State of the Art and Practice in Earthquake-Induced Soil Liquefaction and Its Consequences NAE Report and Additional Comments

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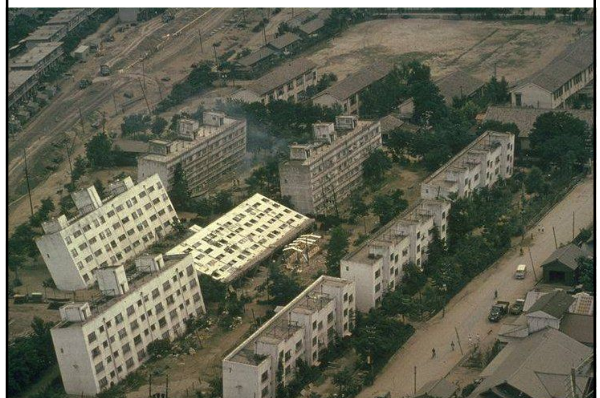
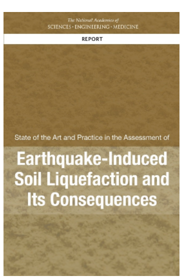


Study Process and Description



Study Sponsors

Bureau of Reclamation

Federal Highways Administration

Nuclear Regulatory Commission

American Society of Civil Engineers and

Geo-Institute

Los Angeles Department of Water and Power

Port of Long Beach

Port of Los Angeles

Statement of Task

- Examine state-of-art and -practice in earthquake induced soil liquefaction assessment
  - ***Sufficiency, quality, and uncertainties in testing, case histories, and modeling***
  - ***Methods to collect and analyze lab and physical modeling data for soil behavior analysis***
  - ***Methods, data gaps, and uncertainties for evaluating consequences of liquefaction***
- Future directions for research and practice

Study Committee

Edward Kavazanjian, Jr. (NAE) *Arizona State University*
Brian F. Atwater (NAS) *USGS and University of Washington*
John T. Christian (NAE) *Consulting Engineer*
James K. Mitchell (NAE/NAS) *Virginia Tech*
James R. Rice (NAE/NAS) *Harvard University*
Jose E. Andrade *California Institute of Technology*
Kandiah "Arul" Arulmoli *Earth Mechanics, Inc.*
Russell Green *Virginia Tech*
Steven L. Kramer *University of Washington*
Lelio Mejia *AECOM*
Ellen Rathje *The University of Texas at Austin*
Yumei Wang *Oregon Department of Geology and Mineral Industries*
Sammantha Magsino *NASEM staff director*

Study Process

- Conducted under the auspices of the National Academies Committee on Geological and Geotechnical Engineering
- Nominations for committee membership broadly solicited
  - Balanced expertise from industry, academe, government
  - Selected by National Academies staff; approved by the President of the National Academies
  - Avoid conflict of interest/too much bias
  - Publicly posted—public invited to comment
- Subject to FACA; all materials submitted to the committee made available to the public upon request
- Rigorous internal and external review process

Information Gathering

- 3 public meetings and webinar
- 2-day workshop with ~90 participants + remote participants
  - Plenary and breakout sessions
    - Case histories/data collection (uncertainties; mechanistic, lab and physical model data; field evidence; characterization of demand)
    - Triggering (susceptibility, demand, resistance, model development)
    - Consequences (residual strength; analytical models; simplified methods; soil/structure interaction)
    - Alternatives to current practice

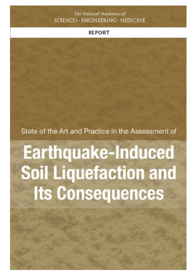
Report Review

- **Internal process check for institutional issues**
- **External independent reviewers**
  - Add more expert input to the process
  - Assist making report accurate, effective, and objective
  - Anonymous to committee until report publicly released
  - Report modified in response to reviews as appropriate
- **Oversight by external report coordinator and monitor**

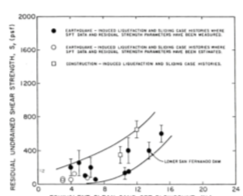
  Robin McGuire and Andrew Whittle
  - Appropriate committee responses to reviewers
  - Recommends when report ready for release

Ronald Andrus, Gregory Baecher (NAE), Ross Boulanger, Jonathan Bray (NAE), K. Önder Çetin, Lloyd Cluff (NAE), Misko Cubrinovski, Ahmed-Waeil Elgamal, Liam Finn, Kenji Ishihara, Michael Lewis

Report Overview



Report Focus



Source: Seed and Harder, 1990

Topics
- Case Histories
- Triggering Analysis
- Consequence Analyses

Approach
- Critical evaluation of current practice
- Potential enhancements to current practice
- New / emerging approaches

Constituencies

- Practitioners
  - The simplified method (current practice)
  - Simplified consequence analyses
  - Advanced analyses
- Owners/Operators
  - Instrumentation and monitoring
- Researchers
  - Advanced analyses
  - Performance-based design

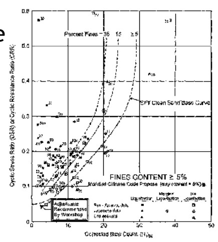
Source: USGS, 2006

Time Frames for Action

Immediate
What we can do now to optimize available methods

Short Term
What we can start doing now to enhance current methods

Long term
What we should do to move beyond current practice



Source: Youd et al., 2001

Eleven Major Recommendations

Data Sufficiency and Quality
(Recommendations 1, 2, and 5)

Uncertainty and Spatial Variability
(Recommendations 3, 4, 6, and 7)

Improved Tools
Recommendations 8 – 11

Source: National Geophysical Data Center

Source: NISEE/PEER, University of California Berkeley

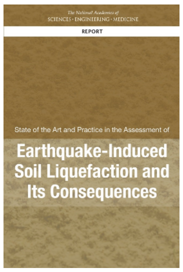
Recommendations (1-5)

1. Establish curated, publically accessible case history databases
2. Establish field observatories for triggering, consequences
3. Use CPT where feasible
4. Use soil mechanics, seismologic principles and experimental data to extrapolate
5. Use geology to improve the geotechnical understanding (case histories and project sites)

Recommendations (6-11)

6. Use methods as they were developed
7. Explicitly incorporate uncertainties
8. Refine, develop, implement performance-based design
9. Use data, fundamental principles, mechanics to develop new techniques
10. Develop / validate computational models using lab and physical model tests, case history data
11. Conduct fundamental research to aid computational model development

Recommendations



Recommendation 1

Establish curated, publicly accessible databases of relevant liquefaction triggering and consequence case history data

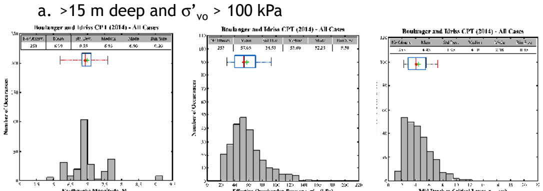
- **Include case histories of interaction with structures**
- **Document with relevant field, laboratory, and physical model data**
- **Develop with strict protocols, including data quality indicators**

Recommendation 1 (cont)

For maximum benefit, case history databases need:

1. **Cases with parameter values beyond the ranges found in current databases:**

   a. >15 m deep and σ'_{vo} > 100 kPa



Source: NASEM, 2016

Recommendation 1 (cont)

For maximum benefit, case history databases need:

1. Cases with parameter values beyond the ranges found in current databases.
2. **The wealth of data from recent earthquakes**

For example

- 1999 M7.4 Kocaeli earthquake, Turkey
- 1999 M7.6 Chi-Chi earthquake, Taiwan
- 2010 M7.1 Darfield earthquake, New Zealand
- 2010 M8.8 Maule earthquake, Chile
- 2011 M9.0 Tohoku earthquake, Japan
- 2011 M6.2 Christchurch earthquake, New Zealand
- 2016 M5.7 Valentine's Day earthquake, New Zealand
- 2016 M6.2, 6.0, and 7.0 Kumamoto, Japan earthquakes
- 2016 M7.8 Kaikoura earthquake, New Zealand

Recommendation 1 (cont)

For maximum benefit, case history databases need:

1. Cases with parameter values beyond the ranges found in current databases.
2. The wealth of data from recent earthquakes
3. **Greater consistency, greater transparency about differences in:**
   a) **Quality**
   b) **Levels of detail**
   c) **Degree of vetting**
   d) **Documentation**

Recommendation 1 (cont)

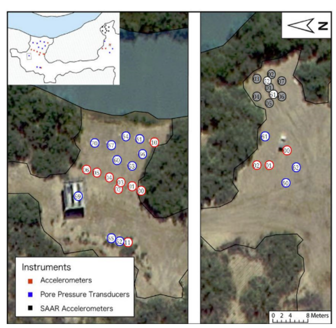
For maximum benefit, case history databases need:

1. Cases with parameter values beyond the ranges found in current databases.
2. The wealth of data from recent earthquakes
3. Greater consistency, greater transparency about differences in the quality, levels of detail, degree of vetting, and documentation
4. **Open access with capabilities for searching**

Recommendation 2

Fill gaps in case history databases by establishing liquefaction observatories at well characterized, well instrumented, and strategically located sites with high probability of earthquake-induced soil liquefaction in coming decade

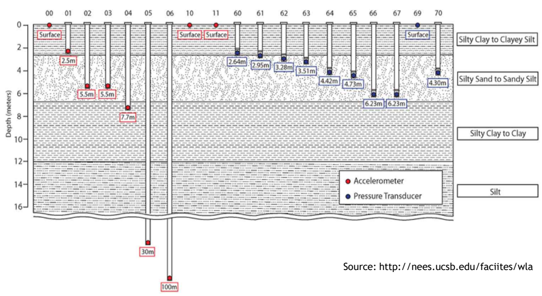
Recommendation 2 (cont)



e.g., Wildlife Liquefaction Array (WLA)

Source: http://nees.ucsb.edu/faciites/wla

Recommendation 2 (cont)



e.g., Wildlife Liquefaction Array (WLA)

Recommendation 3

Use data from the cone penetration test (CPT) where feasible

- **If the standard penetration test (SPT) is used, make hammer energy measurements**
- **Use combination of techniques where possible**

Recommendation 3 (cont)

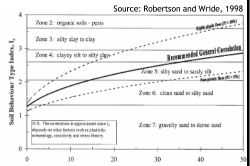
CPT advantages:

1. **Less dependent on operator, setup**
2. **Relatively quick, cost-effective**
3. **Can detect thinner layers**
4. **Can measure Vs with Seismic CPT**

CPT limitations:

1. **No direct measure of soil type, fines content, plasticity index (PI)**
2. **Cannot characterize gravelly soils, denser soils**

Source: Robertson and Wride, 1998



Recommendation 3 (cont)

Role of SPT:

1. **Characterizing denser/deeper/coarser soils**
2. **Samples for soil type, fines content, PI**
3. **Hammer energy measurements needed to reduce uncertainties in blow counts**

Use multiple techniques to minimize uncertainties

- **CPT with SPT for soil type, fines content, PI**
- **CPT with Vs to better understand stiffness, cyclic loading**
- **Vs, instrumented Becker Penetration Test (iBPT) at gravelly sites**

Recommendation 4

When refining or developing new empirical relationships for use in liquefaction analyses, incorporate unbiased estimates for input parameters

- Identify and quantify (when possible) uncertainty
- Use soil mechanics principles, seismologic principles, and experimental data to extrapolate

Recommendation 4

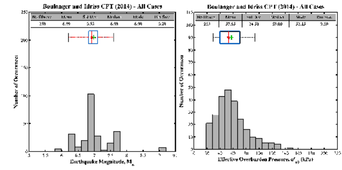
Avoid built-in bias:

- Difficult, if not impossible, to assess the overall uncertainty

Empirical methods equally reliable for conditions well represented in the empirical datasets

Source: NASEM, 2016

Datasets are not well represented across the range of conditions needed in practice



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Recommendation 5

Use geology to improve the geotechnical understanding of case histories and project sites, particularly where potentially liquefiable soils vary in thickness, continuity, and engineering properties

Current site assessment practice: focus on the engineering characteristics of subsurface materials.

Geologic context: basic to assessing liquefaction hazards in case histories and in project work

Recommendation 6

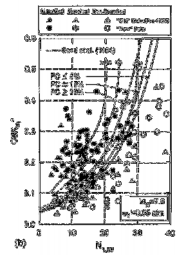
Implement simplified stress-based methods for liquefaction triggering in a manner consistent with how they were developed.

- Avoid using techniques and adjustment factors from one method with other methods
  - Use the method as developed
- Consider using more than one simplified method

Recommendation 6

Implement methods in a manner consistent with how they were developed

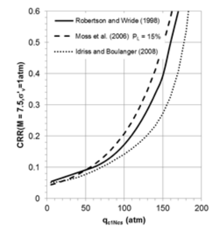
- **Use method-specific r_d, FC correction, Kσ, etc.**
- **Do not mix and match**



Recommendation 6

Consider using more than one method:

- **Different methods can represent epistemic uncertainty**
- **Provides engineer with information to use with their professional judgment**



SOURCE: NASEM, 2016

The r_d Problem

In the equation for calculating CSR,

$$CSR = 0.65\,\frac{\sigma_{vc}}{\bar{\sigma}_{vc}}\,\frac{a_{max}}{g}\,r_d\,\frac{1}{MSF},$$

r_d reduces the shear stress to account for the flexibility of the soil column. Historically, the value has been estimated from the results of a large set of convolution and deconvolution analyses, most performed using the well-known program SHAKE.

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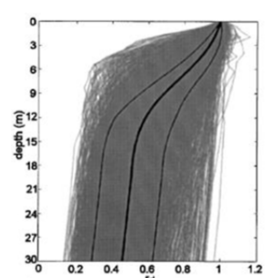
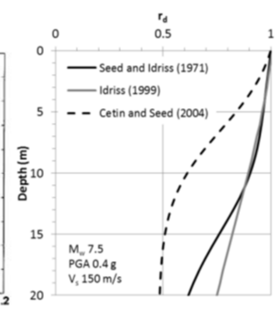
The r_d Problem

The suite of results for r_d



Adopted estimators



The r_d Problem

The expressions used for r_d in the standard liquefaction evaluation procedures (Seed and Idriss et seq.) are significantly larger than the mean or median values from the deconvolution analyses.

This raises the estimates of the imposed shear stresses in any analysis of field evidence or of a proposed site.

It moves all the data points up in a plot of CSR versus SPT, CPT, or v_s results, such as those on the next slide.

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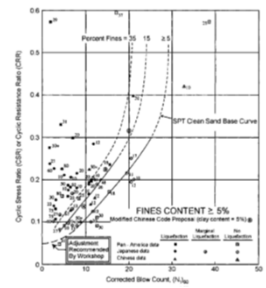
The r_d Problem

Typical CSR-CRR plot from Youd et al. (2001)



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The r_d Problem

Cetin et al. (2004) used r_d values closer to the mean of the deconvolution results, so their points and curves are lower on CSR-CRR plot.

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Cetin et al. (2004) used r_d values closer to the mean of the deconvolution results, so their points and curves are lower on CSR-CRR plot.

An engineer faced with a new site could use either approach, provided the r_d values were consistent with the values used to develop the CSR-CRR plot.

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The r_d Problem

Cetin et al. (2004) used r_d values closer to the mean of the deconvolution results, so their points and curves are lower on CSR-CRR plot.

An engineer faced with a new site could use either approach, provided the r_d values were consistent with the values used to develop the CSR-CRR plot.

However, most of us are tempted to improve things by calculating our own estimated shear stresses using SHAKE or DEEPSOIL. In effect, we are using r_d values substantially lower than those used to develop the plots. We are under-estimating the shear stresses.

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The r_d Problem

In other words, if we use the traditional CSR-CRR plots but calculate our own estimated shear stresses, we will plot the points too low. We will under-estimate the shear stresses with respect to the values used to develop the basic plot. We will under-estimate the liquefaction potential.

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What to do?

- Do not recalculate the stresses; use the standard r_d.

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The r_d Problem

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What to do?

- Do not recalculate the stresses; use the standard r_d.
- Use a CSR-CRR plot based on unbiased stresses.

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The r_d Problem

In other words, if we use the traditional CSR-CRR plots but calculate our own estimated shear stresses, we will plot the points too low. We will under-estimate the shear stresses with respect to the values used to develop the basic plot. We will under-estimate the liquefaction potential.

What to do?

- Do not recalculate the stresses; use the standard r_d.
- Use a CSR-CRR plot based on unbiased stresses.
- **In any case, do not change a parametric estimate in an empirical procedure.**

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Recommendation 7

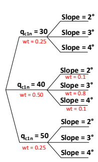
In developing methods to evaluate liquefaction triggering and its consequences, explicitly incorporate uncertainties from field investigations, laboratory testing, numerical modeling, and the impact of the local site conditions on the earthquake ground motions.

Recommendation 7

Uncertainties are present in all aspects of liquefaction assessment—from site characterization to assessing severity of consequences

Influence of these uncertainties should be stated as error bounds, standard deviations, or other statistically appropriate measures

- **Sensitivity analysis**
- **Logic tree**
- **Probabilistic liquefaction hazard analysis (PLHA)**



SOURCE: E. Rathje

Standard Procedure (Idriss & Boulanger 2008)

For horizontal ground,

$$CSR = 0.65\,\frac{\sigma_{vc}}{\bar{\sigma}_{vc}}\,\frac{a_{max}}{g}\,r_d\,\frac{1}{MSF}$$

based on SPT,

$$CRR = f\big((N_1)_{60cs}\big)\cdot K_\sigma$$

$$(N_1)_{60cs} = C_N \cdot C_E \cdot C_B \cdot C_R \cdot C_S \cdot N_m + \Delta(N_1)_{60}$$

based on CPT,

$$CRR = f(q_{c1Ncs})\cdot K_\sigma$$

$$q_{c1Ncs} = C_N \cdot q_{cN} + \Delta q_{c1N}$$

$$FS = CRR/CSR$$

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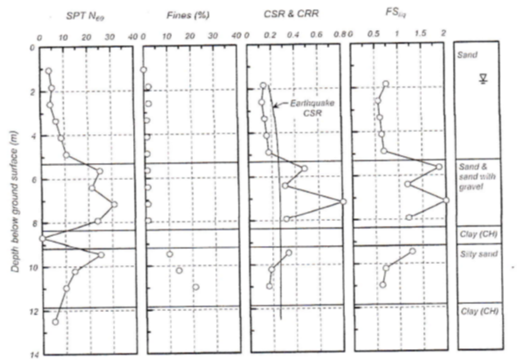

a_{max} = 0.280 *g*   *M* = 6.9

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Parameters for uncertainty analysis

$$COV = \frac{\sigma}{\mu};\quad \zeta^2 = \ln\left(1 + COV^2\right);\quad \lambda = \ln(\mu) + \frac{1}{2}\zeta^2$$

Parameter	COV	ζ^2	Parameter	COV	ζ^2
N_m	0.10	0.009950	MSF	0.20	0.039221
C_N	0.05	0.000400	K_σ	0.07	0.004888
C_N	0.05	0.000400	0.65 factor	0.05	0.002497
C_N	0.05	0.000400	σ_{vc}/σ'_{vc}	0.05	0.002497
C_N	0.05	0.000400	a_{max}	0.10	0.009950
C_N	0.05	0.000400	r_d	0.30	0.039221

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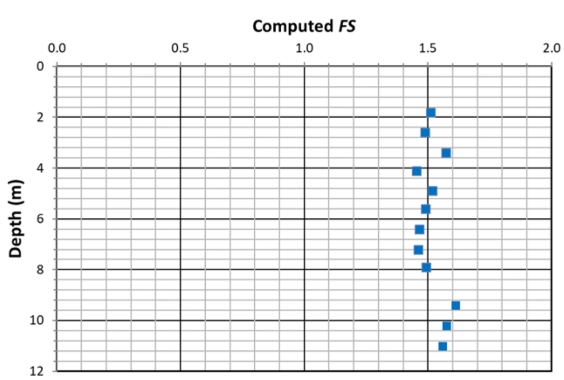

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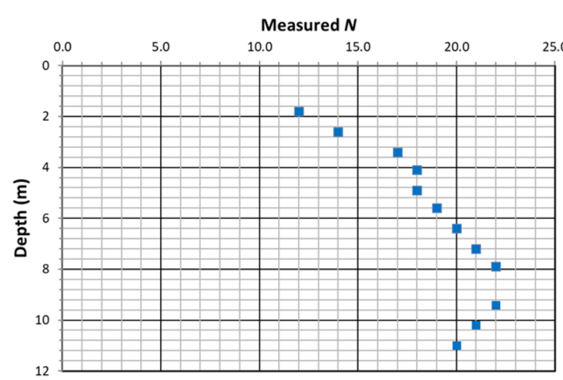

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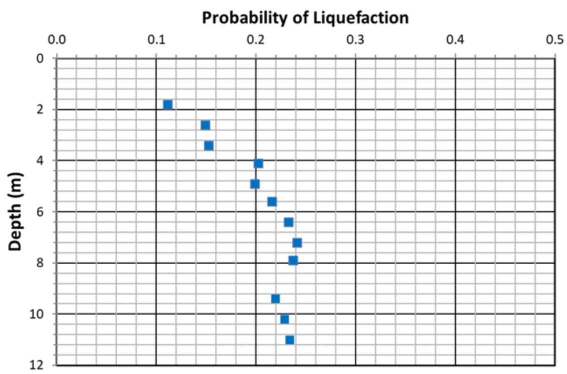

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Comments

- The model uncertainty is much larger than the uncertainty in the location of the critical line.

58

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- For the this typical case based on SPT data, with relatively small COVs, when FS ≈ 1.5, the probability of liquefaction due to model uncertainty is approximately 20%.

59

Comments

- The model uncertainty is much larger than the uncertainty in the location of the critical line.
- For the this typical case based on SPT data, with relatively small COVs, when FS ≈ 1.5, the probability of liquefaction due to model uncertainty is approximately 20%.
- As far as I know, no one has demonstrated that multiplying the correction factors captures their interaction correctly.

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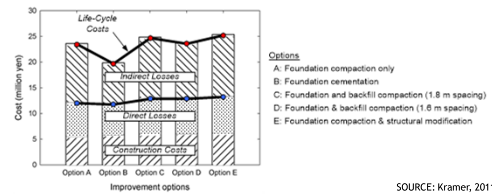
Recommendation 8

Refine, develop, and implement performance-based approaches to evaluating liquefaction

- **Include consequences (ground movement, structural damage) and direct and indirect losses**
- **Account for regional variations in seismicity**
- **Account for all levels of ground shaking**
- **Characterize and account for uncertainties in probabilistic liquefaction hazard analysis (PLHA)**

Recommendation 8

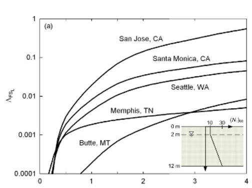
- **Practical procedures for estimation of all significant losses should be developed**
- **Consideration of life-cycle costs can aid in decision-making relative to hazard mitigation options**



SOURCE: Kramer, 2011.

Recommendation 8

- **PLHA can account for:**
  - **local seismic environment**
  - **all levels of shaking**

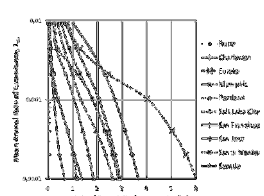


Hazard curves for triggering

SOURCE: Kramer and Mayfeld, 2007

Recommendation 8

- **PLHA can also account uncertainties in consequences**



Hazard curves for lateral spreading

SOURCE: Franke and Kramer, 2014

Recommendation 9

Use experimental data and fundamental principles of seismology, geology, geotechnical engineering, and engineering mechanics to develop new analytical techniques, screening tools, and models to assess liquefaction triggering and post-liquefaction consequences

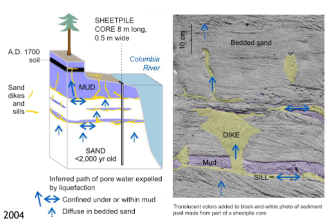
- **Empirical data essential, but insufficient to define behavior over the range encountered in practice**
- **Analyses and models should respect fundamental principles of wave propagation, geology, mechanics, and soil mechanics**

Recommendation 9

- **Geologic investigations provide information on sediment structure, spatial variability, age, other characteristics that affect liquefaction triggering, consequences**
- **Extrapolation beyond bounds of case history data should be guided by fundamental principles**
- **Laboratory testing (cyclic simple shear, cyclic triaxial) also provides guidance for extrapolation**
- **Physical model testing (centrifuge, shaking table) can also provide useful data**

Recommendation 9

- **Geologic investigations provide information on sediment structure, spatial variability, age, other characteristics that affect triggering, consequences**



SOURCE: Takada and Atwater, 2004

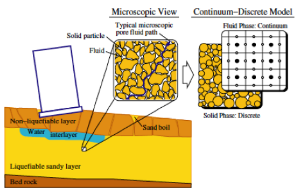
Recommendation 10

Develop and validate computational models for liquefaction analyses

- **Computational models are valuable tools (e.g., when empirical models are not applicable, or give contradictory or inconclusive results)**
- **Laboratory and physical model tests at different spatial scales and case histories to provide insight into fundamental soil behavior**
- **Use laboratory and physical model tests to validate the application of constitutive models to boundary-value problems**

Recommendation 10

- **Complex coupled mechanical and fluid behavior is important, modeling improvements are needed**
- **Discrete element models are promising, but improvements in efficiency, coupling with other simulations across different scales are needed**

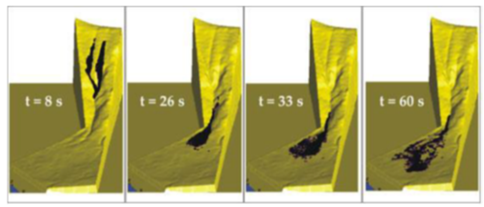


SOURCE: Zeghal and El Shamy, 2004

Recommendation 10

Promising methods for simulation of granular flow are under development

- **Should be extended, validated, and calibrated for practical predictions of behavior.**



SOURCE: Pastor et al., 2009

Going "over the peak"

It is sometimes stated that we need to model the entire liquefaction process from the start to end. Using FEM and FDM we can deal fairly well with conditions leading up to liquefaction, and using meshless methods we are beginning to deal with the flow of liquefied material. The problem is in the transition.

I suspect that this is essentially a chaotic condition and that our modeling efforts may not be successful in the foreseeable future.

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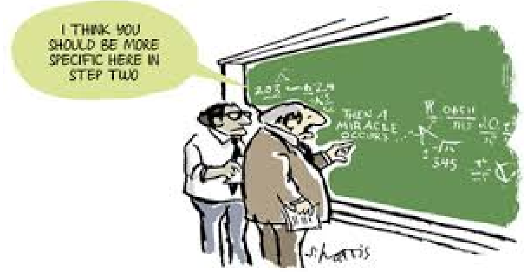
Going "over the peak"



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Recommendation 11

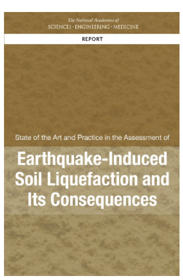
Conduct fundamental research on the stress, strain, and strength behaviors of soils prior to and after liquefaction triggering

- **Devise new laboratory and physical model techniques to aid development of constitutive models**
- **Improved understanding and quantification of post-triggering behavior needed**

Recommendation 11

- **Fabric degradation following triggering poorly understood.**
  - **Data needed for constitutive modeling at these large strains**
  - **Dilation-induced stiffening is poorly documented. Experimental data needed to enable constitutive modeling of this**
  - **Effects of relative density, initial effective stress, initial shear stress need investigation**

Questions / Discussion



Committee on Geological and Geotechnical Engineering

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Thank You