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

Not on footwall

1999 Chi-Chi EQ

Reverse Fault Experiment (Davies et al. 2007)
Broad Area of Building Damage on Hanging Wall of Normal Fault

Not on footwall

1999 Kocaeli EQ
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
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)
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
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

Cracked garage slab
Pushed off foundation
Rupture through piers
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

Foundation detail (schematic)

1m x 1m concrete reinforced with unknown amount of rebar

Scale

0 5 meters

Dextral offset 3 to 3.5m

Tilt-up sidewalk

Porch to door

Bulging soil (0.4m extension)

33cm extension

Bulging soil (~0.5m high)

Back deck collapsed

Structure

Door

1 meter extension

Note: Bunkers appear intact without evidence of structural distress.
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

A  7 m

Soil

Rock

1/280

Unacceptable
Rupture to Surface
Excessive Differential Settlement

B  7 m

Soil with Geogrids

Rock

1/360

Acceptable
No Surface Rupture
Differential Settlement Acceptable

3 cm
Accommodation with Strong Structure

Stronger building modifies the structural response

(Oettle & Bray 2013)
Effects of Foundation Strength & Stiffness

(Oettle & Bray 2013)

15 m deep sand deposit
70 cm reverse fault displ.

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 Foundation

Less Distortion

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° 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

Laser survey (Konagai et al.)

Brim of swimming pool

Distance in EW direction (m)

Distance in NS direction (m)

Height (m)
Anchorage Courthouse

Craig Comartin, SE, with Idriss, Moriwaki, Shah et al.
Anchorage Courthouse: Structural System

Stiff Bay’s “Cantilever” Response

Flexible Bay’s “Deformed” Response

$D_H = 1.2 \text{ m}$  $D_V = 0.8 \text{ m}$

Craig Comartin, SE, CDComartin, Inc.
Diverting Fault Offset

Banco Central after 1972 Managua EQ (Niccum et al. 1976)
Diverting Fault Offset (Shield / Protect Structure)

Soil

Diaphragm Wall

Tiebacks

Normal Fault

Three-story Structure

Seismic Gap

Excavation

Fault

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.)

curb & culvert offsets
culvert offset
curb offset

Fault Trace

Fault Trace

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
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