Seismic Analysis and Design of Retaining Structures and Basement Walls: Lessons from Observed Performance and Recent Research

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With thanks to:
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GEOVIRGINIA 2018
Williamsburg VA
April 9th - 11th
Lessons Learned in Geotechnical Engineering

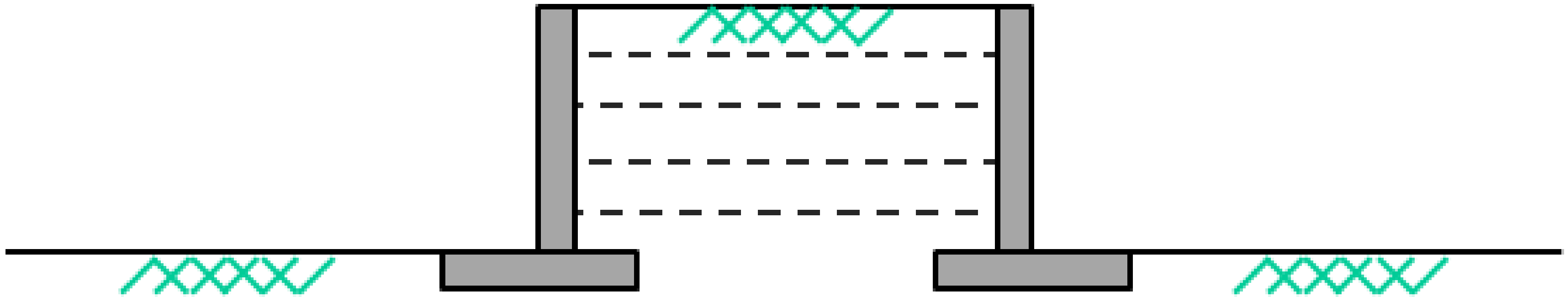
Research funded by VTA, BART, PEER, CalGeo, Caltrans and NSF-NEES-CR Grant No. CMMI-0936376: Seismic Earth Pressures on Retaining Structures.

My Motivation – "Living" with a fault…

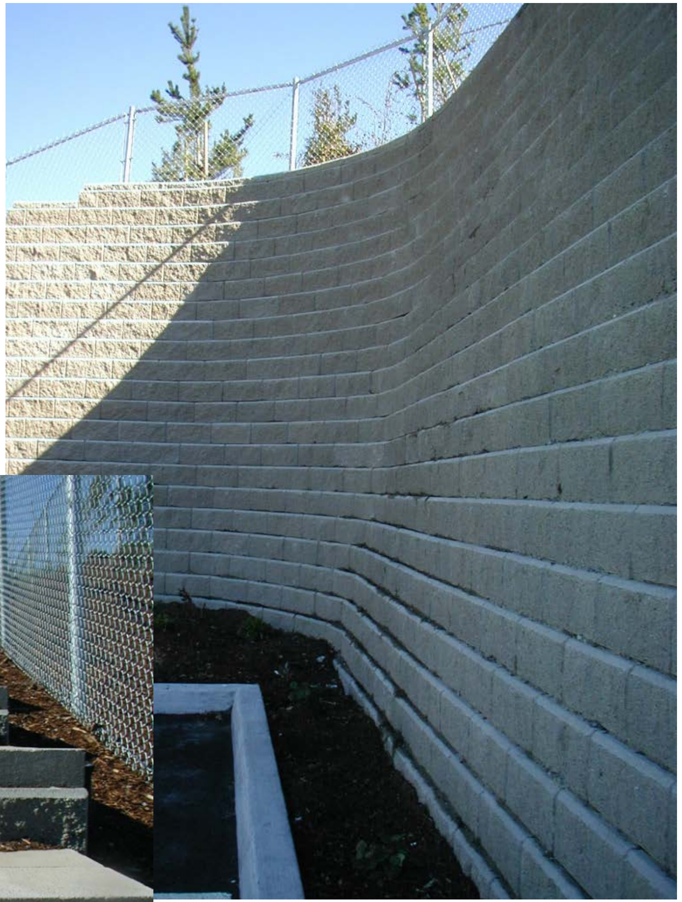
Objectives

- A brief discussion of performance of mechanically stabilized embankments
- Discuss in detail the issues related to the analysis and design of retaining structures and basements
  - Observed performance
  - Current Design Methods
  - Experimental Results
  - Numerical Analyses/Challenges
  - Recommendations

Seismic Performance of Mechanically Stabilized Walls and Embankments

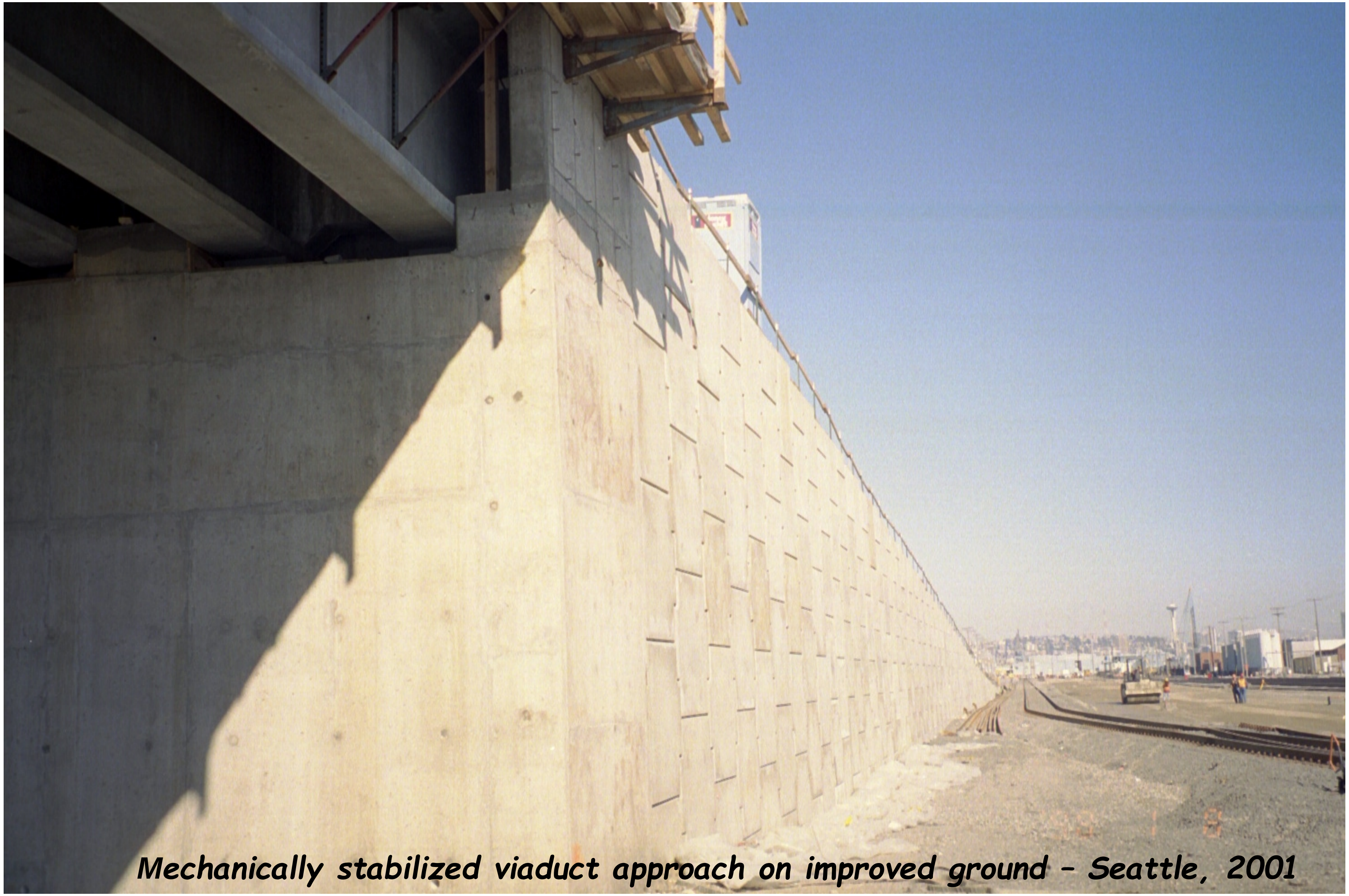


Block Facing Walls



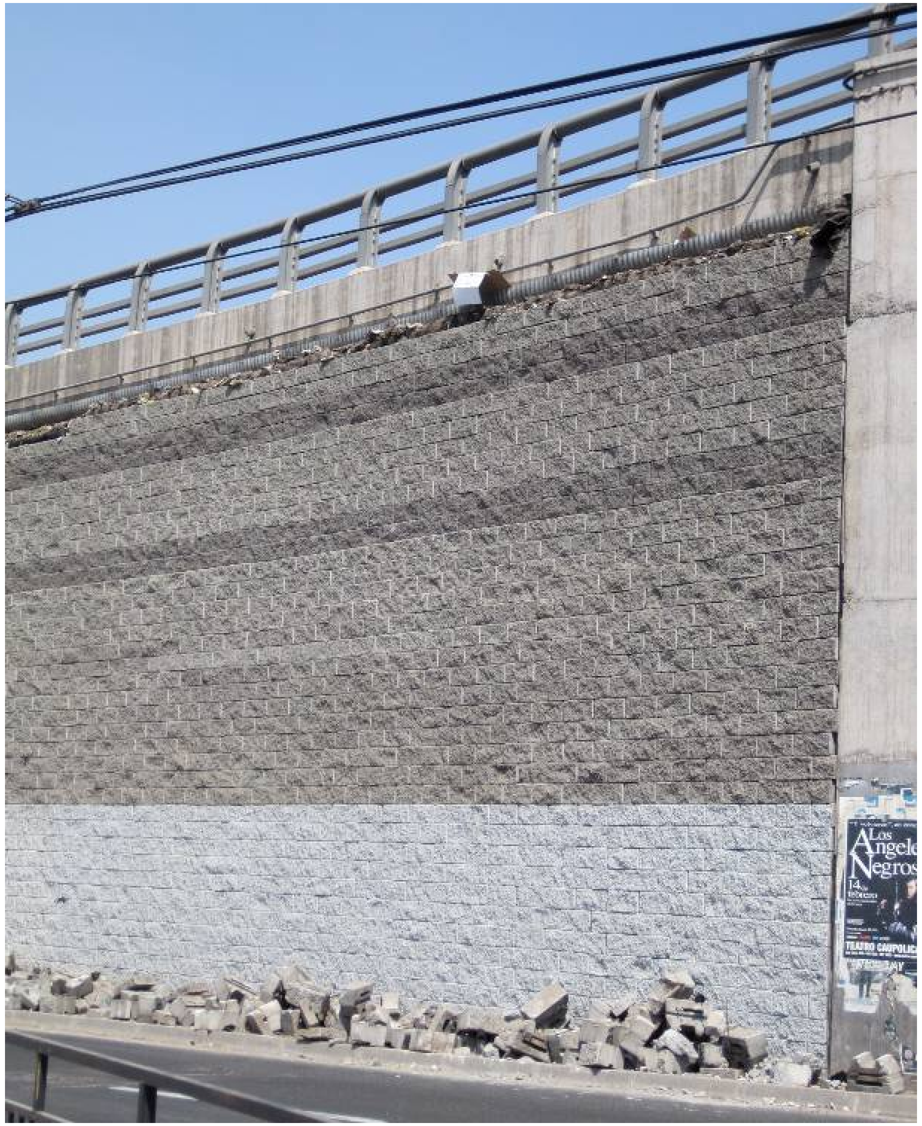
Nisqually 2001, Tacoma, WA

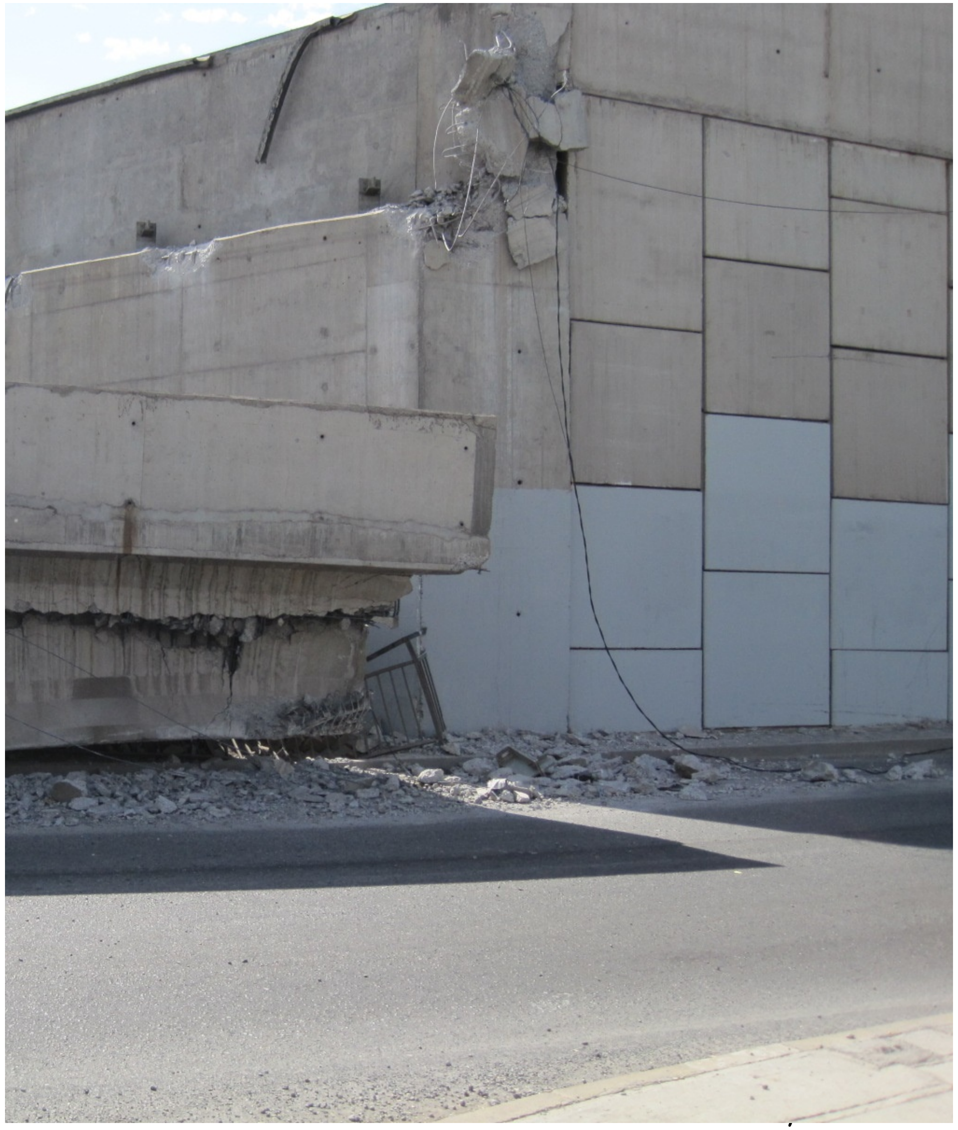
Reinforced Earth™



Mechanically stabilized viaduct approach on improved ground – Seattle, 2001

Chile – 2010 – excellent performance






Old
New
11.03.2010 13:31

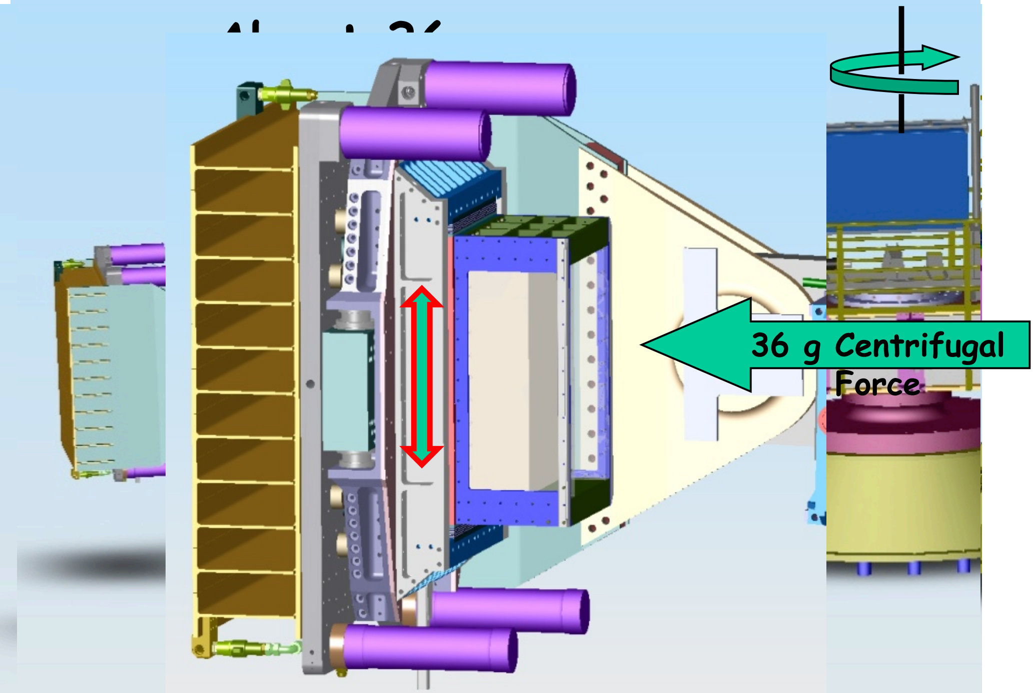
Our Approach: Physical and Numerical Modeling

Use Physical Modeling to Verify Failure Mechanisms

- Why centrifuge?
  - Good scaling relationships
  - Repeatability
  - Reproducibility
  - Cost effectiveness

- UC Davis centrifuge:
  - 9.1m radius, 4,500Kg maximum payload, area of bucket $4m^2$

How does the centrifuge work?



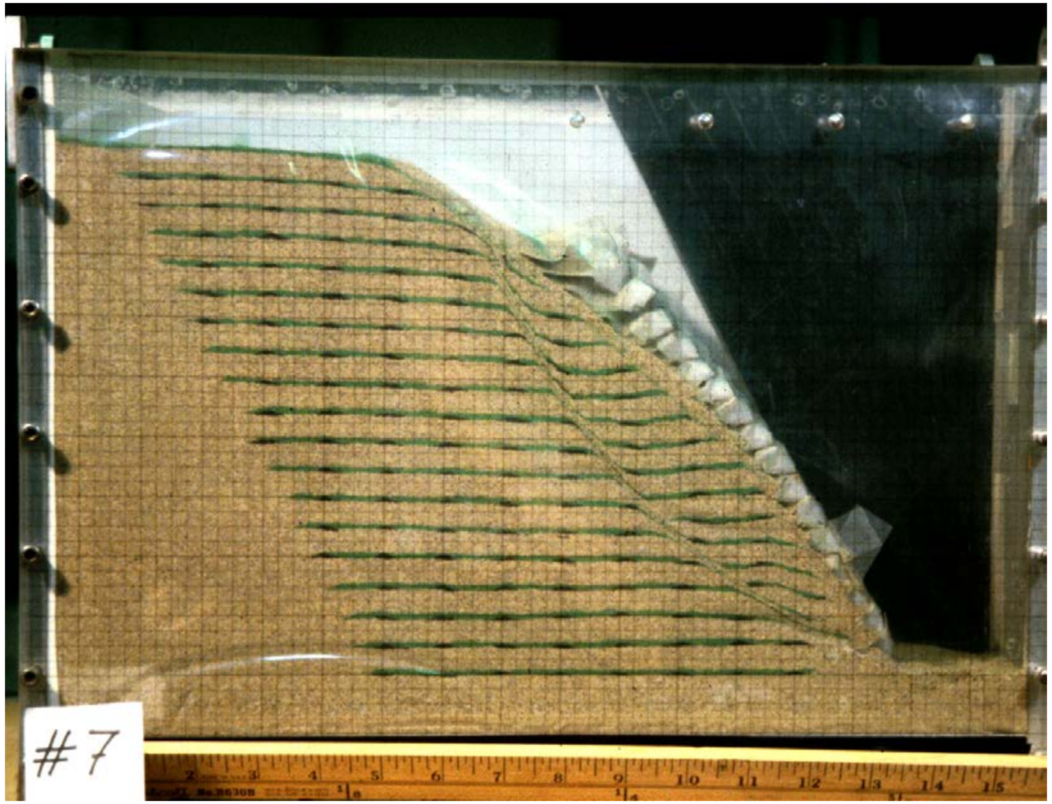
To simulate earthquakes, we have to shake the models while they spin

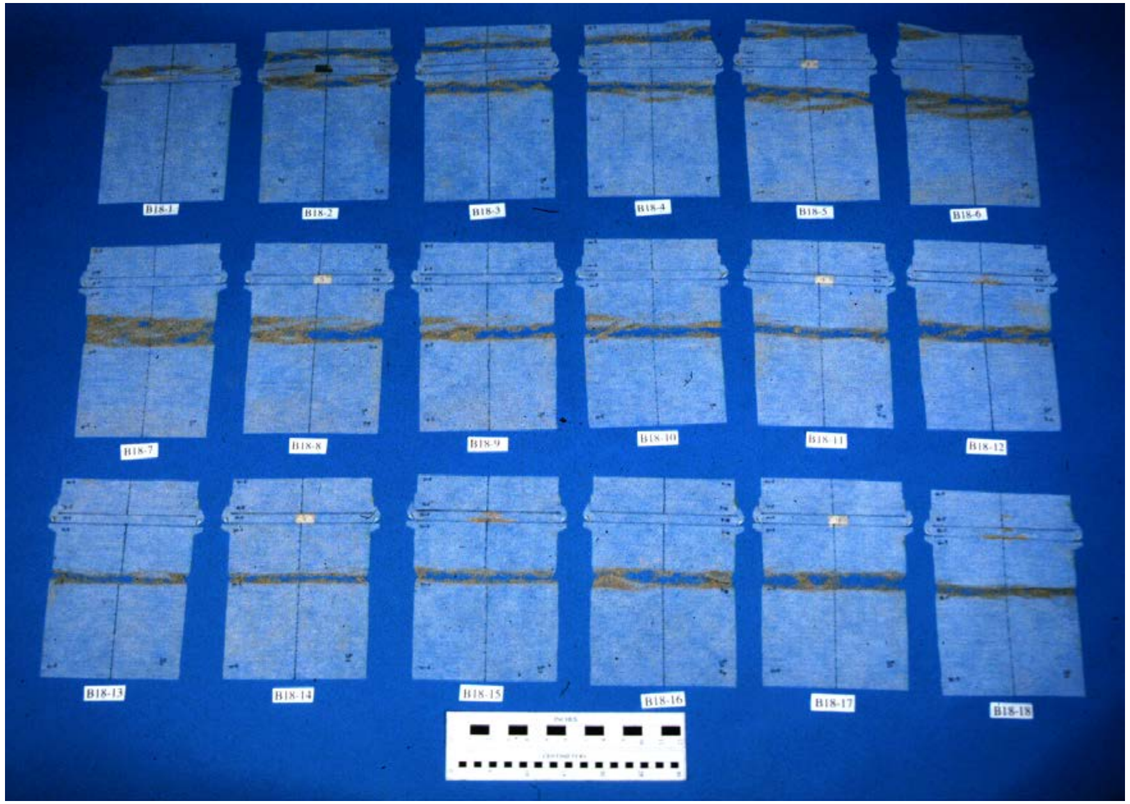
Courtesy Prof. Bruce Kutter

The centrifugal force increases the “weight” of the model to simulate weight of a full scale structure

Parameter	Model Dimension/Prototype Dimension
Length, L	1/N
Area, A	$1/N^2$
Volume, V	$1/N^3$
Mass, m	$1/N^3$
Density, ρ	1
Force, F	$1/N^2$
Moment, M	1/N3
Stress, σ	1
Strain, ε	1
Strain Rate	N
Acceleration, Gravity	N
Acceleration, Dynamic	N
Time, Dynamic	1/N
Frequency	N

Static Centrifuge Experiments

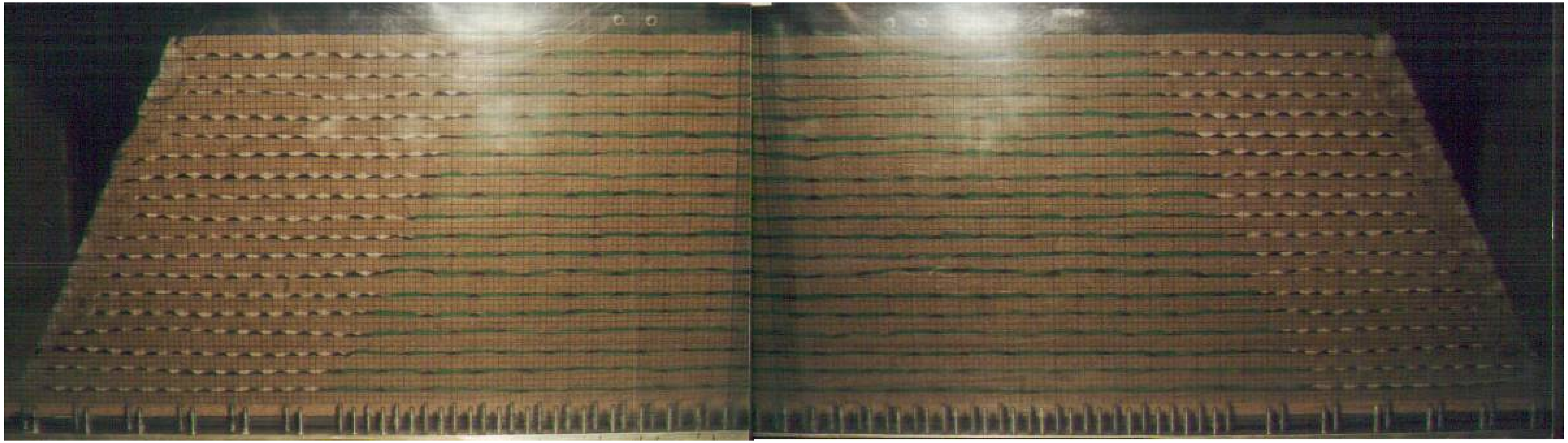




See: Zornberg, J.G., Sitar, N., and Mitchell, J.K. 1998. "Performance of Geosynthetically Reinforced Soil Structures at Failure," J. of Geotechnical and Geoenvironmental Engrg., ASCE,Vol. 124, No. 8, pp. 670-683 [10.1061/(ASCE)1090-0241(1998)124:8(670)](https://doi.org/10.1061/(ASCE)1090-0241(1998)124:8(670))

Seismic Centrifuge Experiments

Height: 15.2 cm (model: 19.2g), 7.3 m (proto)
Relative Density: 75%
Reinforcement: Tru-Grid (70%H-right, 90%H-left)



Summary

- Mechanically stabilized embankments perform very well, especially those using geosynthetic grids or fabric

- Conventional design appears quite adequate for most applications and seismic design guidelines are extremely conservative

- An important element is close spacing (18-24 in.) of the reinforcement layers to achieve good compaction, i.e. 3ft – 90 cm between reinforcements is too much for good compaction.

Nova-Roessig, L. and Sitar, N., "Centrifuge Model Studies of the Seismic Response of Reinforced Soil Slopes" *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 3, March 1, 2006, DOI: 10.1061/(ASCE)1090-0241(2006)132:3(388)

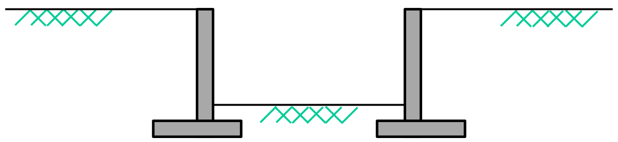
Conventional Retaining Structures and Basements

- Discuss in detail the issues related to the analysis and design of retaining structures and basements
  - Observed performance
  - Current Design Methods
  - Experimental Results
  - Numerical Analyses/Challenges
  - Recommendations

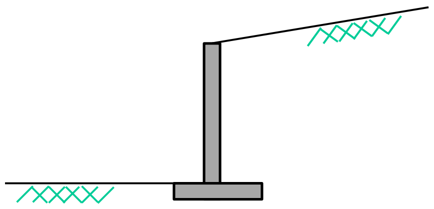
Types of Retaining Structures

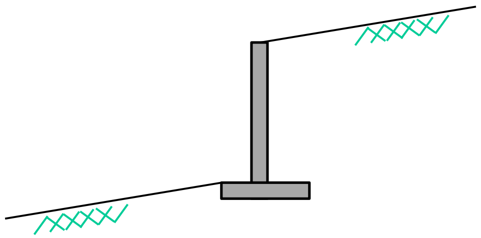
Flexible/Yielding

- Level ground

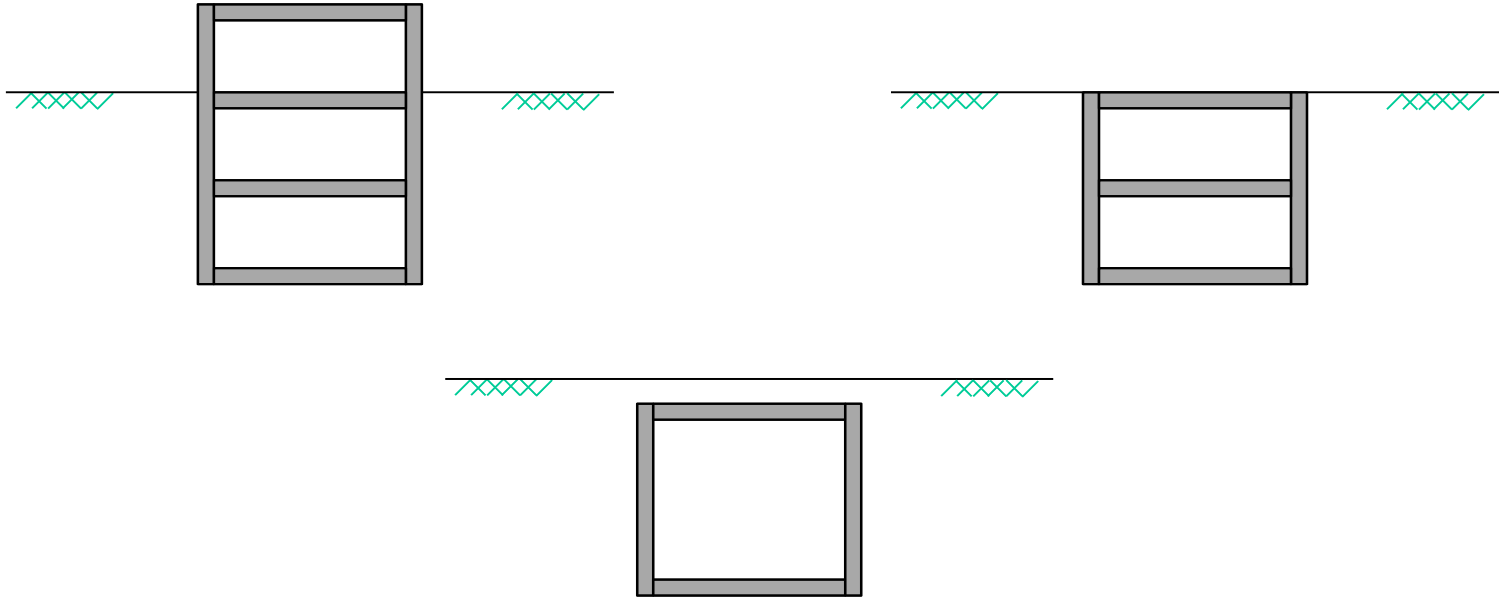


- Sloping ground





- “nonyielding” – walls that do not satisfy the movement condition



Present Design Guidance (such as it is…)

- Confusion regarding the type of analysis to use, especially the yielding and non-yielding designation

- ?... recommendations: e.g FEMA 750
  - "In the past, it was common practice for geotechnical engineers to reduce the instantaneous peak by a factor from 0.5 to 0.7 to represent an average seismic coefficient for determining the seismic earth pressure on a wall. ...

    …This approach can result in confusion on the magnitude of the seismic active earth pressure and, therefore, is not recommended. Any further reduction to represent average rather than instantaneous peak loads is a structural decision and must be an informed decision made by the structural designer."

Past Performance

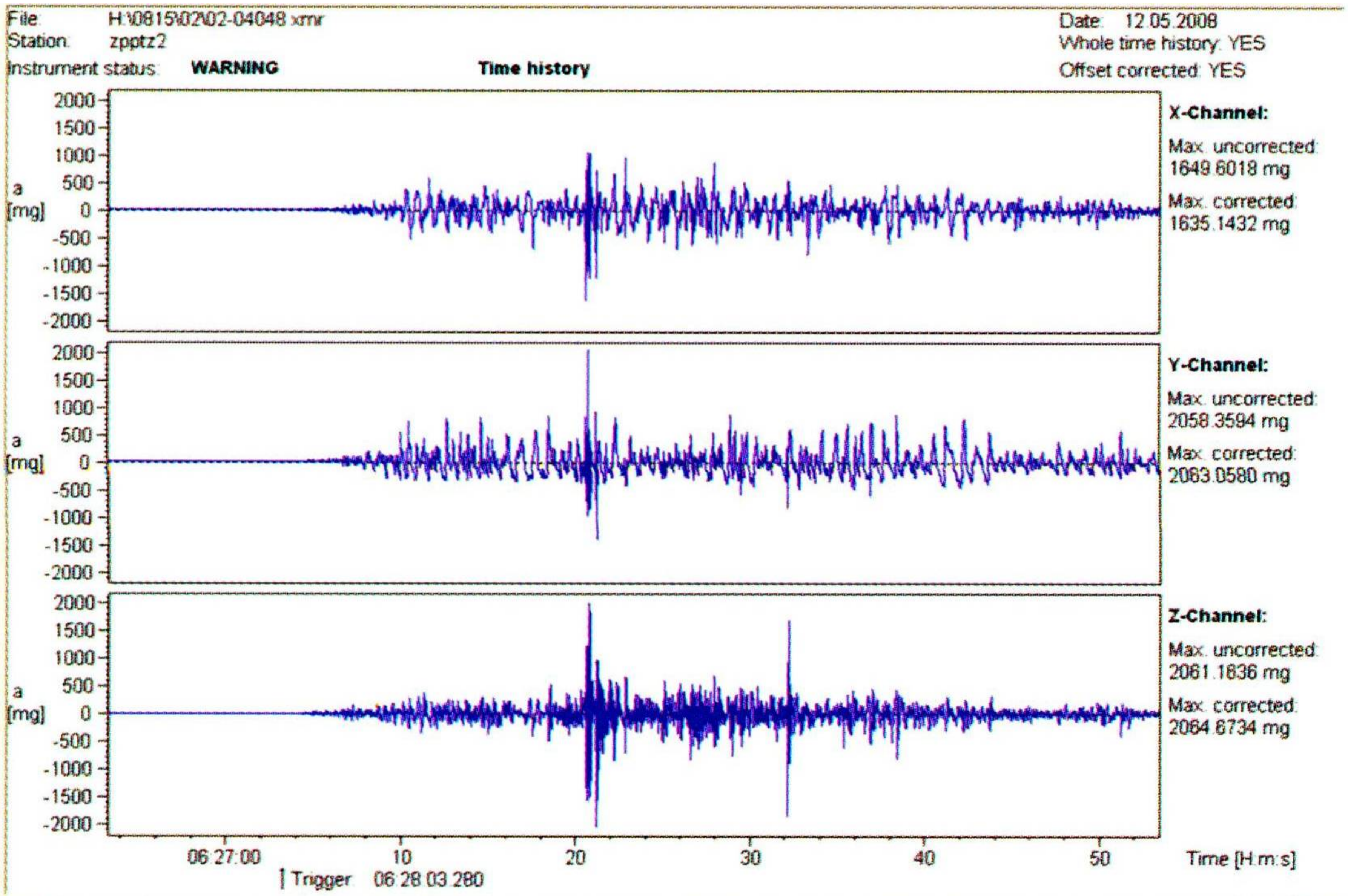
Delphi: polygonal wall and temple of Apollo 548 B.C., temple destroyed by quake 373 B.C., other major quakes 551, and 1870 A.D.

Taiwan, 1999

A lot of problems with old walls on sloping ground and with sloping backfill. No problems with base-ments and flat ground ….

Wenchuan – 2008 – Traditional retaining structures

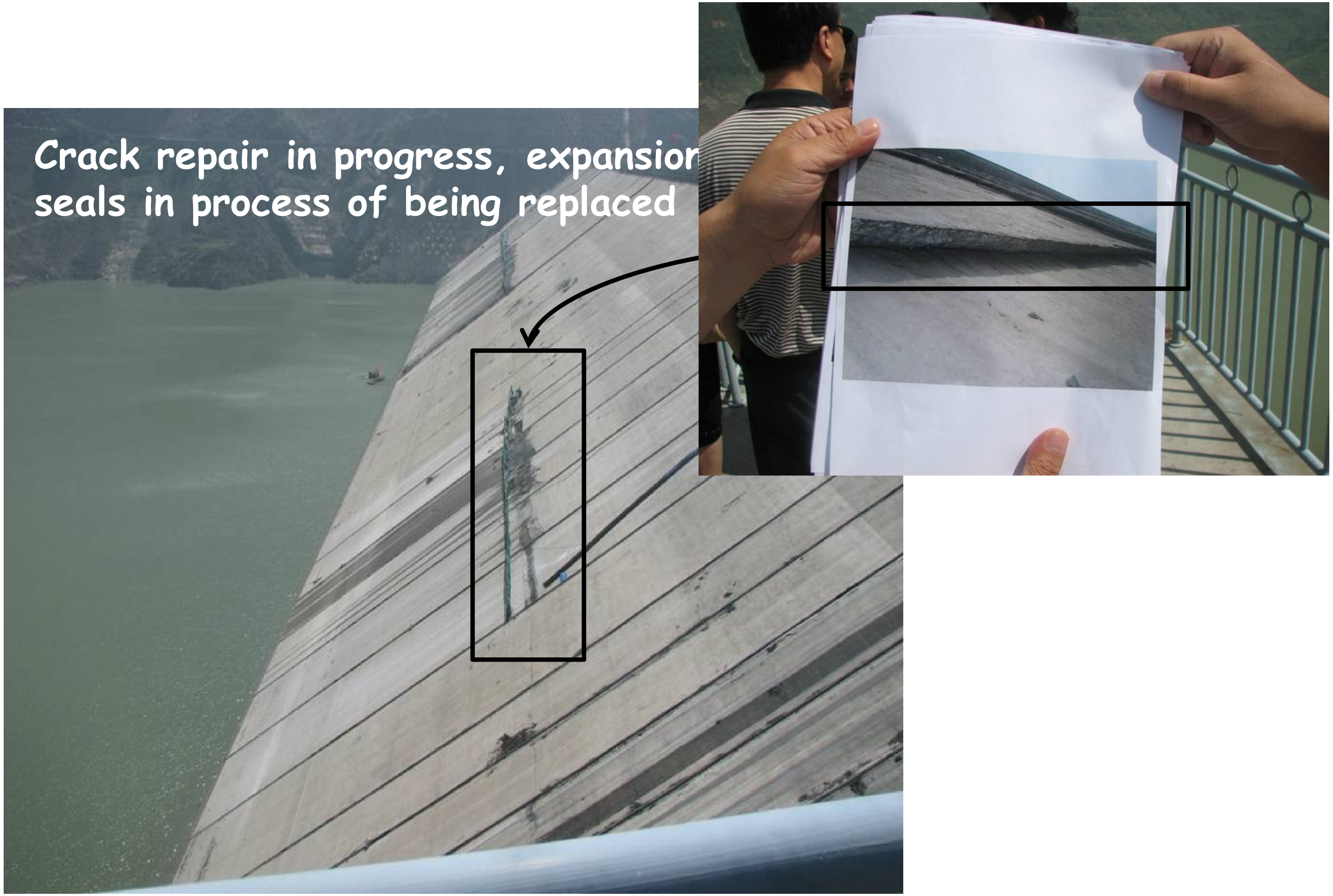
Zipingpu Dam, China 2008



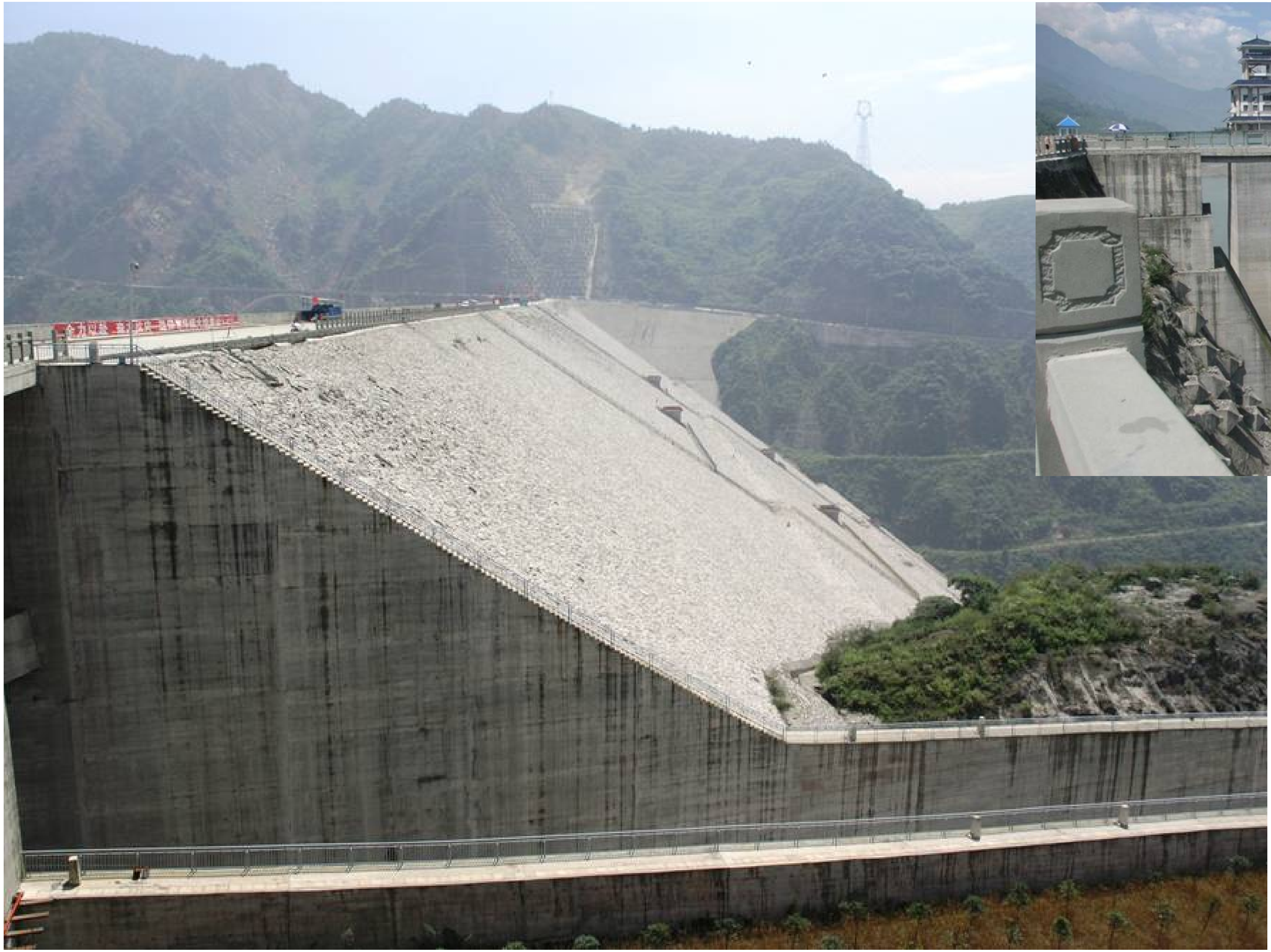
Favorable performance under seismic load

Crest Acceleration at Zipingpu Dam during Wenchuan Earthquake


Crest Settlement
~ 73 cm at center



Crack repair in progress, expansion seals in process of being replaced




Spillway

Chile – 2010

Great Tohoku Earthquake – 2011

- No reported failures of underground structures/basements
- Segmented geosynthetically reinforced structures performed well
- Minor damage to conventional retaining walls on sloping ground

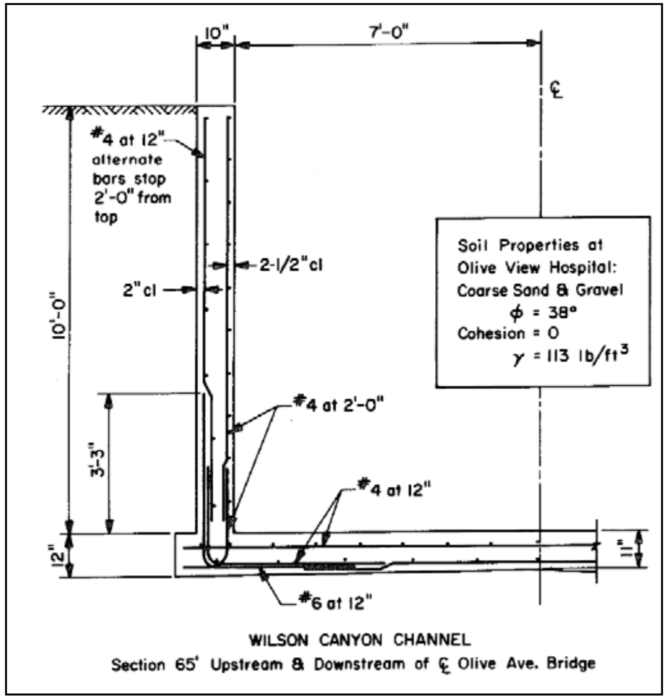
Iquique – 2014 – cantilever walls without footings

G. Candia - RCINDIM - National Research Center for Integrated Natural Disaster Management
CONICYT/FONDAP/15110017

Railway Overpass, SR 1 at Kekerengu, Kaikoura Earthquake

Railway Overpass, SR 1 south of Kekerengu, Kaikoura Earthquake

U-Wall Damage During 1971 San Fernando Earthquake, Clough & Fragaszy (1977)



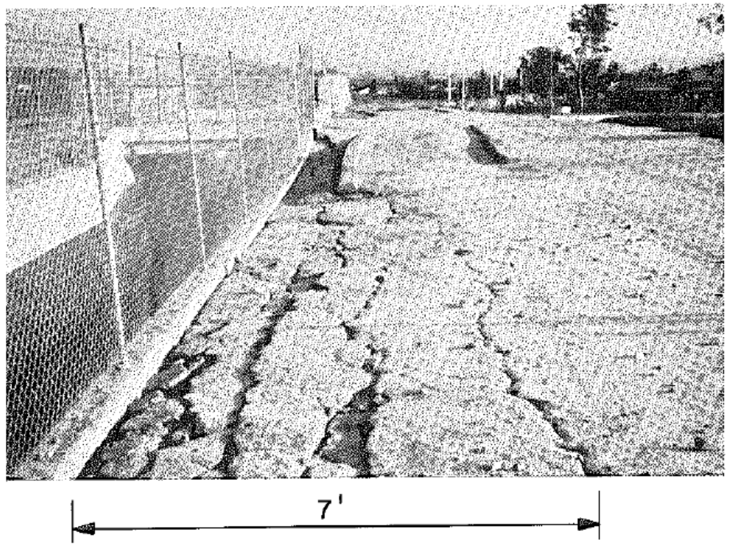
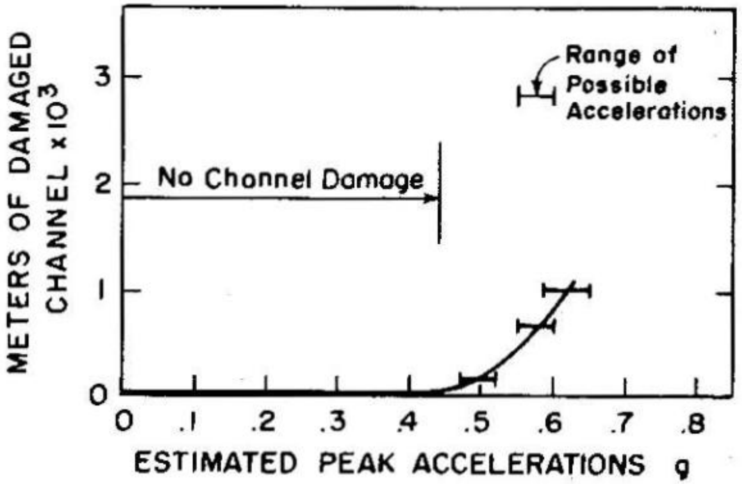


Figure 1.4 Wilson Canyon Channel. Cracking in soil as a result of wall displacements. Fine cracking was detected a distance of 15 ft behind wall.



Typical Methods of Analysis

Mononobe and Okabe (M-O)

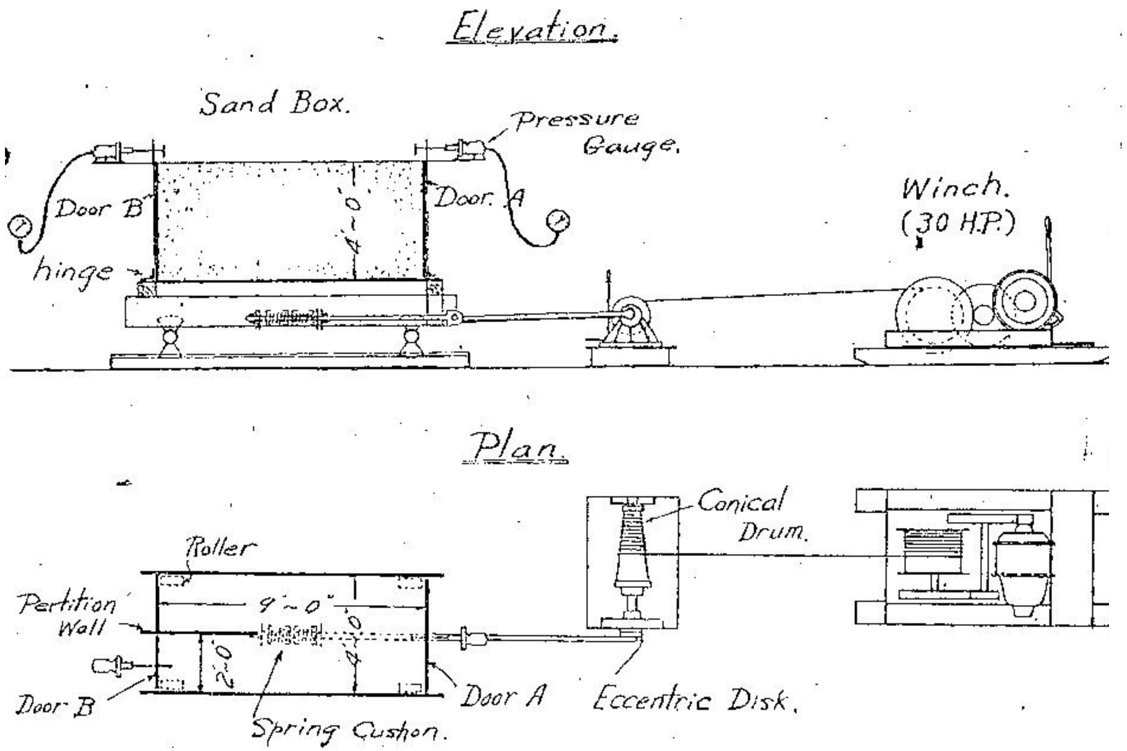
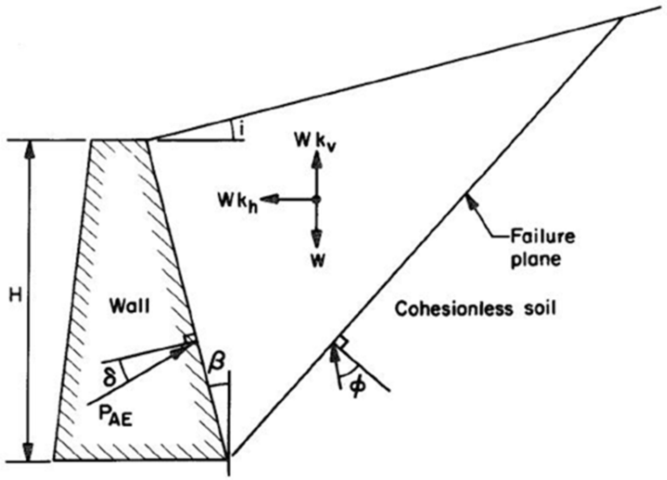


Fig. 5.

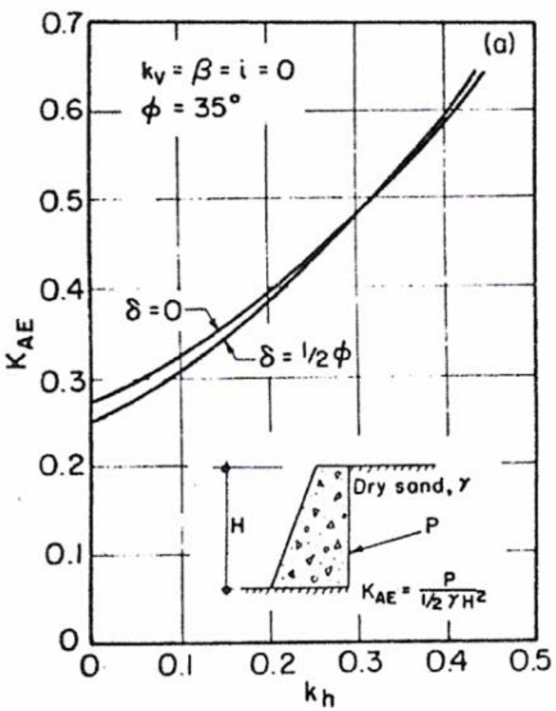
Mononobe and Matsuo, 1929



$$P_{AE} = \frac{1}{2}.\gamma.H^2.(1-k_v).K_{AE}$$

- **Assumes a fully developed Coulomb wedge**
- **Force applied at 1/3H**

Seed and Whitman, 1970



Modified from Mononobe and Matsuo, 1929

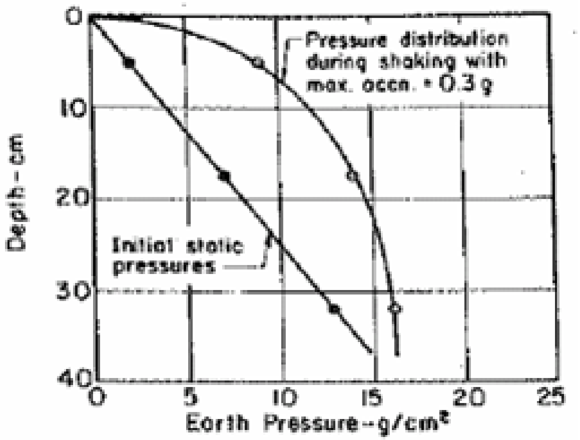
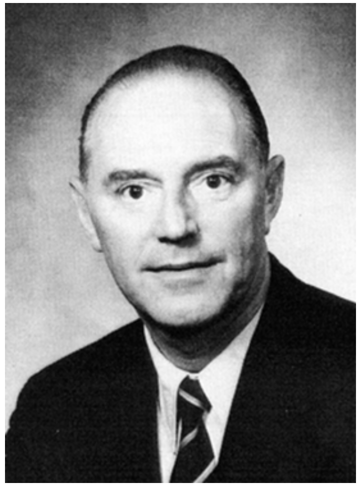
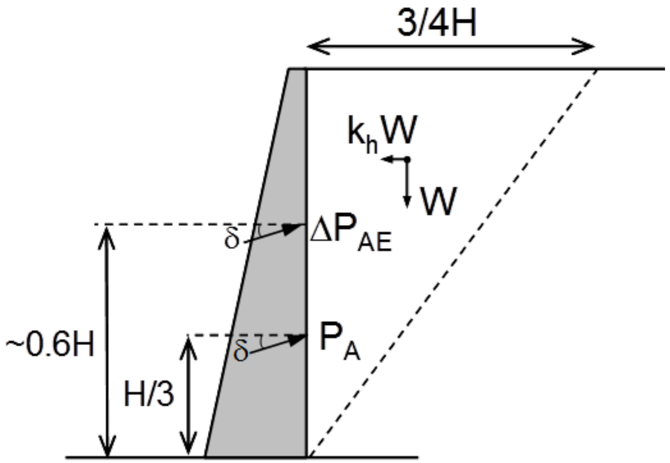


Fig. 21 EFFECT OF BASE MOTIONS ON EARTH PRESSURE DISTRIBUTION (after Matsuo)

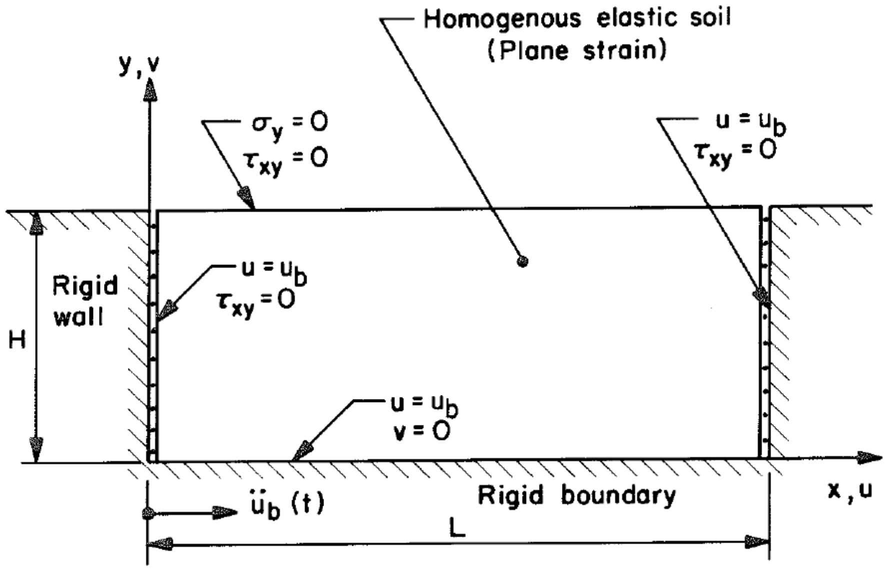


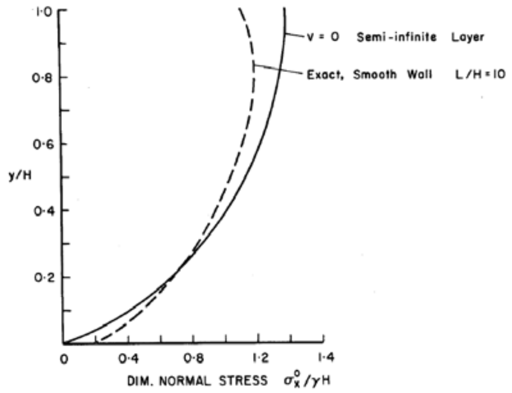


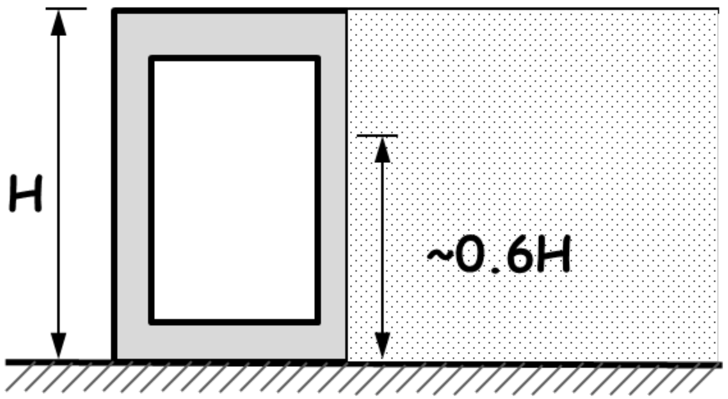
$$\Delta P_{AE} = \frac{1}{2} . \left(\frac{3}{4} . k_h\right) . \gamma . H^2$$

- **Solution is asymptotic to M-O for PGA < 0.4g**
- **Seismic earth pressure increment at 0.6H**

Wood (1973) – Non-Yielding (Rigid) Walls







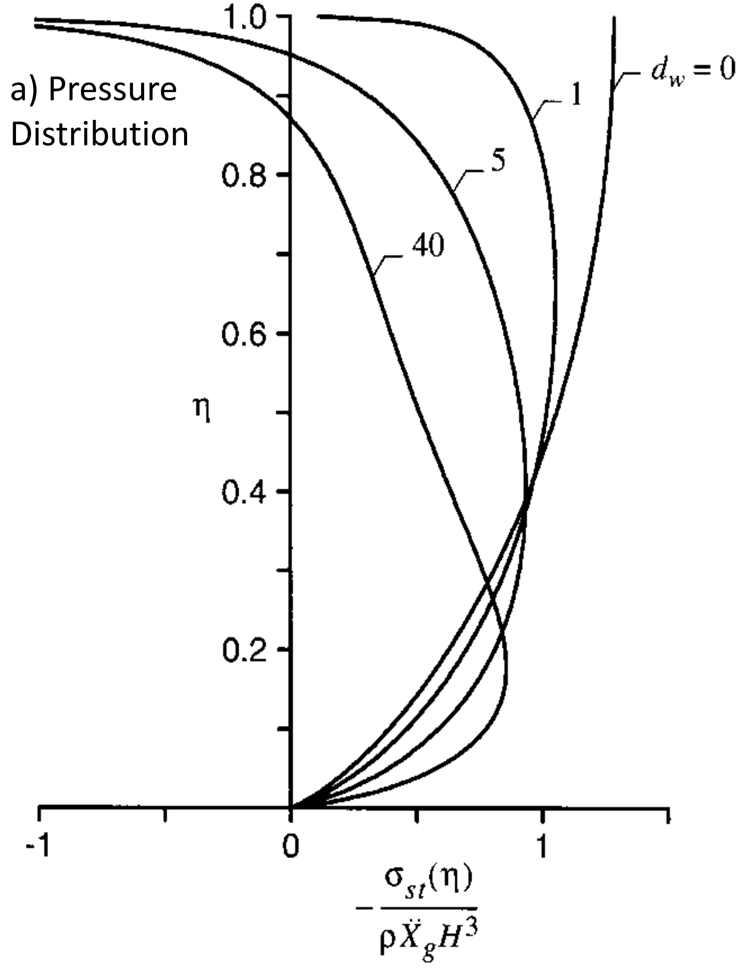
$$\Delta P_{AE} = F_p . k_h . \gamma . H^2 \quad , F_p = [0.9 \; 1.1]$$

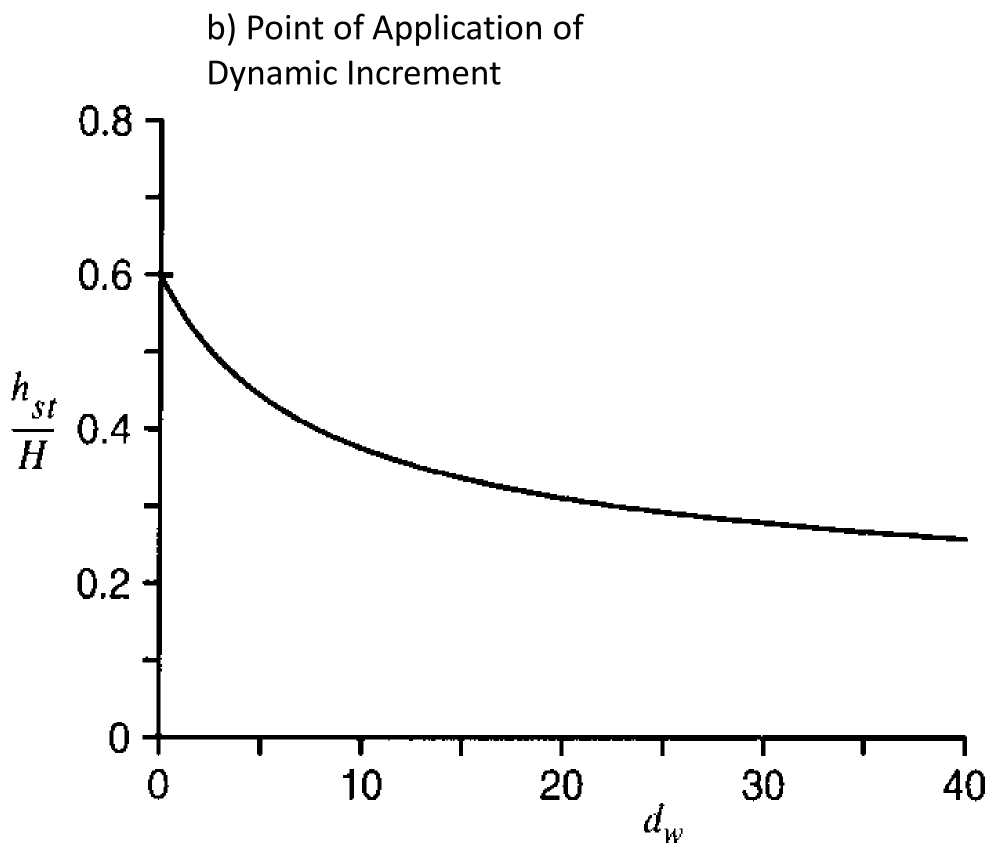
- **Homogeneous linear elastic soil and connected to a rigid base**
- **Seismic earth pressure increment at 0.6H**

Point of Load Application

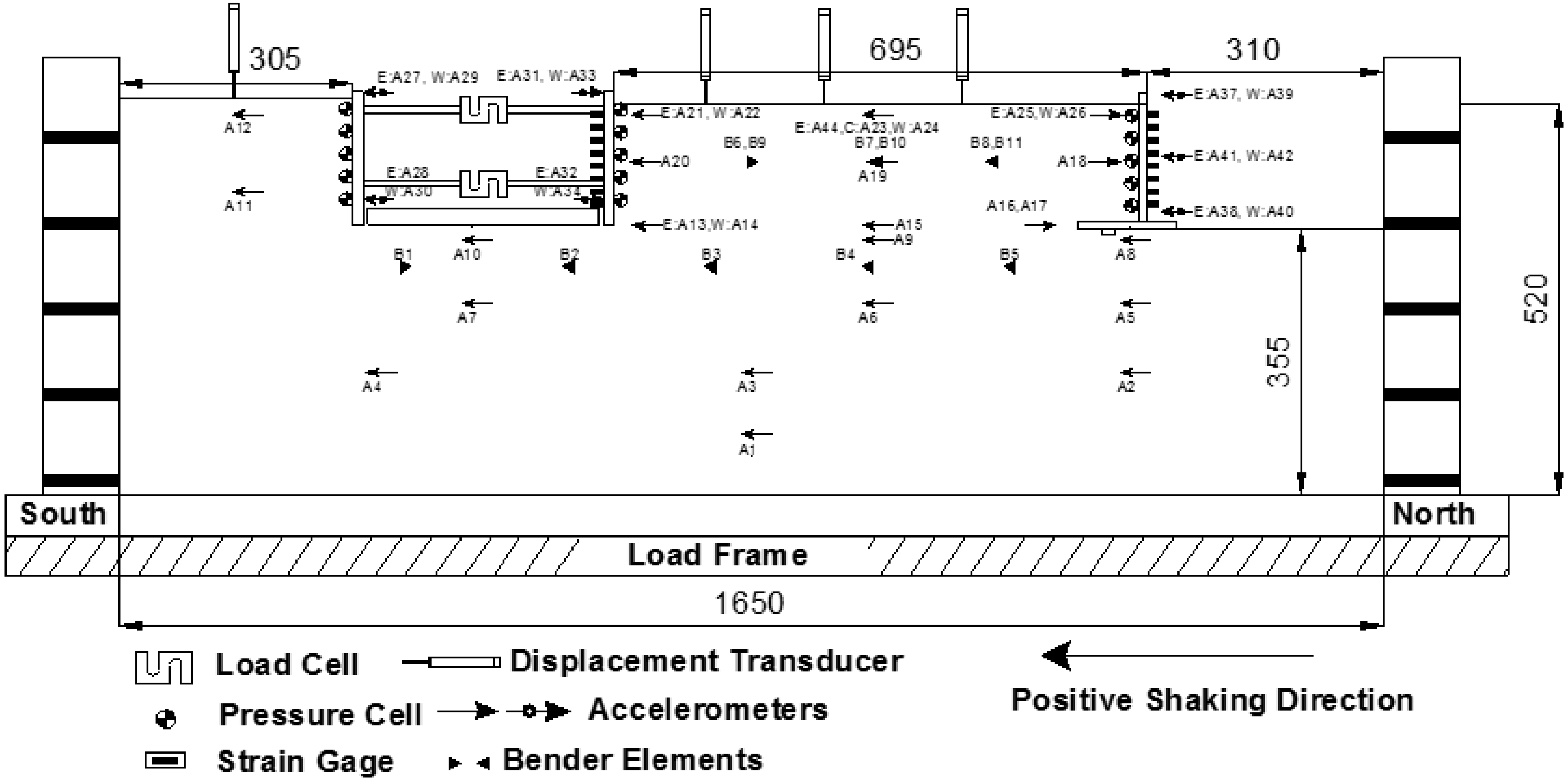
Author	Point of Application
Mononobe-Okabe (1926-1929)	0.33H
Seed and Whitman (1970)	0.6H
Nandakumaran and Joshi (1973)	<0.65H
Krishna et al. (1974)	~0.5H
Sherif et al. (1982)	~0.42H
Prakash and Brasavanna (1969)	varies with acceleration
Ichihara and Matsuzawa (1973)	varies with acceleration
Ortiz et al. (1983)	varies, but higher than H/3
Woodward and Griffiths (1992)	varies with acceleration
Steedman and Zeng (1990)	varies, but higher than H/3
Mylonakis et al. (2007)	0.33H

Younan and Veletsos (2000) – Elastic Solution f(stiffness & rotation)

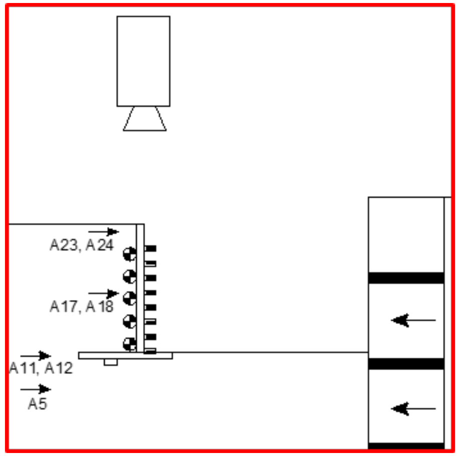




Centrifuge Experiment
Geometry & Instrumentation Layout



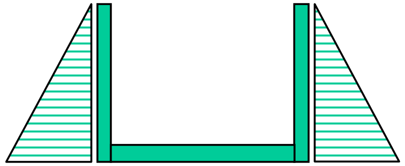
Centrifuge Modeling - Spinning and Shaking

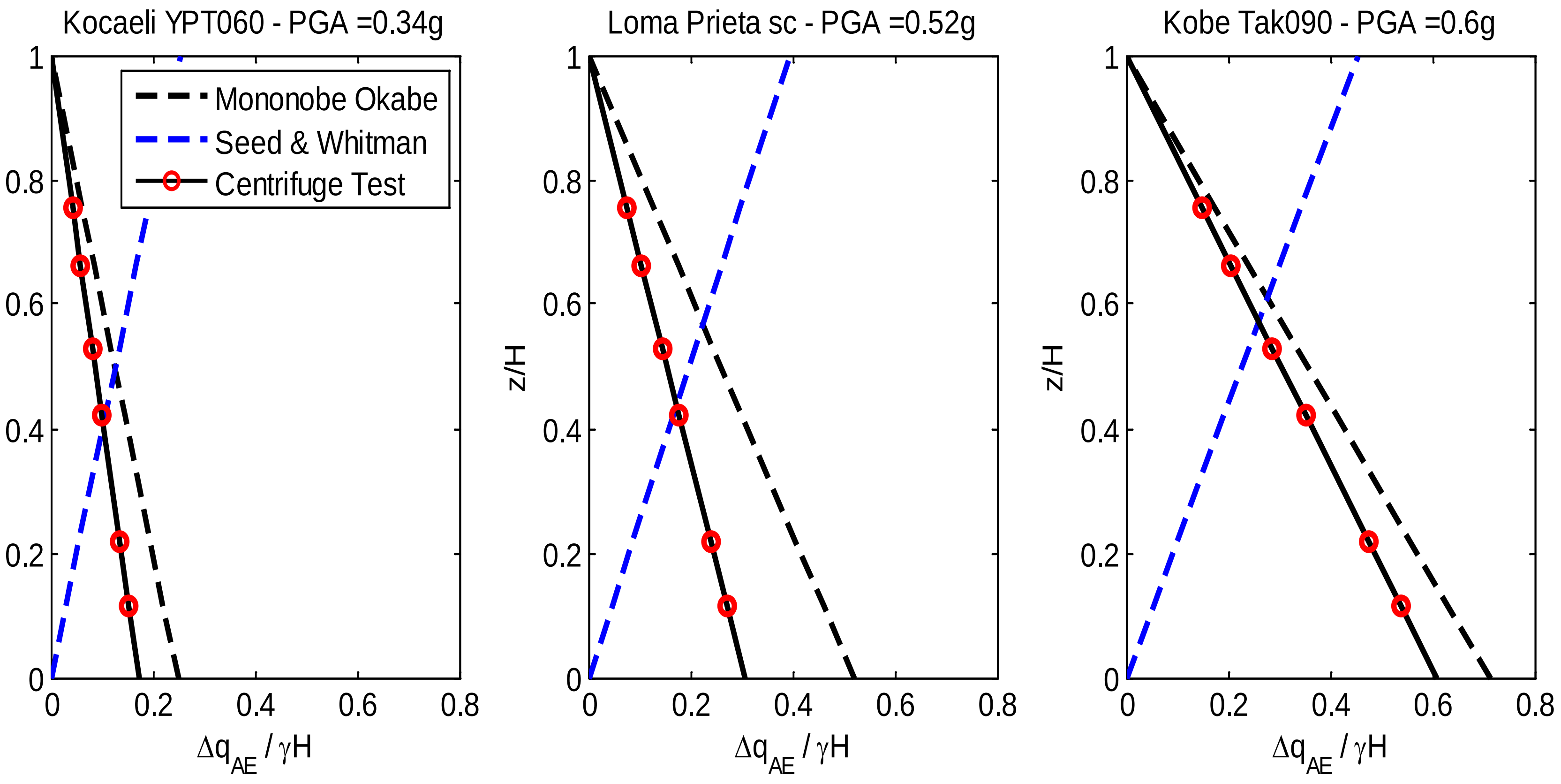


Results

Earth Pressure Time History

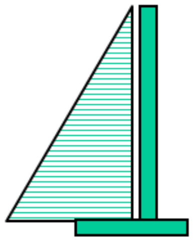
Seismic Pressure Increment
Fixed Base Cantilever Walls in Sand

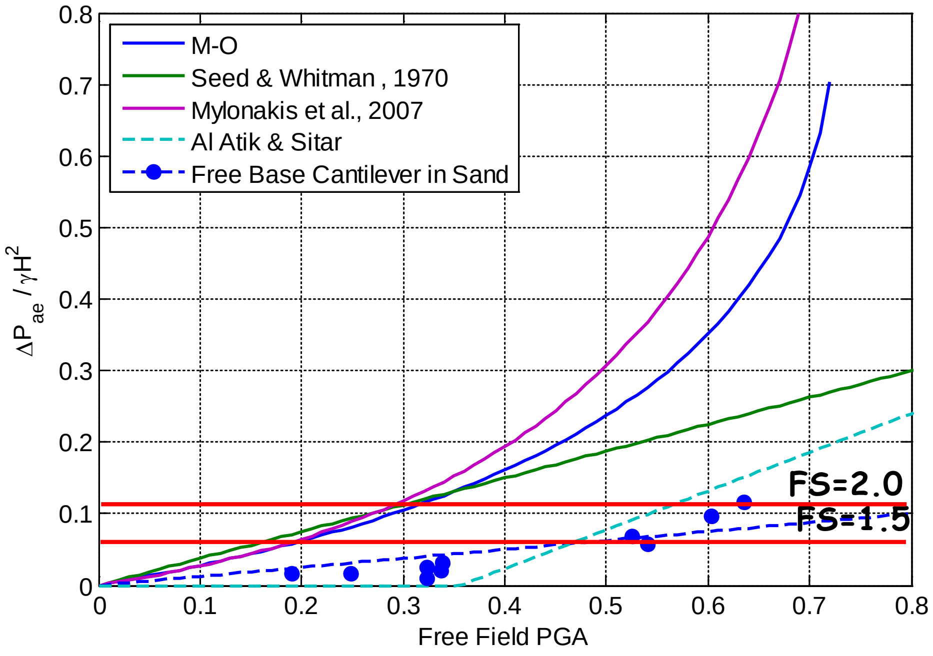


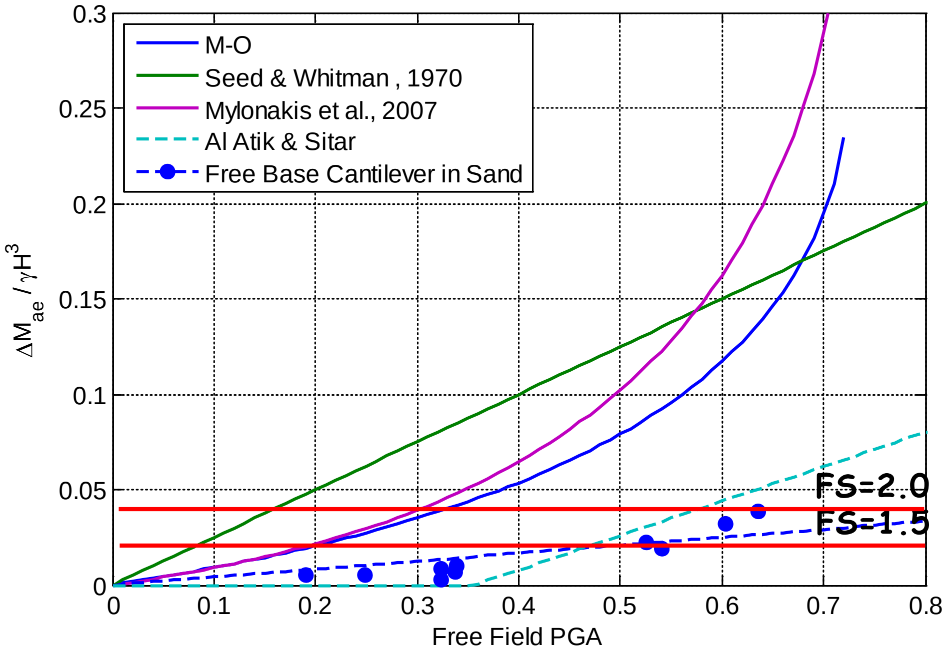


Typical Design Considerations (cont.)

- ✓ **Displacing Cantilever Wall**

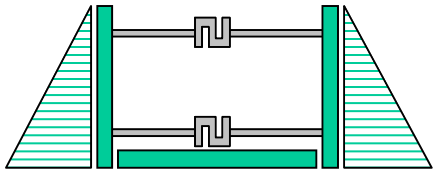


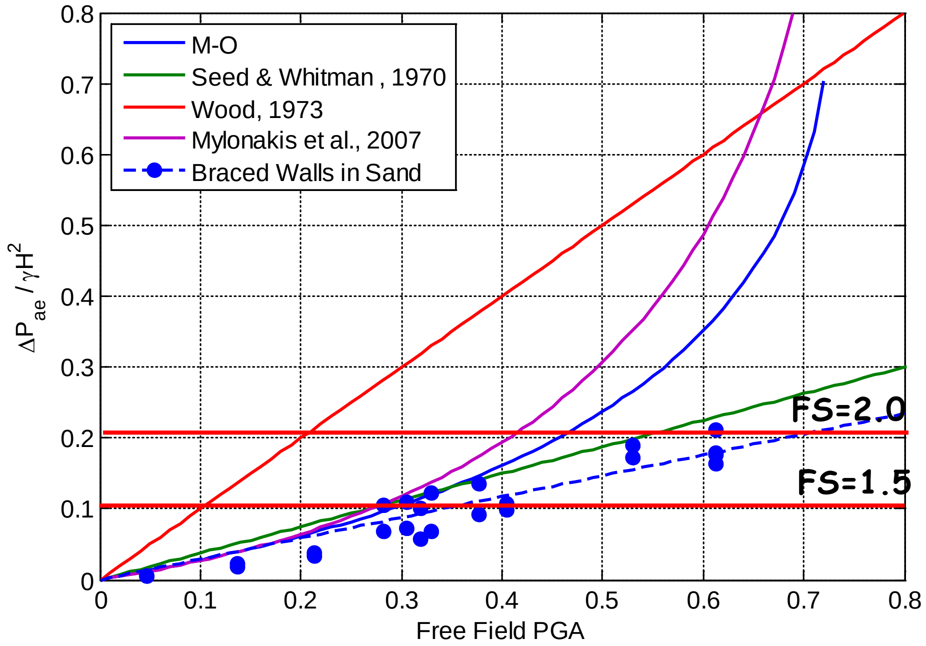


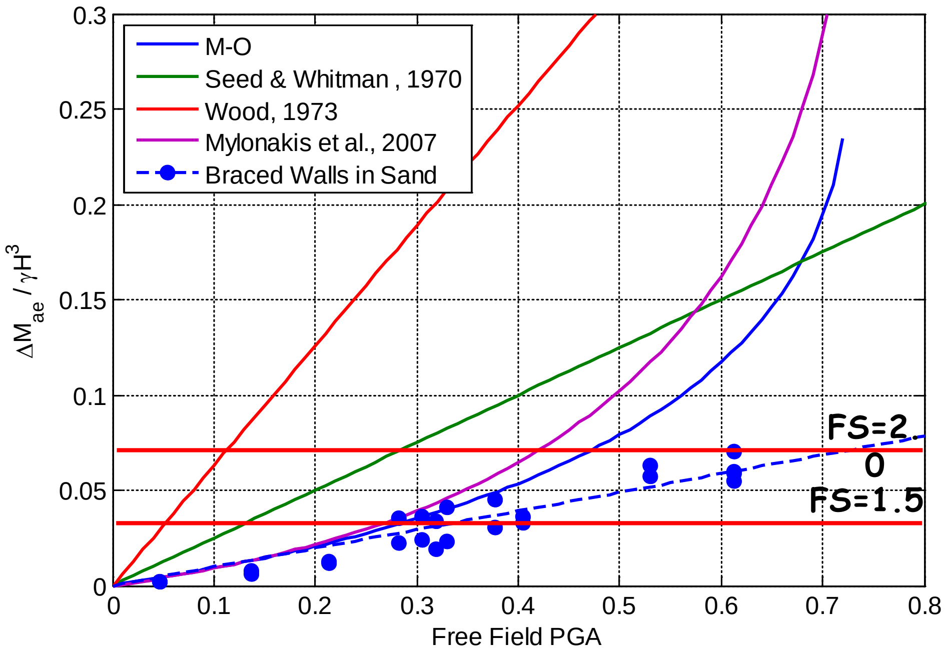


Typical Design Considerations

✓ **Stiff-Embedded Structure**

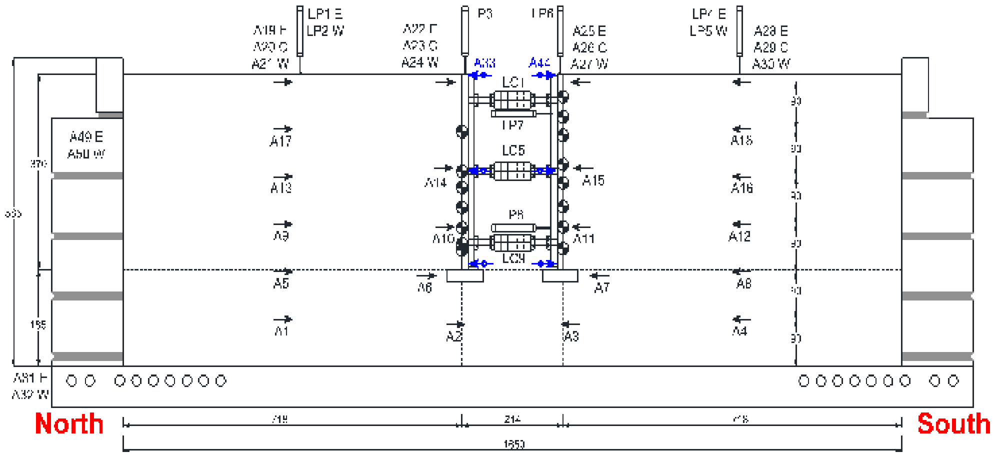




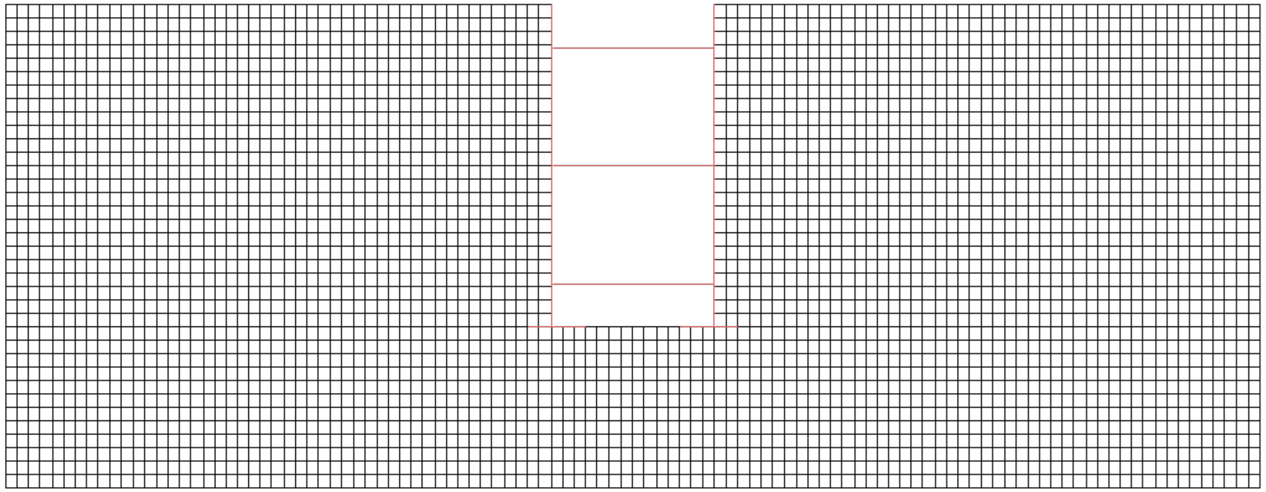


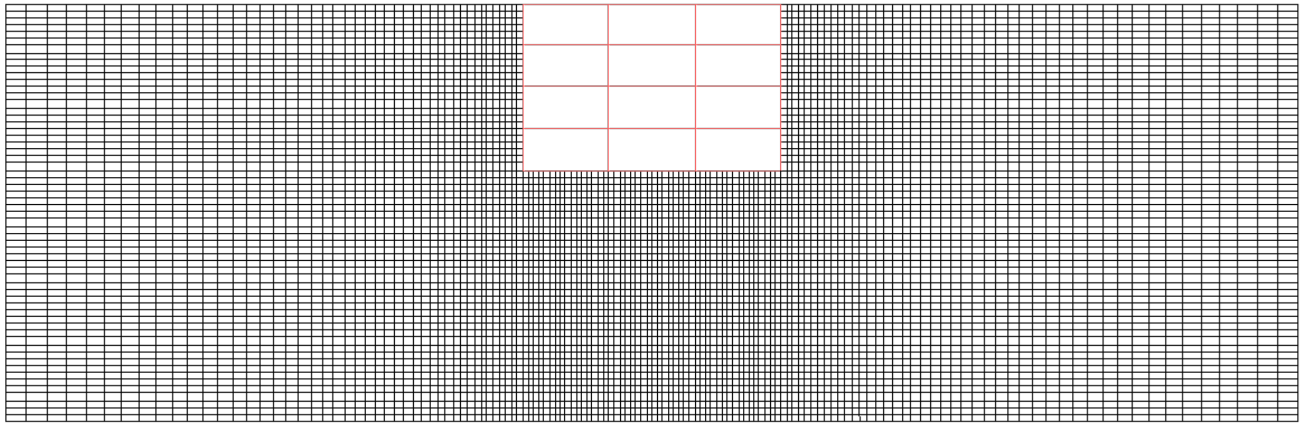
Stiff Walls - Basements

Centrifuge Experiments

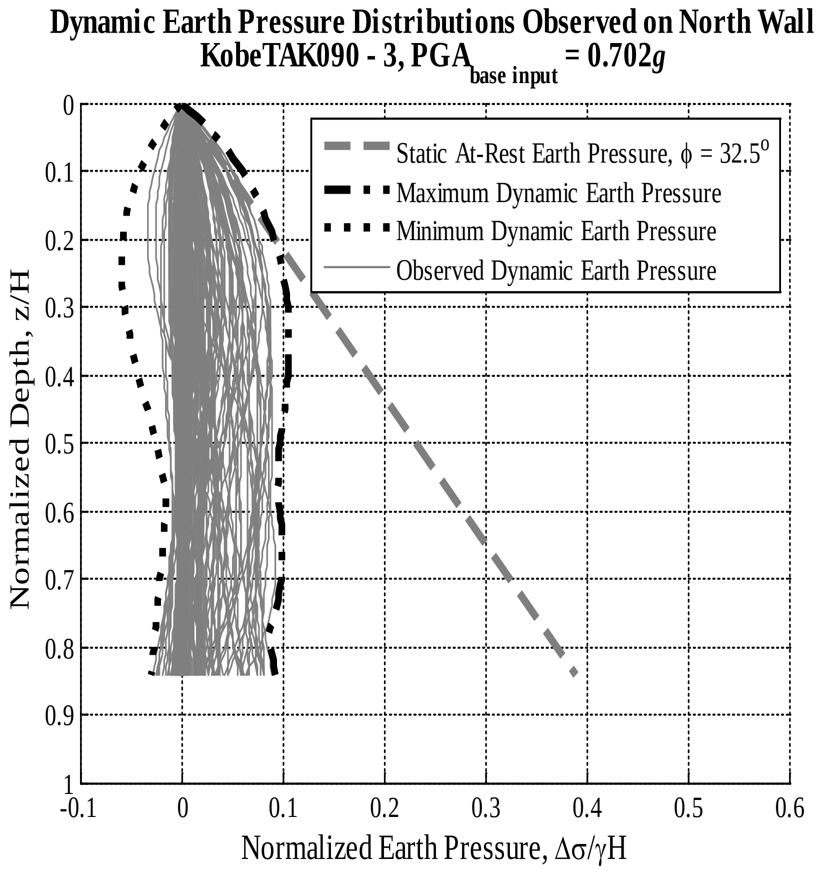


Numerical Models - FLAC

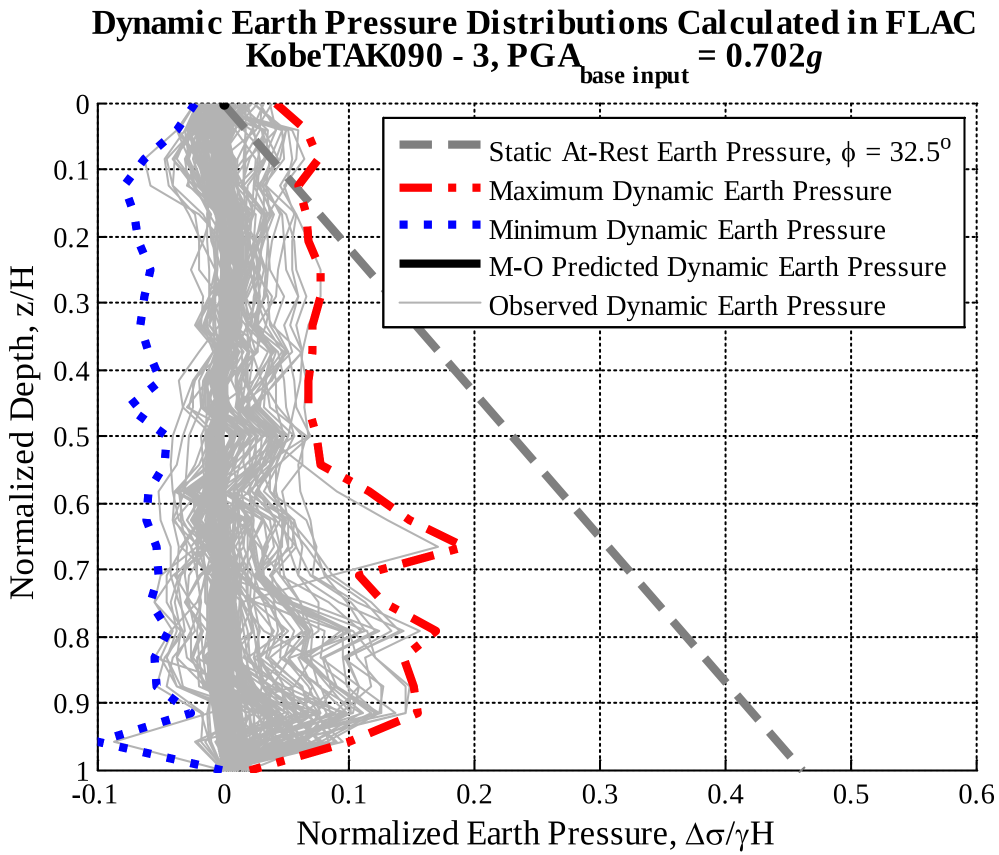




Observed and Modeled Dynamic Earth Pressure

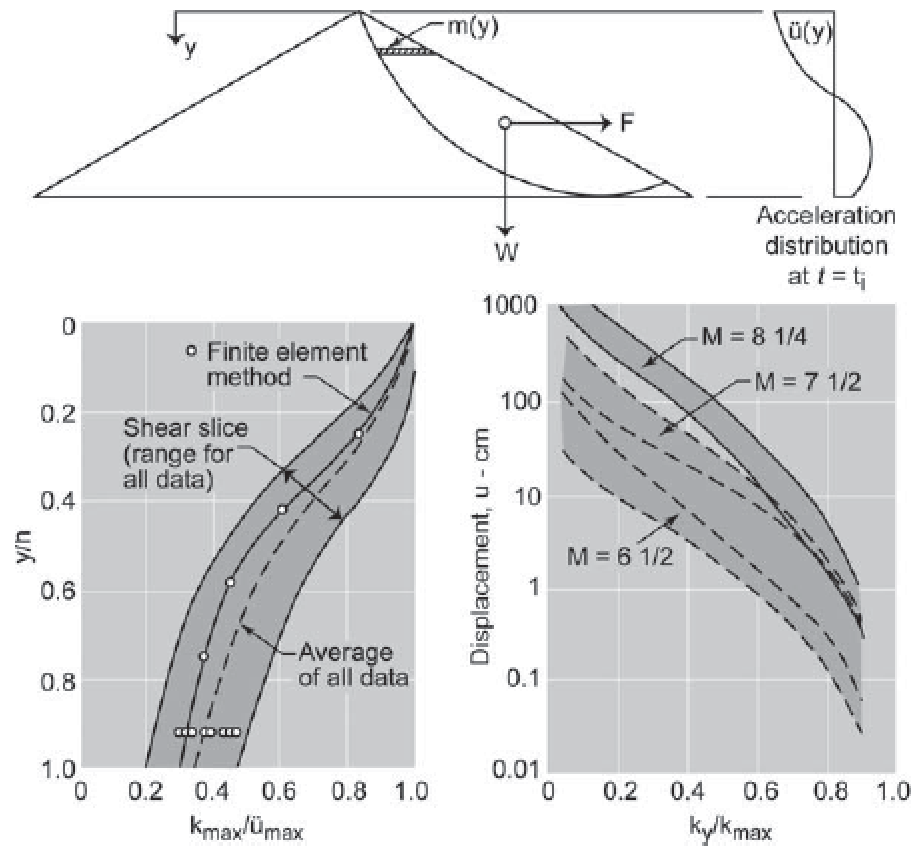


Centrifuge Model

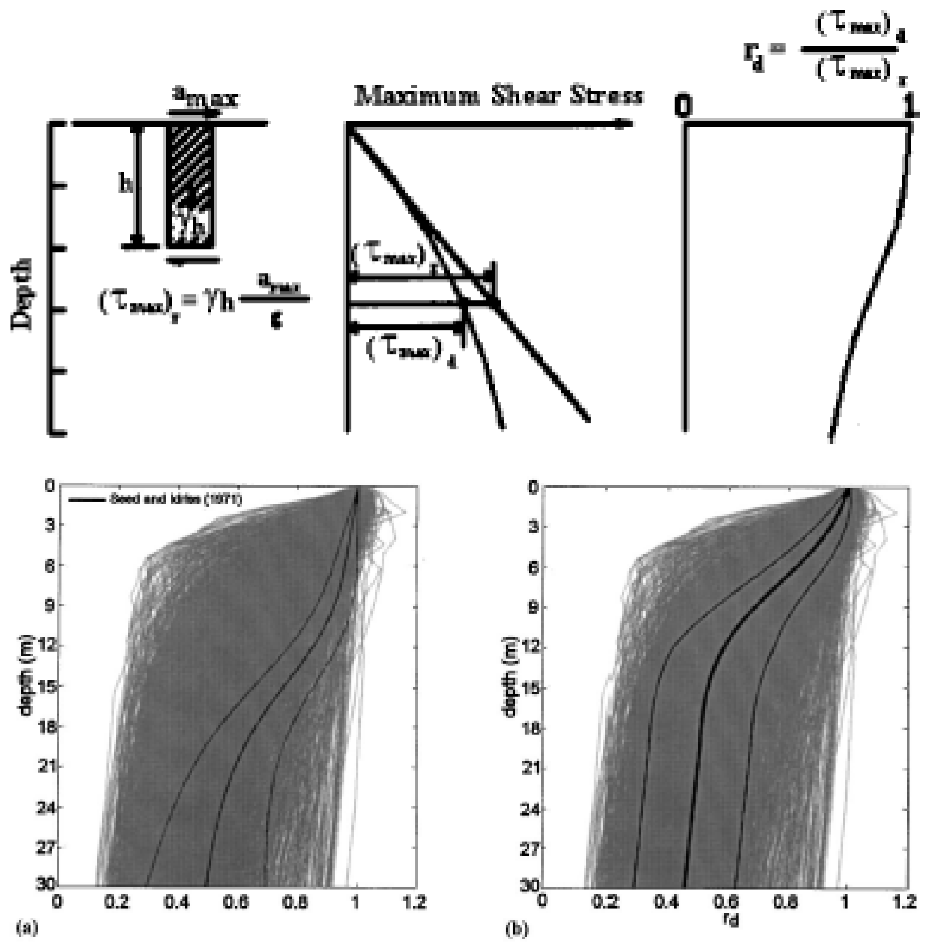


FLAC Simulation

Effective Seismic Coefficient



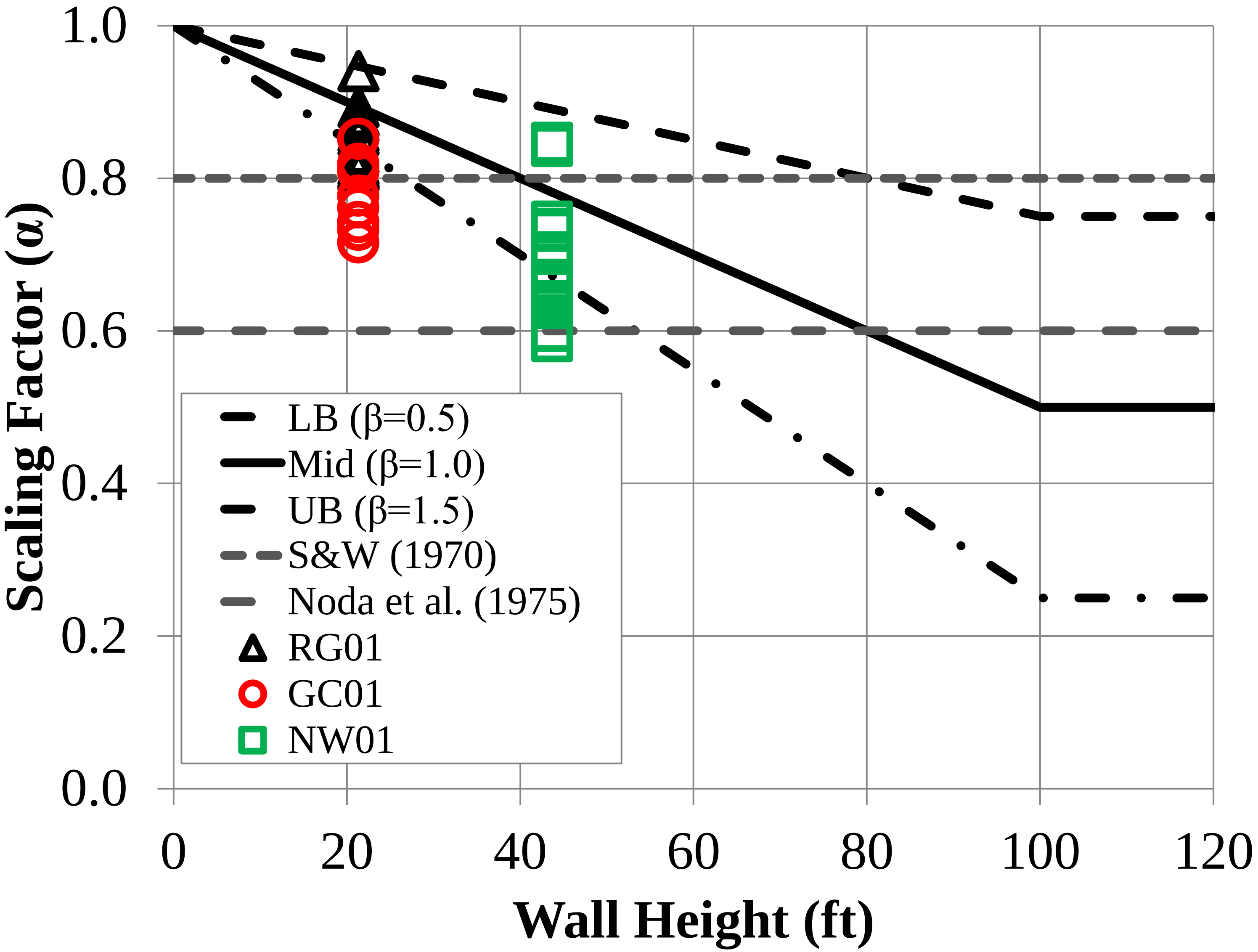
Makdisi & Seed (1978)
[from Anderson et al. (2008)]



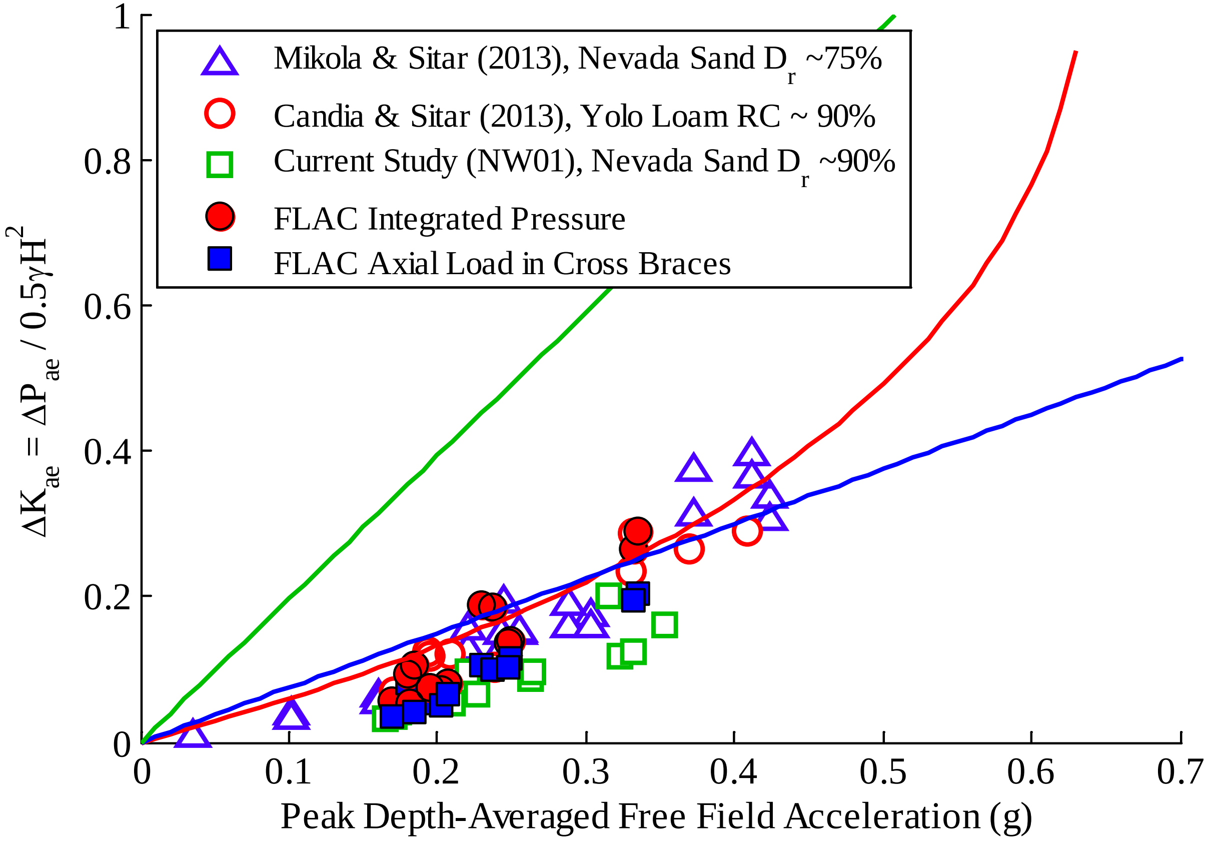
Seed & Idriss (1971)
[from Cetin et al. (2004)]

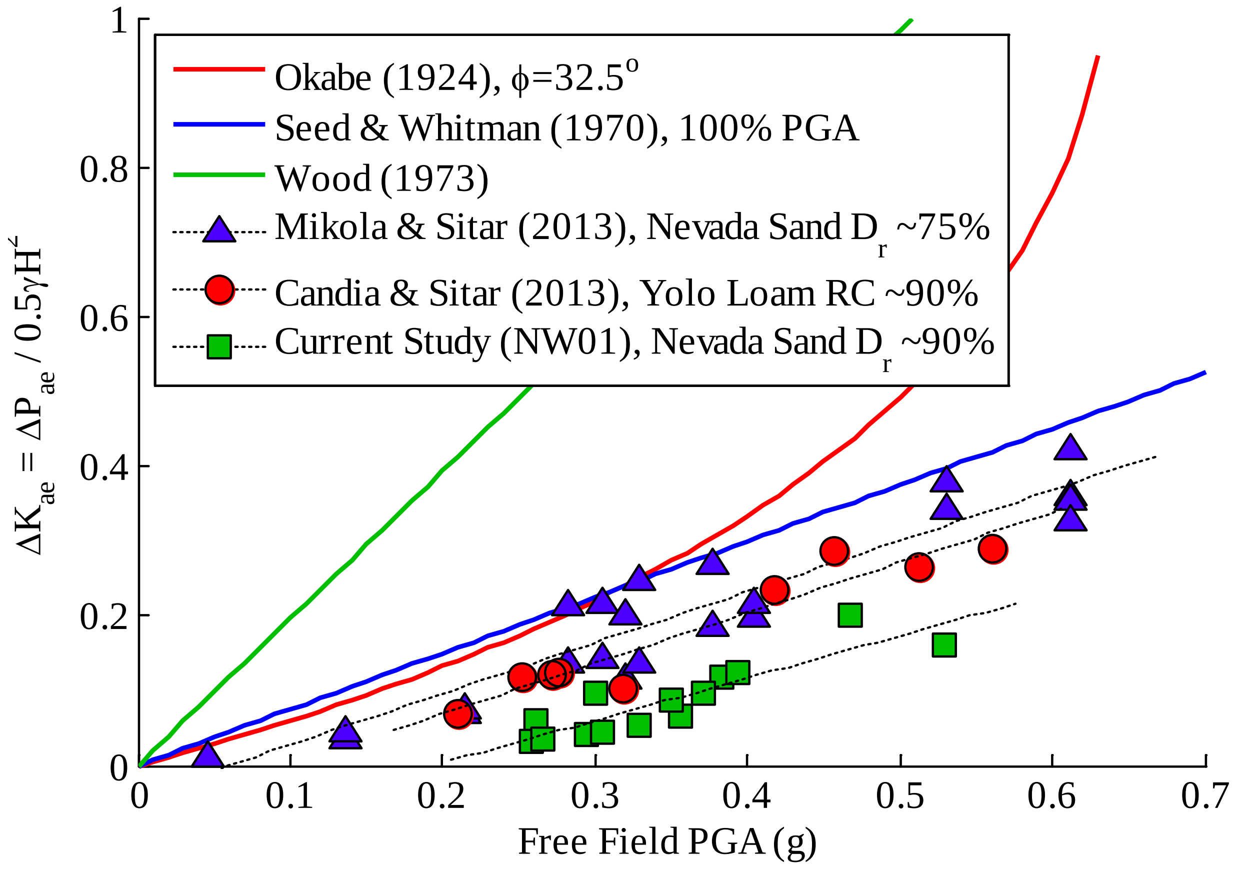
Effective Seismic Coefficient

NCHRP Report 611 (Anderson et al., 2008)

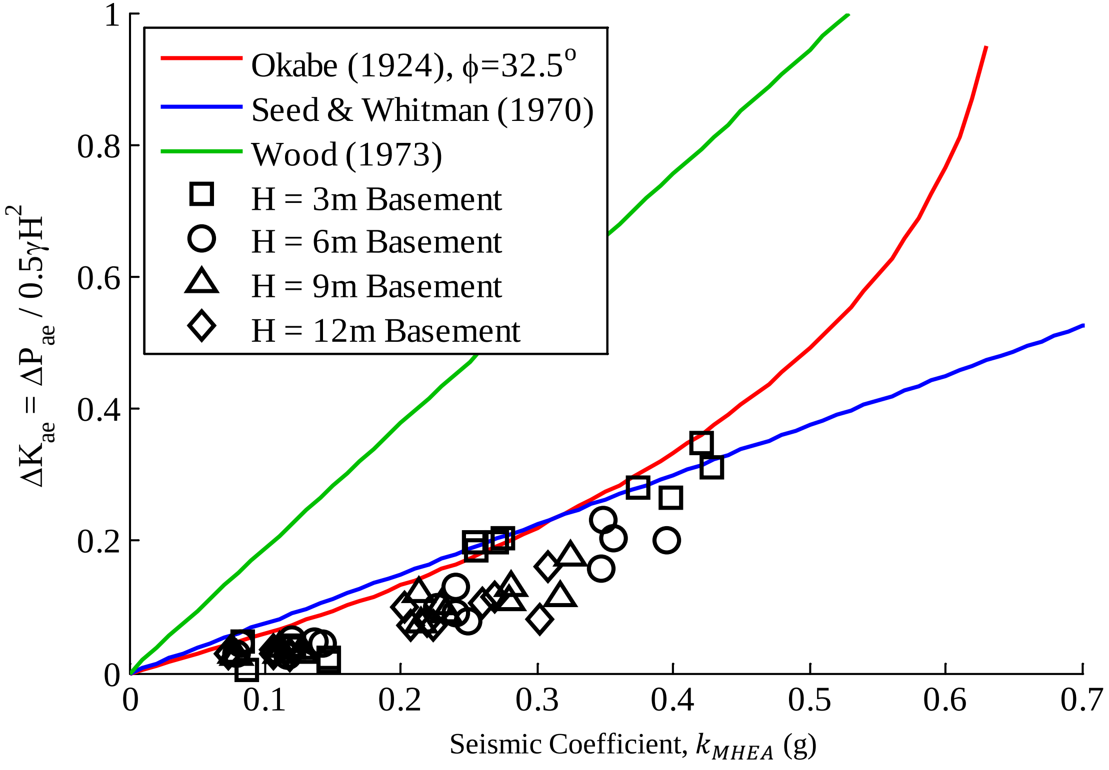


Dynamic Earth Pressure Coefficient
Numerical and Centrifuge Model Results

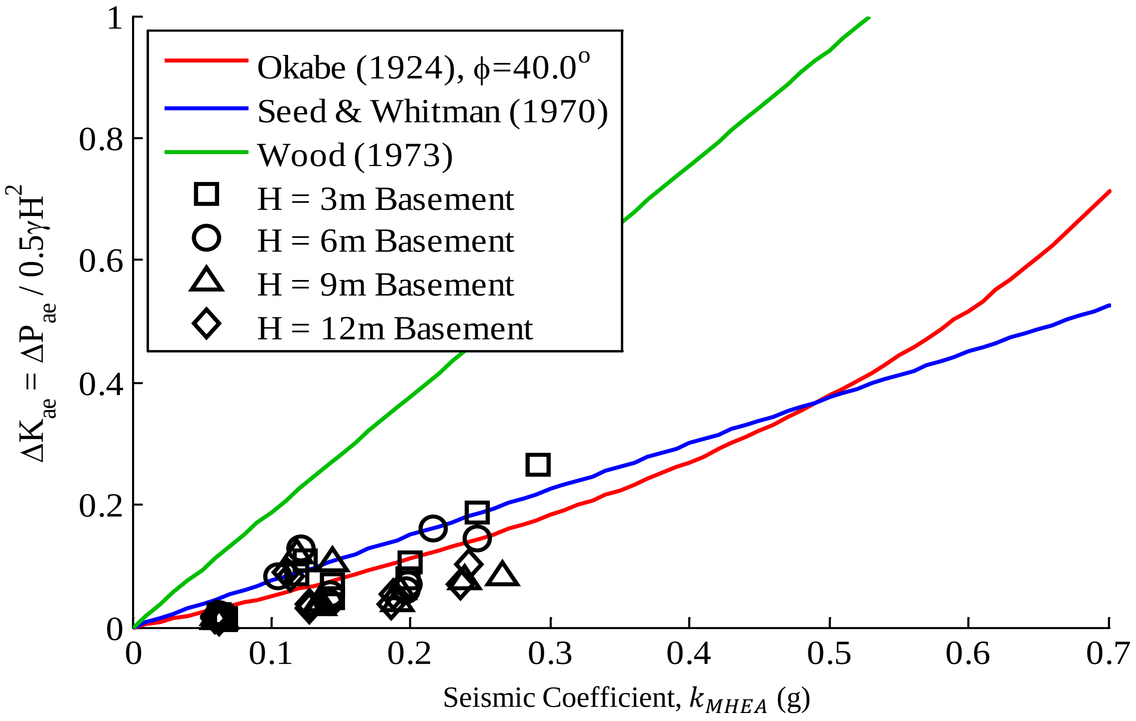




Site Effects



Site Class D



Site Class C

Conclusions

- Earth pressure during seismic loading increases with depth similar to static and the "inverse triangle" does not represent this condition

- Mononobe – Okabe solution is overly conservative at high PGA> 0.4 - 0.5 g and fails to converge for high acceleration > 0.7 g with cohesionless soil.

- Our results show that for cantilever and stiff basement walls lateral earth pressure increment is insignificant for a large range of ground motions. However, inertial forces on the walls have to be properly accounted for.

- The height of the wall or depth of embedment should be considered for structures >6.5m
  - More important for deeper structures
  - Already used in other geotechnical earthquake engineering applications (e.g., seismic slope deformation, liquefaction)

Recommendations for Design

1. Obtain PGA and use Seed & Whitman (1970)

2. Obtain PGA, reduce using NCHRP guidelines, and use Mononobe-Okabe method

3. Perform 1-D site response analysis, compute depth-averaged acceleration, and use Mononobe-Okabe method

4. Perform calibrated 2-D or 3-D dynamic analysis and compute demands on the structure

References:

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