Seismic Fragility of Flood Control Levee Systems

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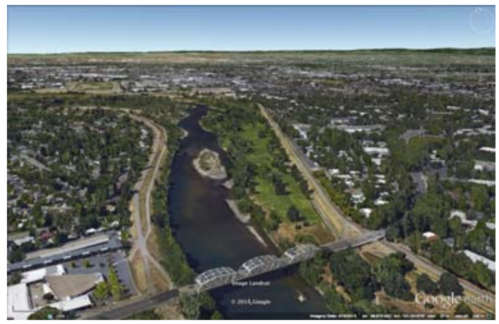
Levees

Definition: man-made or natural embankments along rivers or water bodies

Purpose: flood protection

Can be *intermittently* loaded



American River, Sacramento

Levees

Definition: man-made or natural embankments along rivers or water bodies

Purpose: flood protection

Can be *intermittently* or *continuously* loaded

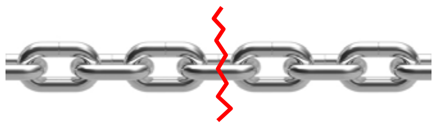
Sacramento-San Joaquin Delta

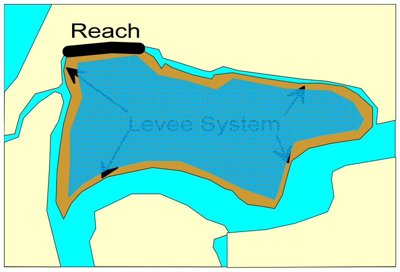
Levee Taxonomy

Series system when impounding water

Failure of any link constitutes system failure

System: assemblage of levees providing flood protection

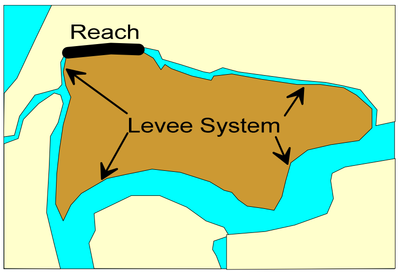


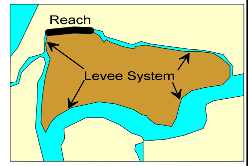


Levee Taxonomy

Reach: length of levee with uniform capacity and demand distributions

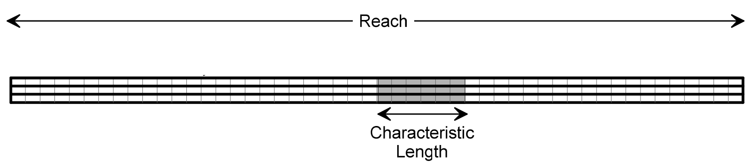
Physics-based vs legal/jurisdictional

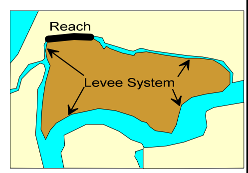




Levee Taxonomy

Characteristic length: length of levee system components between which statistical independence may be assumed (unknown *a priori*)

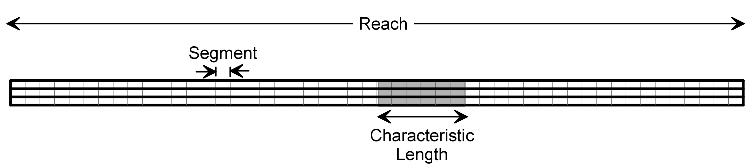




Levee Taxonomy

Characteristic length: length of levee system components between which statistical independence may be assumed (unknown *a priori*)

Segment: length of levee with uniform capacity (represented by cross-section)



Question addressed here:

How to assess seismic risk for levee systems?

Current & recommended practices

Key concepts

Outline

- Levee system taxonomy
- Segment risk
- System risk
- Summary

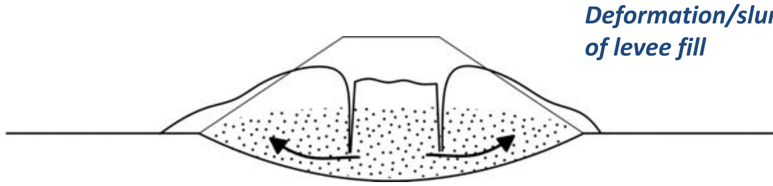
Segment

- Deformation mechanisms
- Consequent risk
- International guidelines
- Empirical fragility model

Segment

Deformation Mechanisms

Deformation/slumping of levee fill

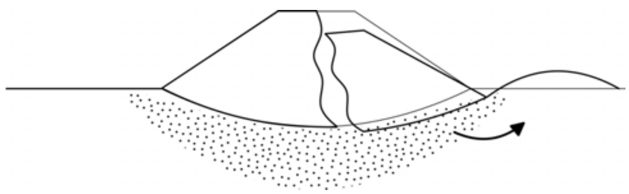


Miller and Roycroft 2004
Sasaki 2009
Sasaki et al. 2012
Green et al. 2011
Kwak et al., 2016a

Segment

Deformation Mechanisms

Sliding/bearing failure

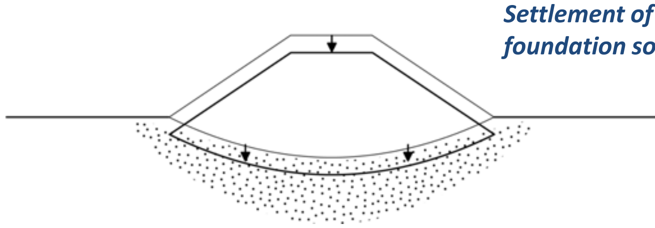


Miller and Roycroft 2004
Sasaki 2009
Sasaki et al. 2012
Green et al. 2011
Kwak et al., 2016a

Segment

Deformation Mechanisms

Settlement of foundation soils



Miller and Roycroft 2004
Sasaki 2009
Sasaki et al. 2012
Green et al. 2011
Kwak et al., 2016a

Segment

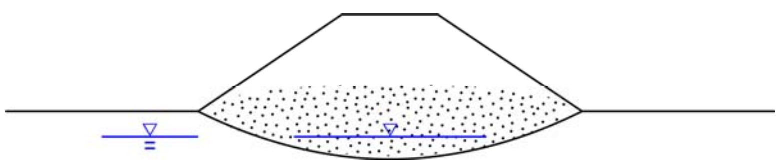
Performance data

MLIT-SWO 2008

Segment

Consequent Risk

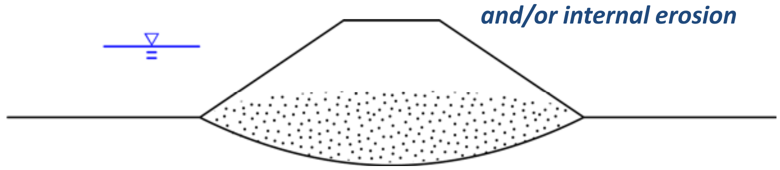
Intermittent impoundment: potentially low risk



Segment

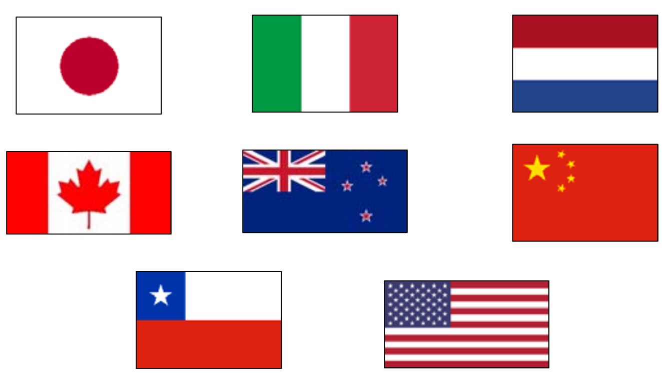
Consequent Risk

Continuous impoundment: high risk from overtopping and/or internal erosion



Segment

International Guidelines



EQS paper describes provisions in various guidelines, using consistent framework.

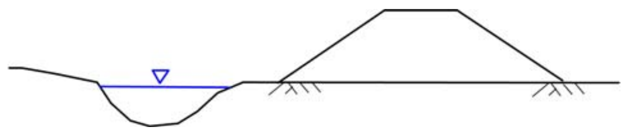
Recommended best practices summarized here…

Zimmaro et al. 2017a

International Guidelines

Framework (segments):

Screening

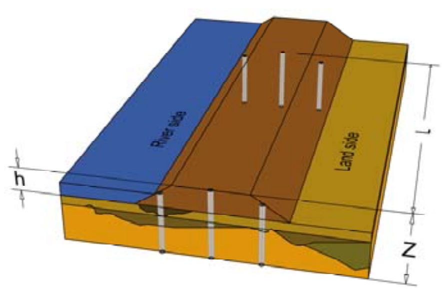


International Guidelines

Framework (segments):

Screening

Site characterization



International Guidelines

Framework (segments):

Screening

Site characterization

Ground motion hazard

PSHA or DSHA

Site response

Flood return period

International Guidelines

Framework (segments):

Screening

Site characterization

Ground motion hazard

Strength loss potential

Liquefaction

Cyclic softening

International Guidelines

Framework (segments):

Screening

Site characterization

Ground motion hazard

Strength loss potential

Flow slides and ground deformations

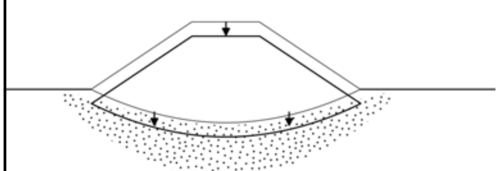
Flow slide: limit equilibrium

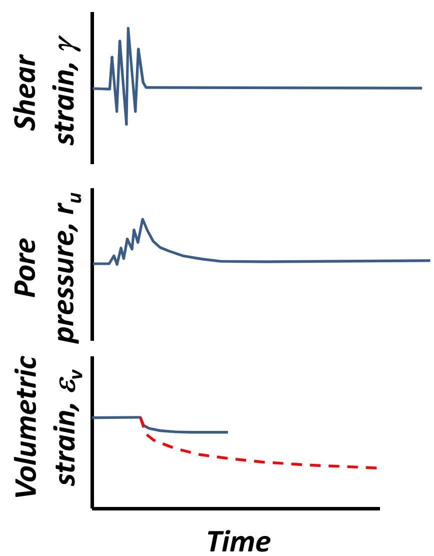
Deformations: Newmark or similar

Seismic compression

Accelerated creep (peat)

Accelerated creep in peat





Shafiee et al. 2015

International Guidelines

<u>Framework (segments)</u>:

Screening

Site characterization

Ground motion hazard

Strength loss potential

Flow slides and ground deformations

Risk mitigation

Prepare for post-event repair

Pre-event repair

International Guidelines

<u>Framework (segments)</u>:

Screening

Site characterization

Ground motion hazard

Strength loss potential

Flow slides and ground deformations

Risk mitigation

Hazard is computed at location of segment

Variability / uncertainty in ground motion

International Guidelines

Framework (segments):

Screening

Site characterization

Ground motion hazard

Strength loss potential

Flow slides and ground deformations

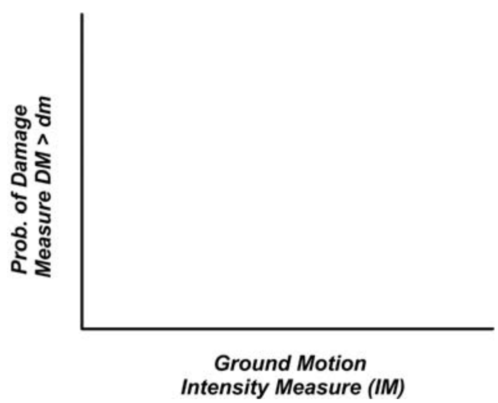
Risk mitigation

Predicted using geotechnical models

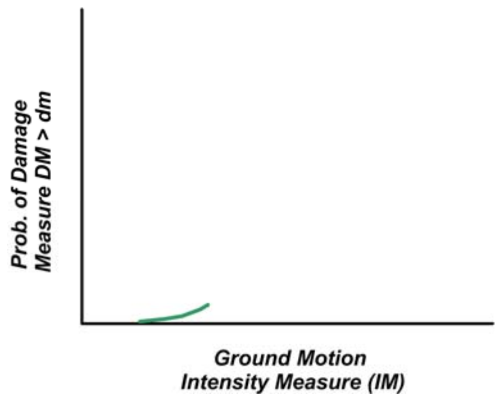
Uncertainty often undefined

Fragility poorly quantified

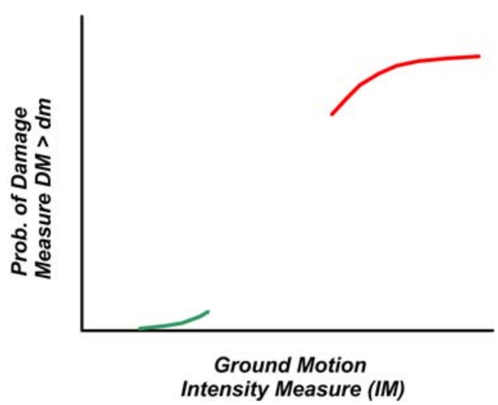
Levee Fragility



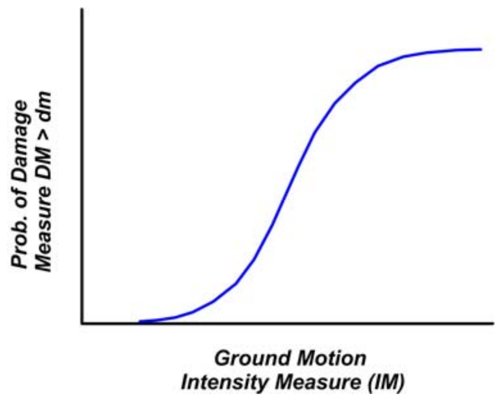
Levee Fragility



Levee Fragility



Levee Fragility



Segment

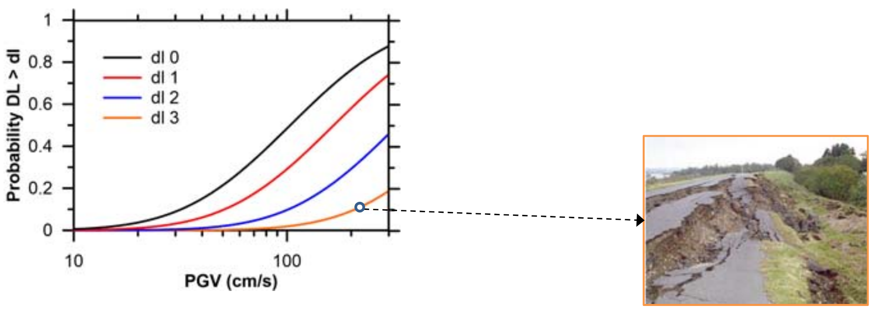
Empirical Fragility Model

- Observed damage following 2004 and 2007 events
- Model conditioned on ground motion, water level, geology
- Fragility conditioned on damage level (DL)

MLIT-SWO 2008

Segment

Empirical Fragility Model

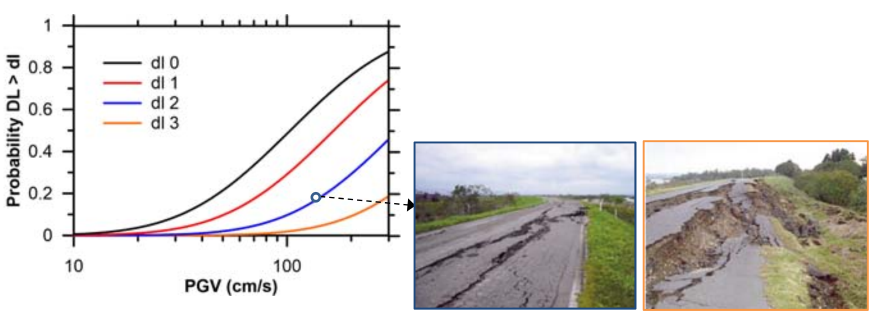


High water
Poorly consolidated sediments

Kwak et al. (2016a)

Segment

Empirical Fragility Model

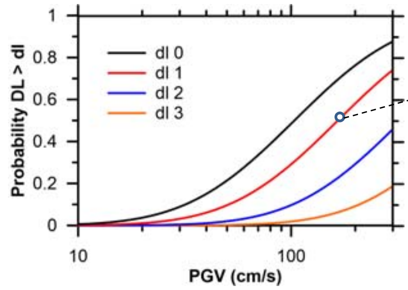


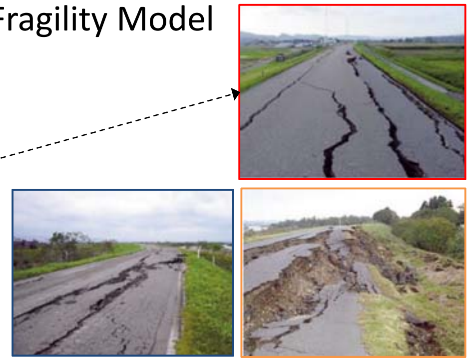
High water
Poorly consolidated sediments

Kwak et al. (2016a)

Segment

Empirical Fragility Model



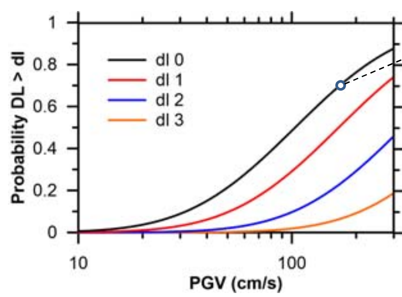


High water
Poorly consolidated sediments

Kwak et al. (2016a)

Segment

Empirical F

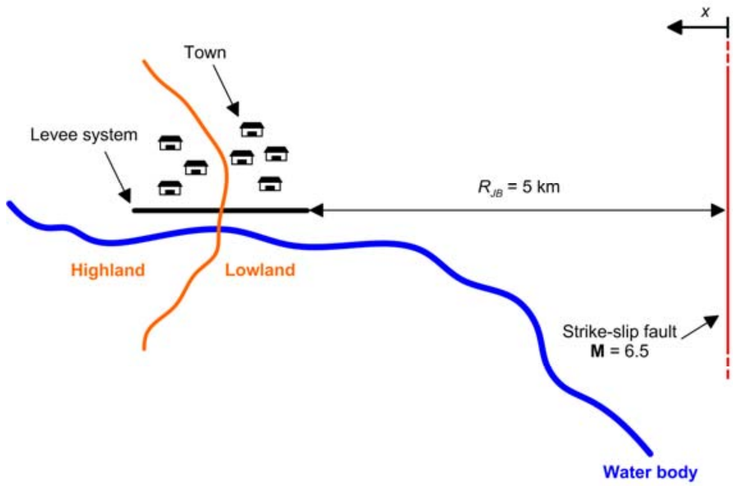


Applicability: Intermittently loaded levees with predominantly granular foundation soils (not soft clays or peats)

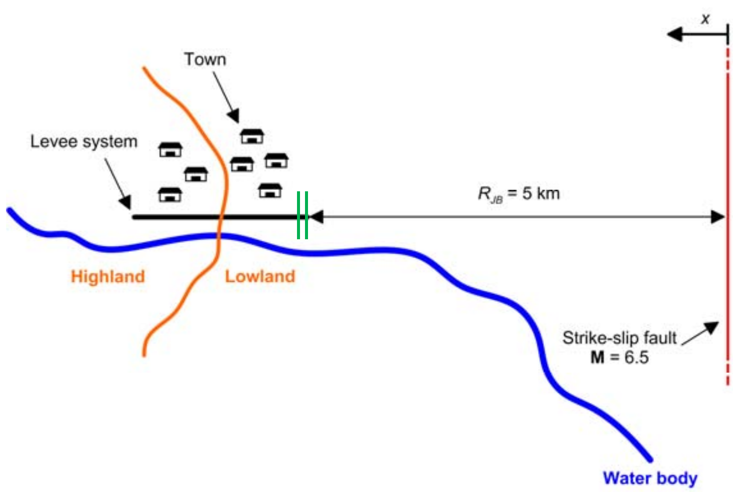
Curves represent *capacity* distributions in PGV space

Kwak et al. (2016a)

Example: Segment Fragility



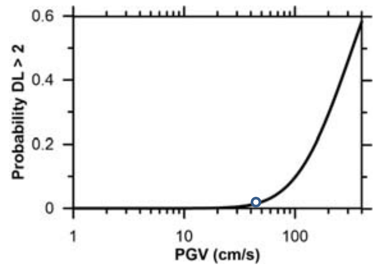
Example: Segment Fragility



Example: Segment Fragility

Fragility from model

Fixed median IM of PGV = 46 cm/s, $P_f|E$ = 0.016



Example: Segment Fragility

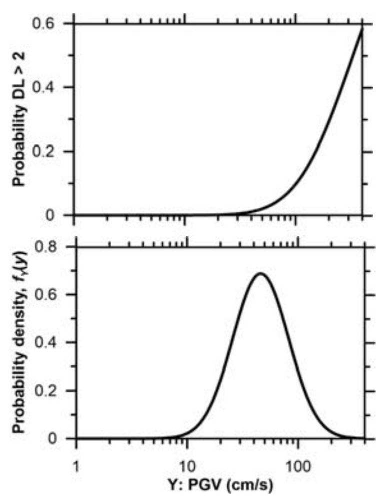
Fragility from model

Fixed median IM of PGV = 46 cm/s, $P_f|E$ = 0.016

Variable IM – convolve fragility with IM distribution

$$P_f \mid E = \int_y f_Y(y \mid E) P_f(y)\, dy$$

$P_f|E$ = 0.035



Outline

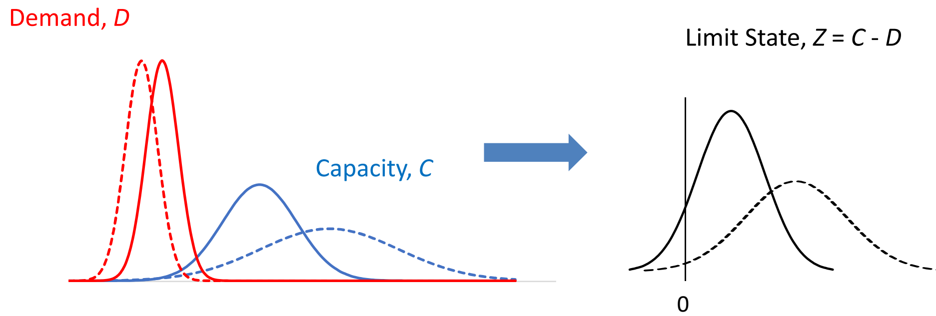
- Levee system taxonomy
- Segment risk
- **System risk**
- Summary

System Risk

- Concepts of *limit state* and *spatial correlation*
- Past practice
- Recommended approaches

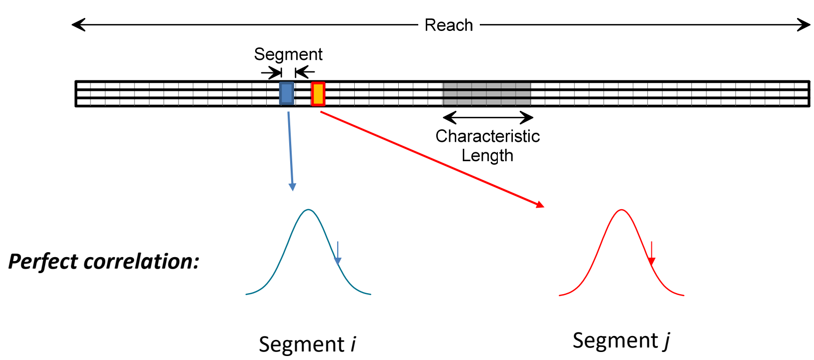
System Risk

Limit State Distribution



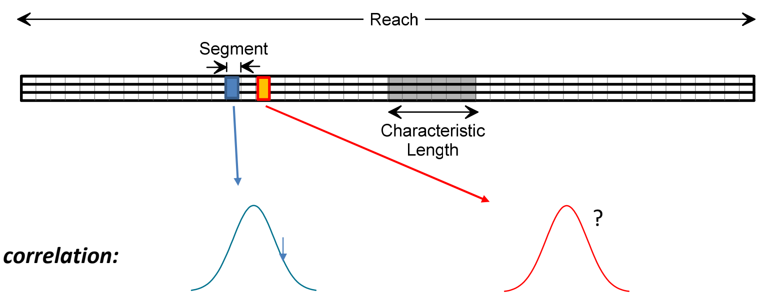
System Risk

Correlation of Limit States



System Risk

Correlation of Limit States



Zero correlation:

Segment *i*

Segment *j*

System Risk

Significance of Correlation

<u>Perfect correlation</u>

$$P_{f,sys} \mid E = \max\left[P_{f,seg} \mid E\right]$$

$\boldsymbol{P_{f,sys} | E = 0.035}$

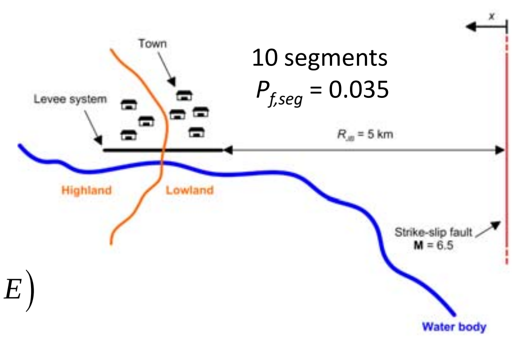
<u>Zero correlation</u>

$$P_{f,sys} \mid E = 1 - \prod_{i=1}^{n}\left(1 - P_{f,seg} \mid E\right)$$

$\boldsymbol{P_{f,sys} | E = 0.30}$

10 segments

$P_{f,seg}$ = 0.035



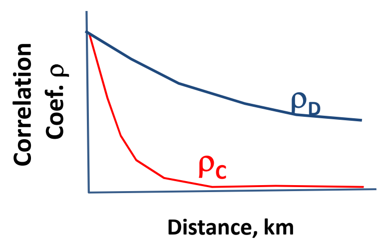
Ang and Tang, 2007

System Risk

Correlation Models

Demand, ρ_D:

Derived from ground motions
Depends on geologic conditions



Capacity, ρ_C:

Derived from field performance (or assumed)
Depends on damage level

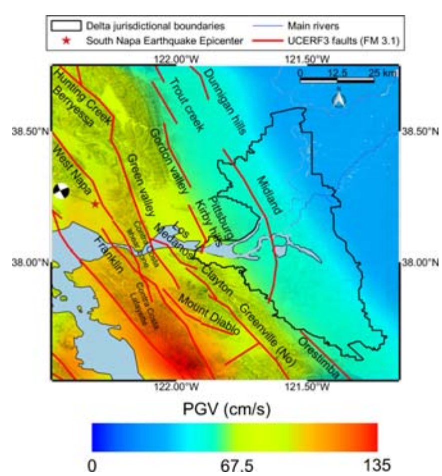
Jayaram and Baker, 2009
Kwak et al., 2016b

System Risk

Previous Approaches, Seismic Applications

Demand taken from hazard maps

- Assumes essentially perfect correlation



Deverel et al. 2016

System Risk

Previous Approaches, Seismic Applications

Demand taken from hazard maps

- Assumes essentially perfect correlation

$\rho_D < 1$

System Risk

Previous Approaches, Seismic Applications

Demand taken from hazard maps

- Assumes essentially perfect correlation

Capacity taken from analysis of representative section within reach

- Perfect correlation within reaches
- Zero correlation between reaches

Bias: Depends on L_{Reach} vs. L_{Char}

Unknown variability

Zimmaro et al. 2017a

System Risk

Recommended Approaches

Monte Carlo Simulation

Segment-specific demand and capacity models

Correlation Models

Cholesky decomposition

System fails if any segment has $Z < 0$

Repeat N times, evaluate $P_{f,sys}$

Kwak et al. 2016b

System Risk

Recommended Approaches

Level Crossing Statistics (LCS)

Used previously in Netherlands for flood applications

Reach-specific limit state function

FORM to evaluate segment failure probabilities

LCS to evaluate ρ_Z and $P_{f,reach}|E$

If $L_{Char} < L_{Reach}$, combine reaches with zero correlation

Vrouwenvelder, 2006
Jongejan and Maaskant, 2016
Zimmaro et al. 2017b

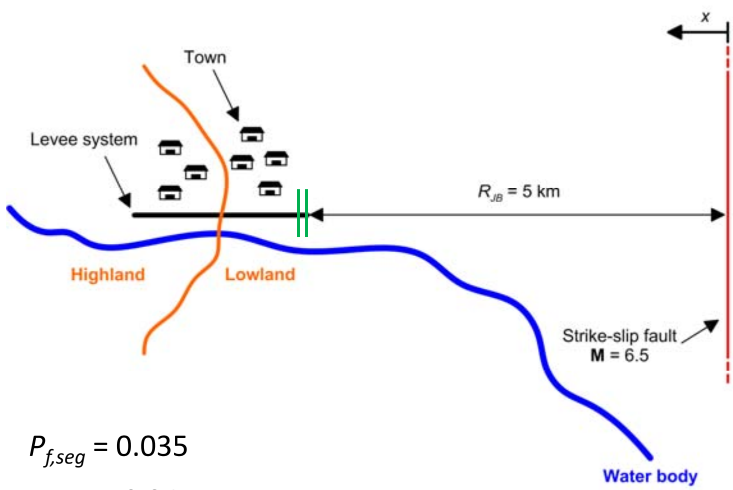
System Risk

Recommended Approaches

Both approaches require event conditioning. Why?

- Earthquakes occur one at a time
- PSHA maps: many sources for each site, with strong spatial correlation
- ∴ system risk should be computed at the event level
- Can be repeated across multiple events

Example



$P_{f,seg}$ = 0.035

$P_{f,Sys}$ = 0.24

Summary

- Risk of distributed systems requires models for hazard, fragility, and spatial correlations (of demands and capacities)
- Most previous work for seismic applications uses *ad hoc* approximations and judgement
- Application requires scenario-based demands
- $\rho_D > \rho_C$
- Two recommended procedures: LCS more computationally efficient

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