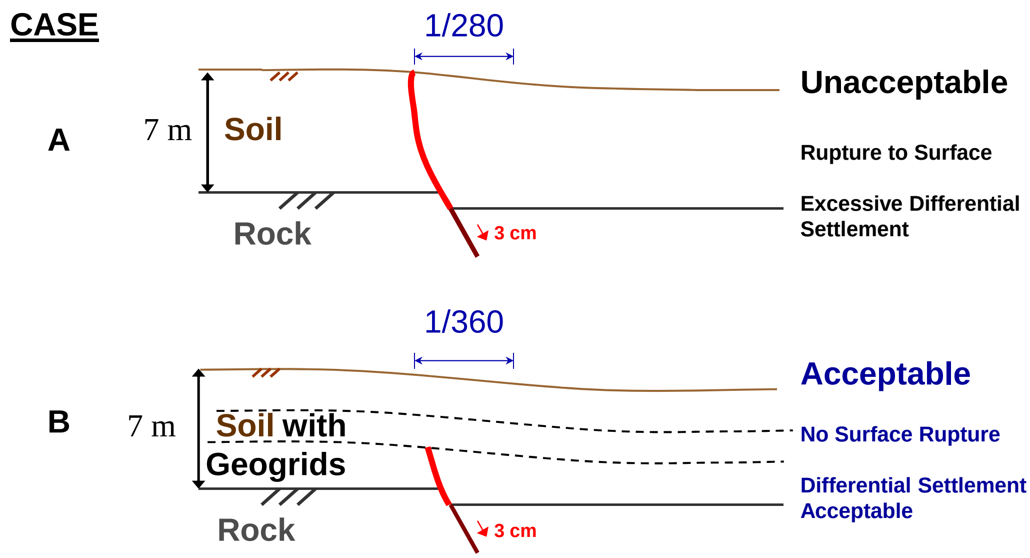


Primary Active Faults with > 4 inches of potential offset



Bending Moment Active Faults with < 1.5 inches of potential offset

RESULTS OF NUMERICAL ANALYSIS (Bray 2001)



APPLICATION 2:

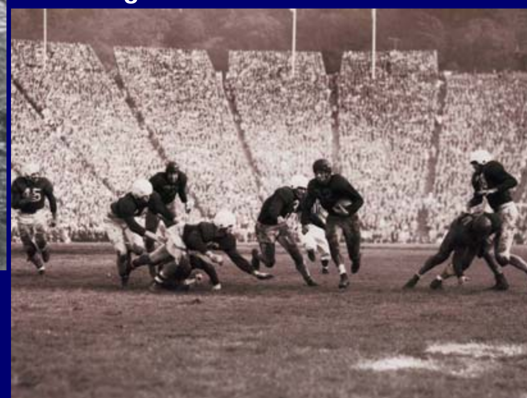
California Memorial Stadium Retrofit, Northern California

Lead & SE: Forell/Elsesser Engineers, Inc. (David Friedman, Rene Vignos, et al.)
GE & Geologists: AMEC Geomatrix (Donald Wells, Bert Swan, Jim French, et al.)
Other Designers:, HNTB, Studios, WSP Flack + Kurtz, & Bellecci & Assoc.
UCB: Ed Denton, Bob Milano, Stan Mar, & Brian Main; General Contractor: Webcor Builders
Independent Peer Reviewers: Loring Wyllie of Degenkolb Engineers & John Baldwin of WLA
UCB Seismic Review Com.: J. Bray, N. Sitar, C. Comartin, J. Moehle, F. Filippou, & Others

California Memorial Stadium Construction & Use

John Galen Howard, the Strawberry Canyon site, 1922

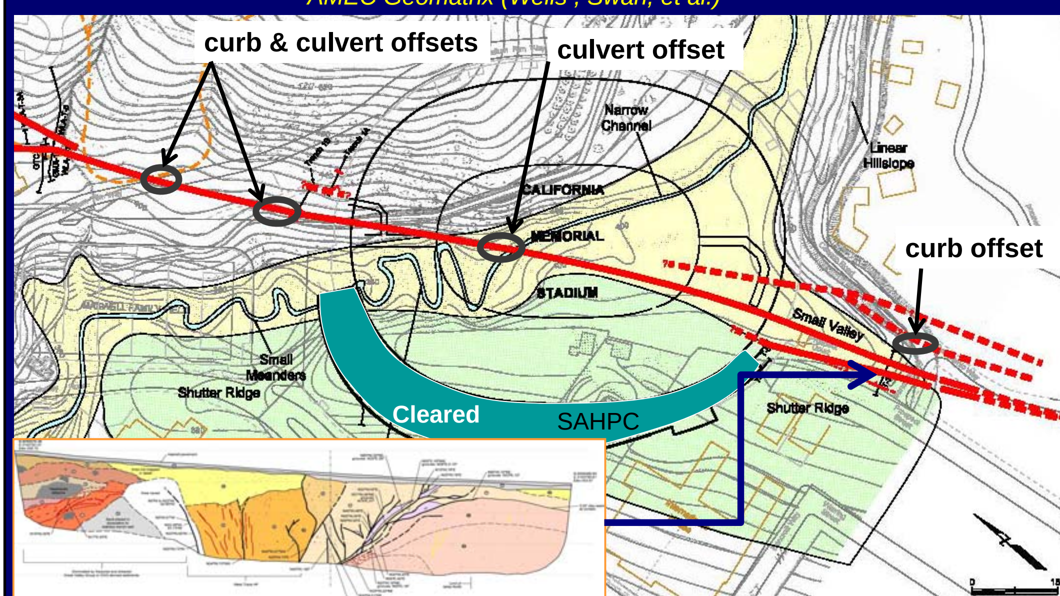
1923 Big Game - CAL: 9 Stanford: 0



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

CHARACTERIZING HAYWARD FAULT

AMEC Geomatrix (Wells , Swan, et al.)



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

CHARACTERIZING HAYWARD FAULT

Fault Rupture Design Guidance

AMEC Geomatrix (Wells, Swan, et al.)

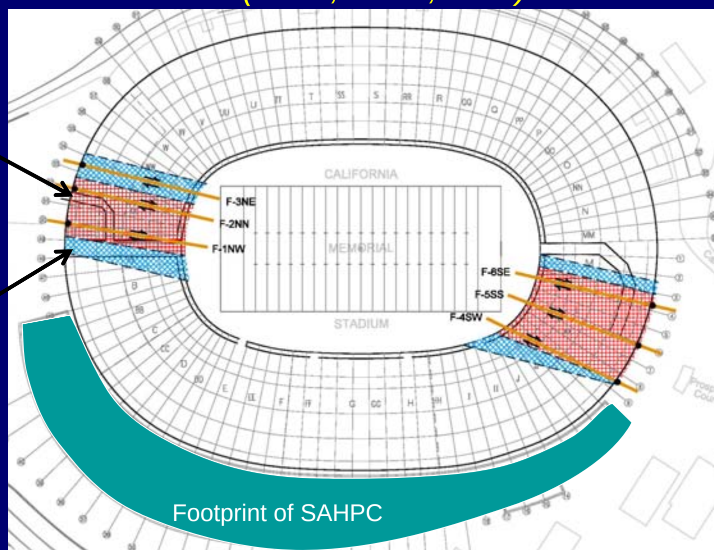
Primary:

3 - 6.2 ft H

1 - 2 ft V

Secondary:

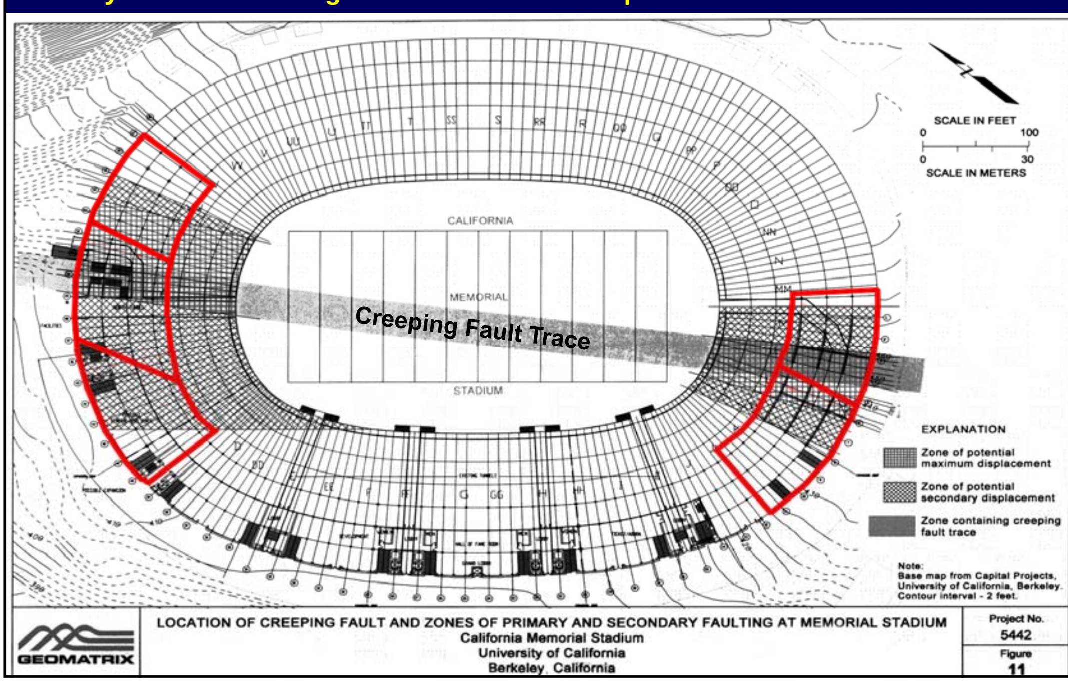
< 1 ft H



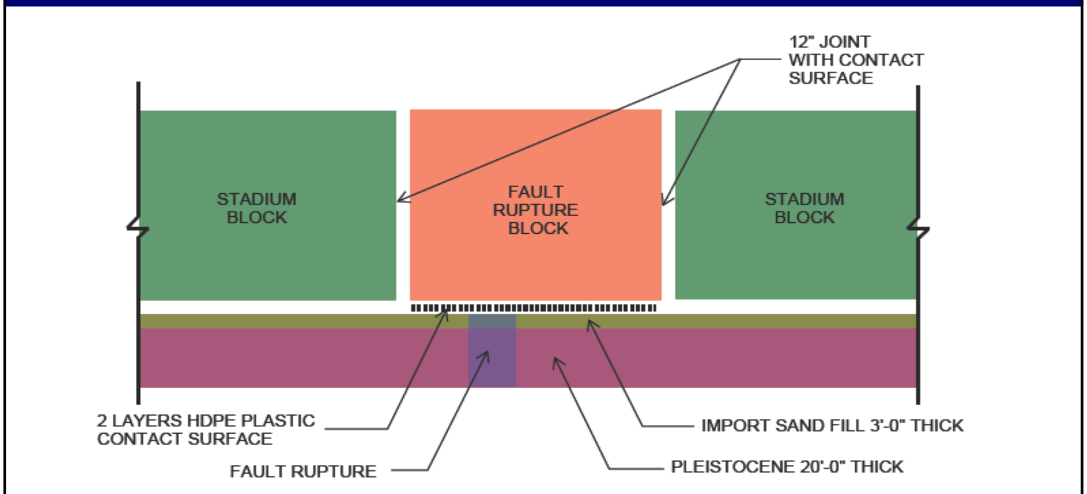
UCB Seismic Review Committee

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

Early Scheme for Mitigation Surface Fault Rupture Hazard – 5 Skewed Blocks



Improved Design Concepts

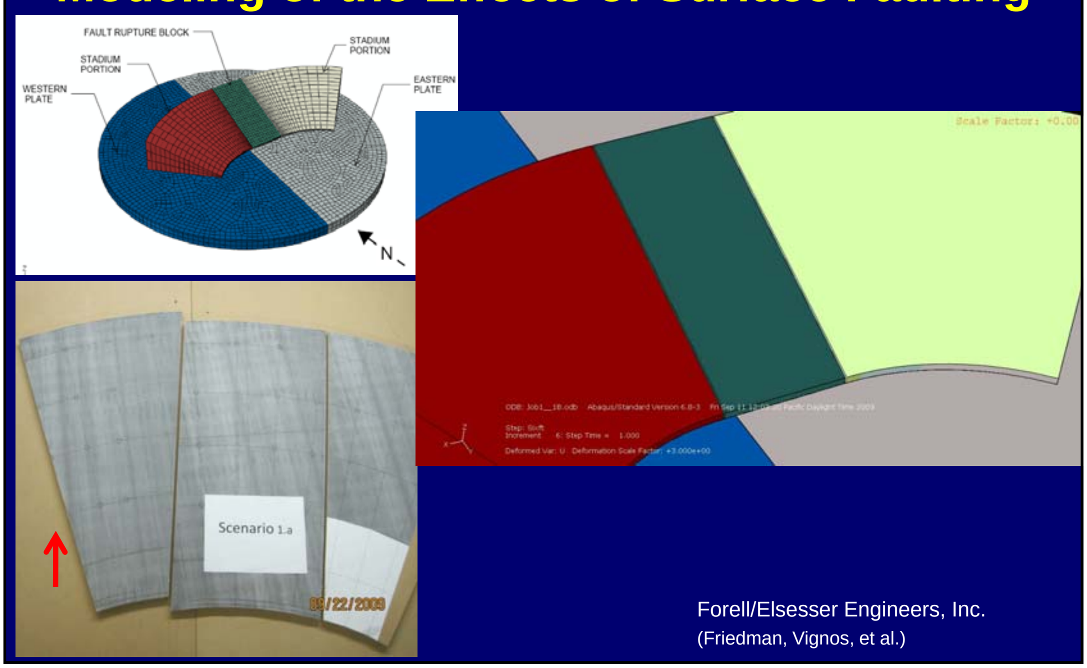


UCB Seismic Review Committee
(Bray, Sitar, Comartin, Moehle, et al.)

AMEC Geomatrix
(French et al.)

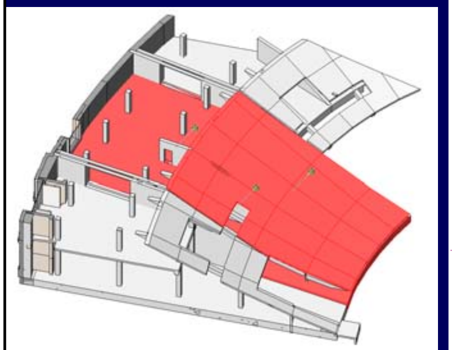
Forell/Elsesser Engineers, Inc.
(Friedman, Vignos, et al.)

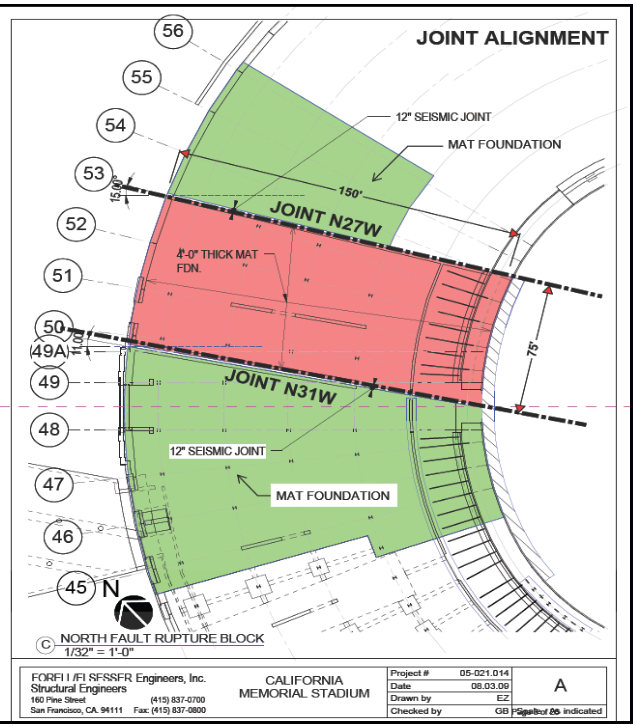
Modeling of the Effects of Surface Faulting



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

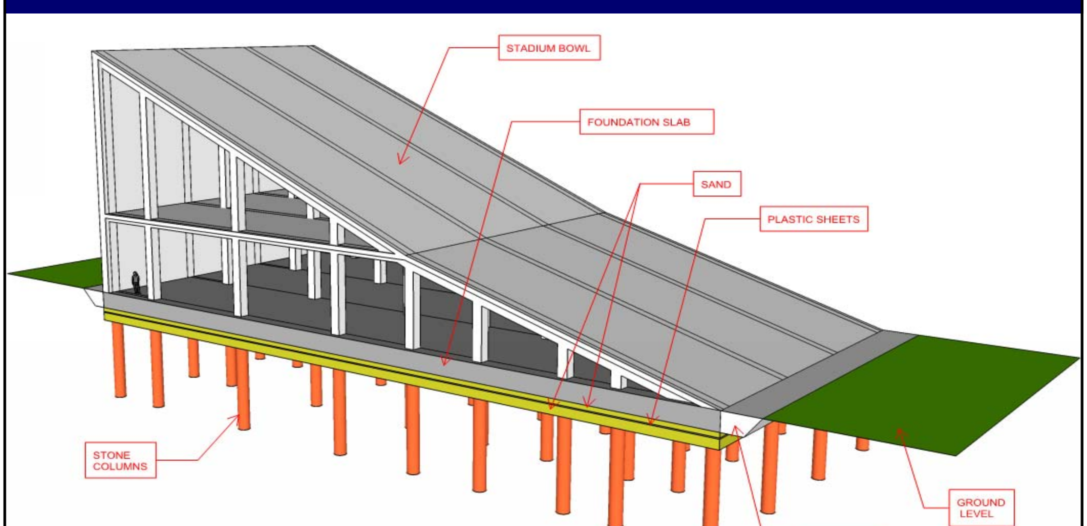
North Fault Rupture Block





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

CMS Fault Rupture: Details



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

South Fault Rupture Block: Construction

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

CONCLUSIONS

- Surface faulting is affected by:
  - fault characteristics
  - overlying soil
  - foundation & structure
- Effects of surface fault rupture can be acceptable or unacceptable
- Surface fault rupture can be analyzed and mitigated similar to other ground movement hazards, e.g., landslides & mining subsidence
- A-P Act should return to its original intent of avoiding “hazardous” faults