12 ICG

September 17-21, 2023
Auditorium Parco della Musica
Roma, Italy

12th International Conference on Geosynthetics

# Migrating to probabilistic internal stability analysis and design of reinforced soil walls

Richard J. Bathurst

GeoEngineering Centre at Queen's-RMC

Kingston, Canada

17 September 2023

Organised by: AGI Associazione Geotecnica Italiana igs Italy

With the endorsement of: igs



## Course Outline

1. Overview of geosynthetic reinforced soil walls: The history of GRS walls is briefly reviewed including important new construction methods and materials. The basic components of these systems are explained. The relatively higher sustainability of these systems over conventional earth retaining wall systems is highlighted.

2. Design and analysis of GRS walls. External: global and internal design limit states are presented. The characterization of the mechanical properties of geosynthetic reinforcement materials is discussed and how these properties are determined from physical testing and used in internal stability design and analysis is demonstrated. The new stiffness method recently adopted in the US and Canada is explained. The essential features of emerging probabilistic methods of analysis are introduced.

3. Seismic design: GRS walls have most often performed well during earthquake. Examples of their performance under seismic loading are given. The reasons for their good performance are explained and the design methods used to quantify the additional seismic-induced external and internal loading are discussed.

# Seismic design and performance of geosynthetic reinforced soil walls during earthquake

r.j. bathurst
123

# Geosynthetic reinforced soil walls have demonstrated good performance during earthquake

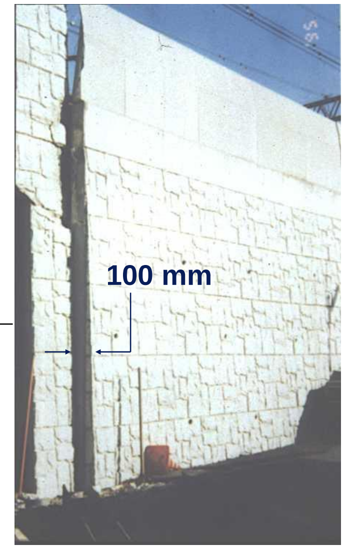
r.j. bathurst
124

## Great Hanshin Earthquake (Kobe 1995) M=6.8, $a_g$ = 0.6g

Conventional gravity structures

6.2 m high

geosynthetic reinforced soil wall

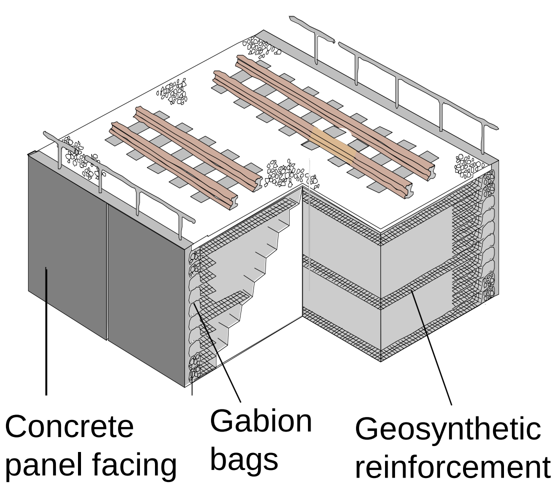



courtesy of Fumio Tatsuoka

r.j. bathurst

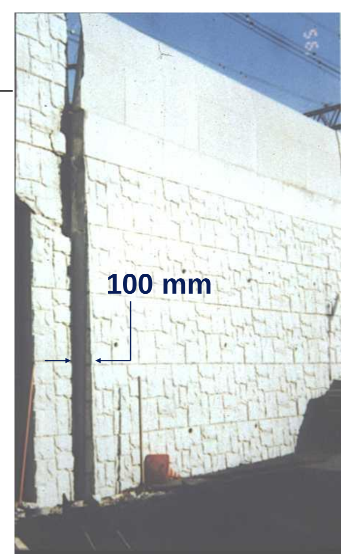
125

## Great Hanshin Earthquake (Kobe 1995) M=6.8, $a_g$ = 0.6g




6.2 m high

geosynthetic reinforced soil wall



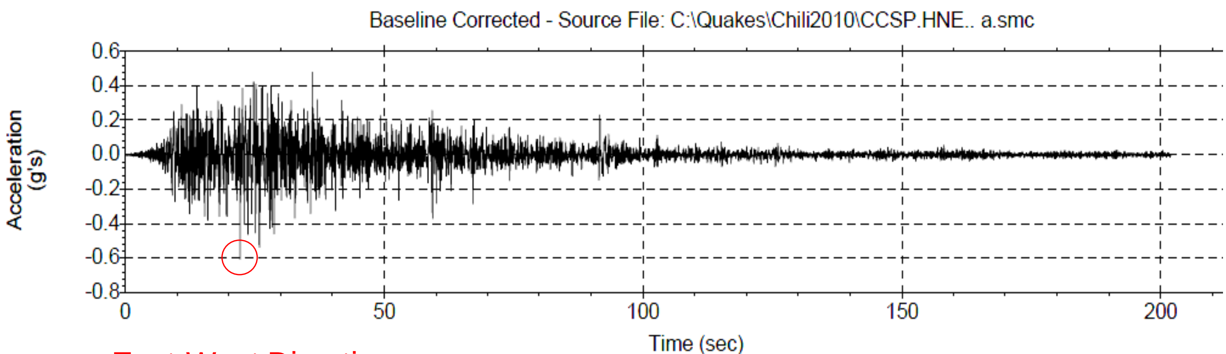

courtesy of Fumio Tatsuoka

r.j. bathurst

126

## Concepcion, Chile Ground Motion, E-W Direction (2010 Maule Earthquake, $M_w$ = 8.8)

PGA = 0.61g
Significant Duration = 76 sec.
Bracketed Duration = 152 sec. (A ≥ 0.05g)




East-West Direction

r.j. bathurst 127

## Summary of Wall Performance in Maule Chile 2010 Earthquake

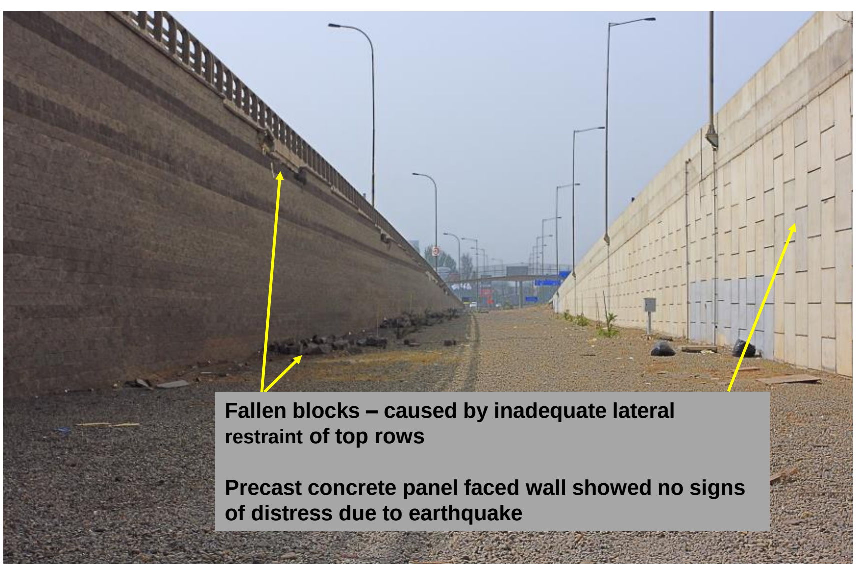
- Magnitude 8.8, PGA ranged from 0.2g to 0.5g in central valley (Santiago to Talca), and 0.65g horizontal / 0.6g vertical in Concepcion
- Walls had very little damage, if any, even though adjacent bridges had significant damage or even collapsed
- Wall types evaluated included panel and block faced MSE walls, concrete gravity and semi-gravity walls, with heights ranging to 12 m+ for all these wall types
- Most walls designed in accordance with AASHTO, but typically for $k_h$ = 0.1g to 0.2g in central valley and 0.25g to 0.4g on coast, using good quality backfill

r.j. bathurst 128

## Summary of Wall Performance in Maule Chile 2010 Earthquake

- Magnitude 8.8, PGA ranged from 0.2g to 0.5g in central valley (Santiago to Talca), and 0.65g horizontal / 0.6g vertical in Concepcion
- Walls had very little damage, if any, even though adjacent bridges had significant damage or even collapsed
- Wall types evaluated included panel and block faced MSE walls, concrete gravity and semi-gravity walls, with heights ranging to 12 m+ for all these wall types
- Most walls designed in accordance with AASHTO, but typically for $k_h$ = 0.1g to 0.2g in central valley and 0.25g to 0.4g on coast, using good quality backfill

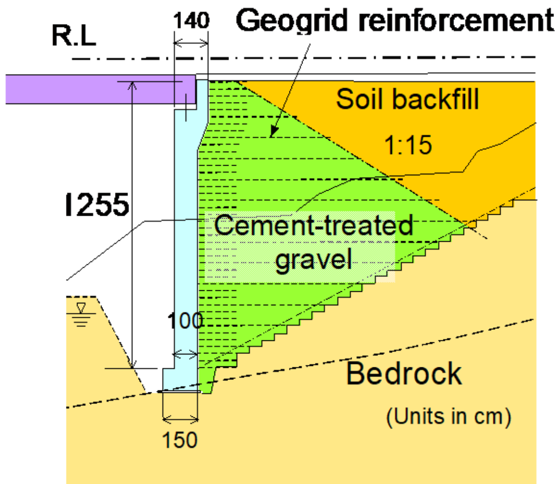
r.j. bathurst 129




Modular block geogrid and precast concrete panel steel reinforced MSE walls supporting abutment fills, Americo Vespucio/Independencia Santiago area

r.j. bathurst 130

## Soil-cement GRS bridge abutment (Japan)



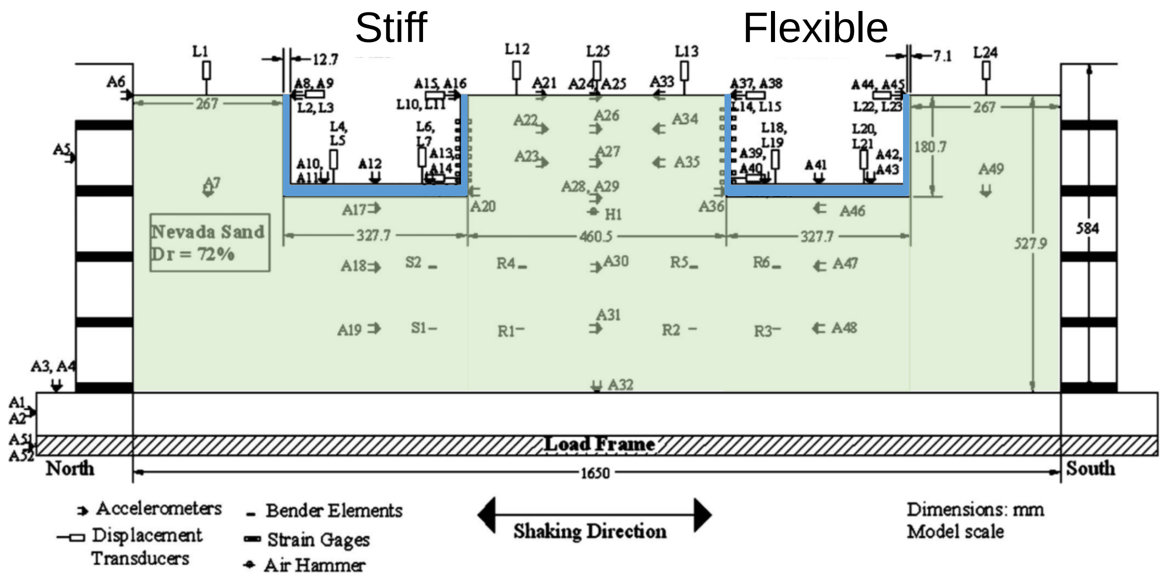

(Aoki et al. 2005)

r.j. bathurst 131

## When do we need to carry out seismic analysis?

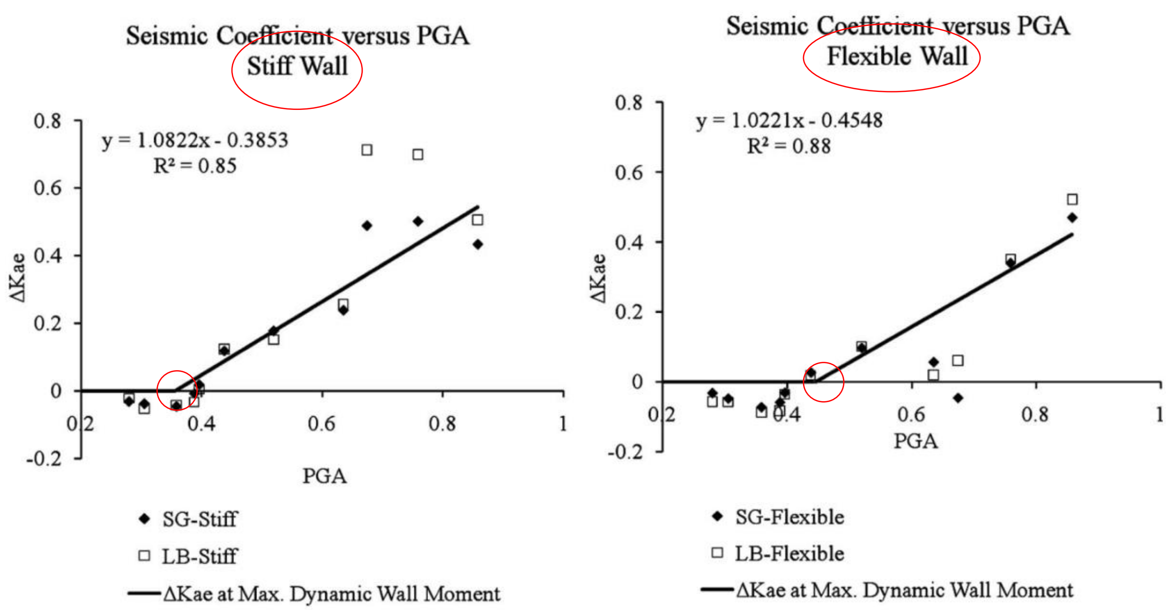
r.j. bathurst 132

Centrifuge cantilever wall testing (Atik & Sitar 2010)



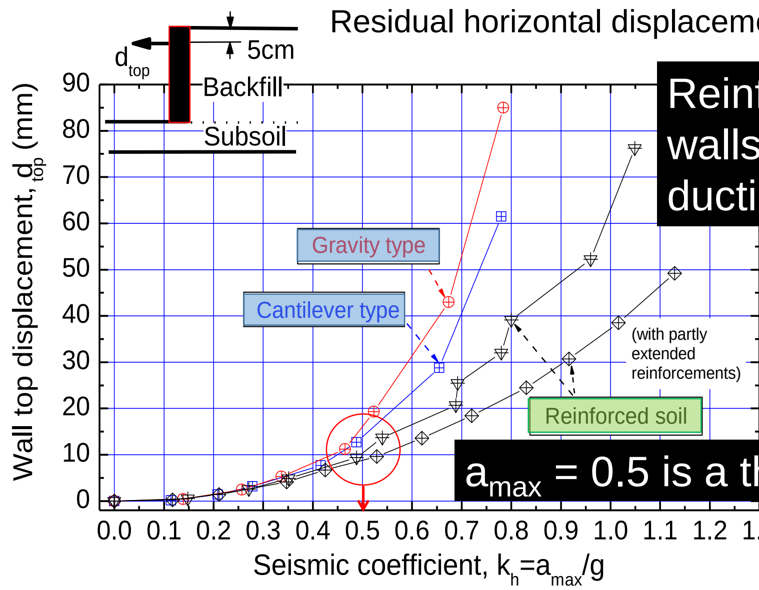

r.j. bathurst 133

Back-calculated dynamic earth pressure coefficients as function of peak ground acceleration




r.j. bathurst 134

Residual horizontal displacements near wall top

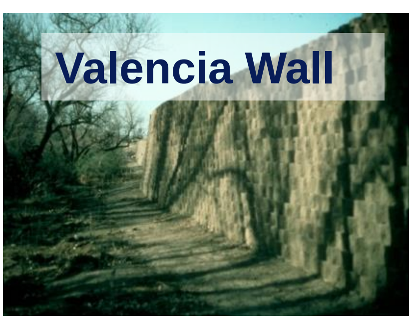



**Reinforced soil walls are more ductile**

$a_{max}$ = 0.5 is a threshold value

**Koseki, J., Bathurst, R.J., Güler, E., Kuwano, J. and Maugeri, M. Seismic stability of reinforced soil walls, Keynote paper, 8th International Conference on Geosynthetics, Yokohama, Japan, 18-22 September 2006.**

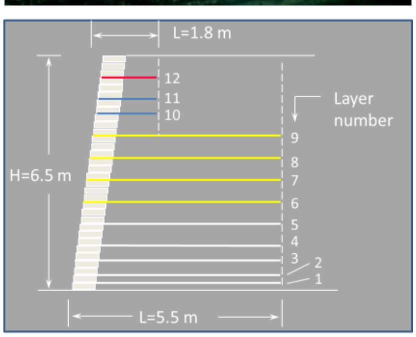
r.j. bathurst 135




Northridge Earthquake, California, USA (1994)
M = 6.7

← **No detectable facing movements!**

$a_g$ = 0.5g




Bathurst and Cai (1995)

r.j. bathurst 136

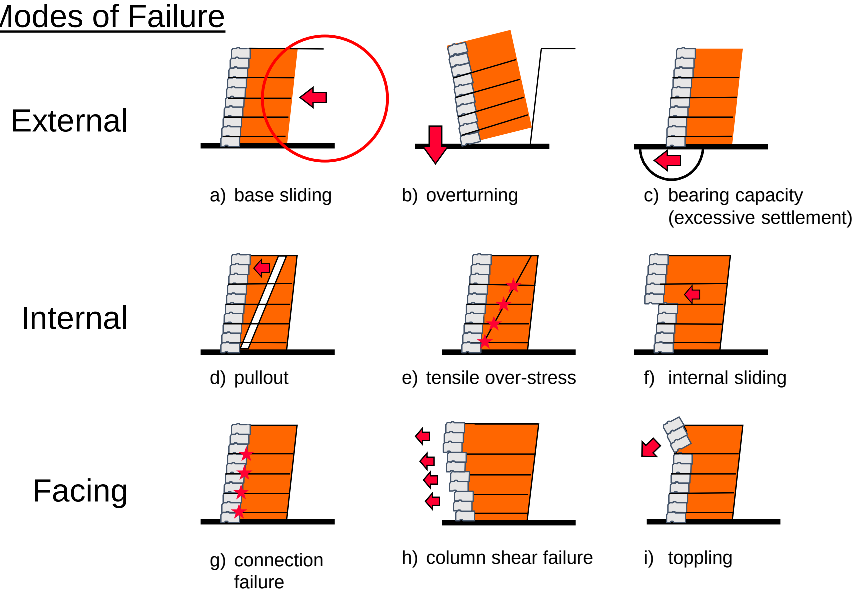
## AASHTO (>2012) specifications require seismic analysis for wall internal and external stability if:

- $A_s$ > 0.4g or if in Seismic Zone 4 (SDCD)
- Significant liquefaction can occur, or sensitive clays are present, that impact wall stability due to earthquake
- Wall supports another structure that must itself be designed for seismic loading, and poor seismic performance of the wall could impact the seismic performance of the supported structure
- In addition, if in Seismic Zones 2 or 3, seismic analysis required if:
  - Exposed wall height plus average surcharge depth > 10 m
  - Wall has abrupt changes in alignment
    (e.g., corners and short radius turns at an enclosed angle of 120° or less)
  - For gravity and semi-gravity walls, the backfill does not meet Article 7.3.6.3 of the LRFD Bridge Construction Specifications and is not adequately drained to prevent water build up

Major improvement over previous AASHTO specification that required seismic analysis **for all cases**

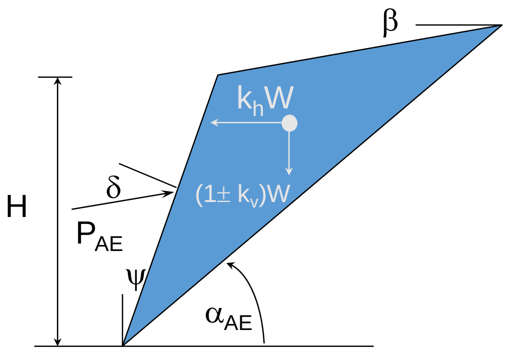
r.j. bathurst 137

## Modes of Failure




r.j. bathurst 138

# Mononobe-Okabe theory



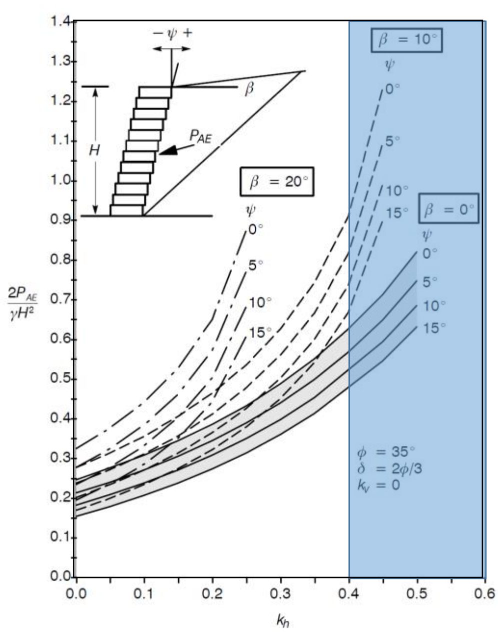

$$P_{AE} = 1/2\ (1 \pm k_V)\ K_{AE}\ \gamma\ H^2$$

$$\tan\theta = k_h / (1 \pm k_V)$$

$$\alpha_{AE} = f(\phi, \theta, \beta, \psi, \delta)$$

$$K_{AE} = \frac{\cos^2(\phi + \psi - \theta) / \cos\theta \cos^2\psi \cos(\delta - \psi + \theta)}{\left[1 + \sqrt{\dfrac{\sin(\phi + \delta)\sin(\phi - \beta - \theta)}{\cos(\delta - \psi + \theta)\cos(\psi + \beta)}}\right]^2}$$

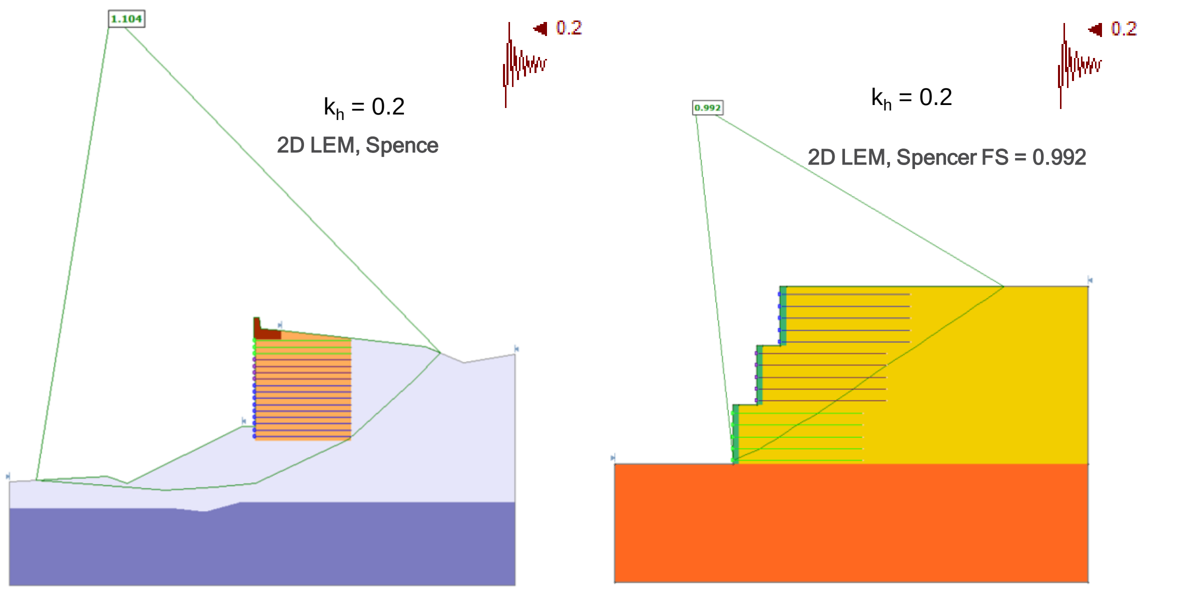
r.j. bathurst 139




Influence of seismic coefficient, $k_h$, backslope angle, β, and wall inclination angle, ψ, on dynamic earth force, $P_{AE}$

Bathurst and Cai (1995)

r.j. bathurst 140

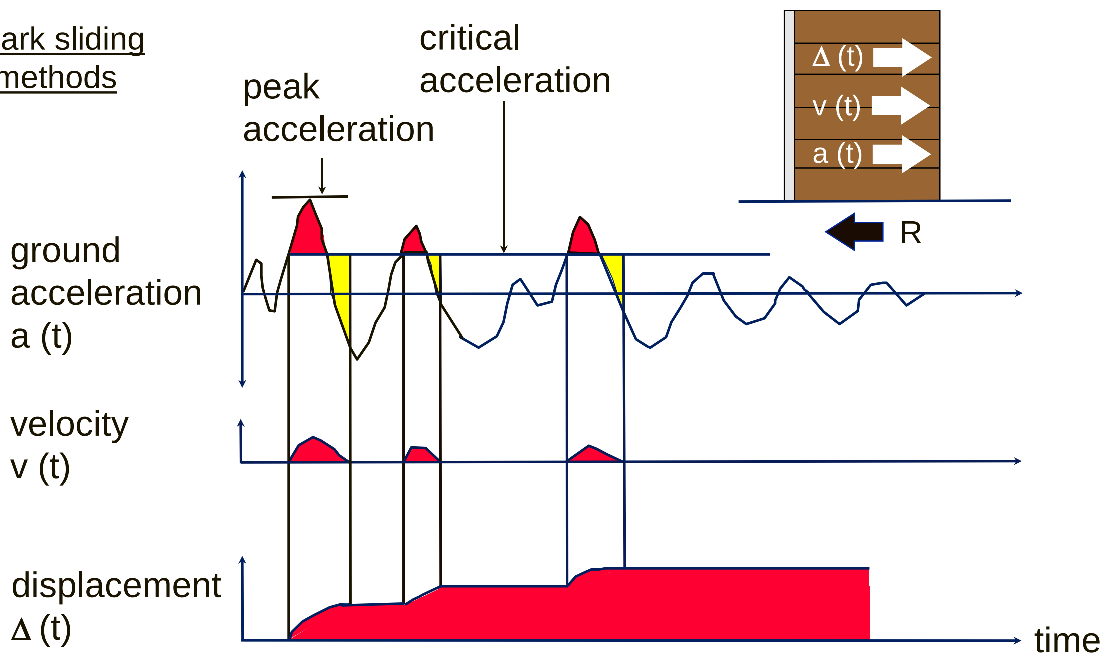



Limit equilibrium (Spencer) method of slices

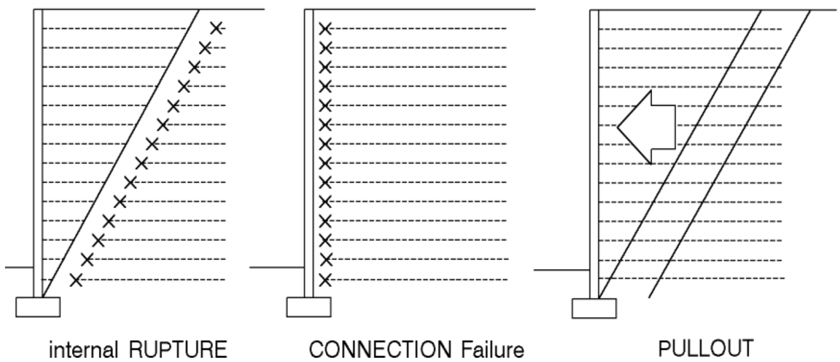
Courtesy of Dr. Sina Javankhoshdel at ROCSCIENCE

r.j. bathurst 141

<u>Newmark sliding block methods</u>



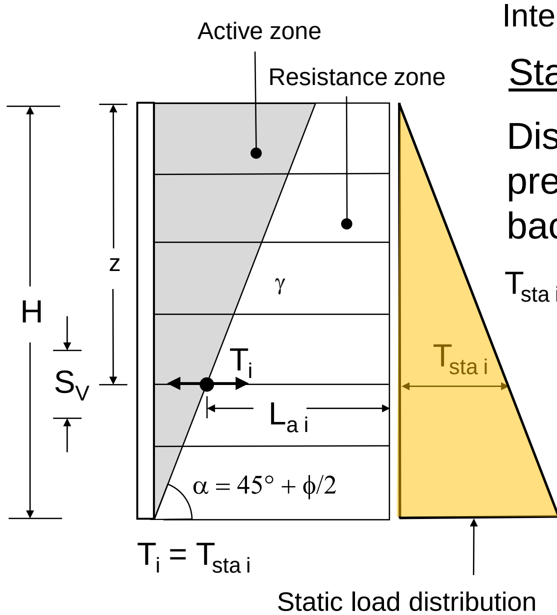

r.j. bathurst 142




Internal modes of failure

r.j. bathurst 143

Internal distribution of reinforcement loads




## Static loading

Distribution of lateral earth pressure using the Simplified (tie-back wedge) method

$T_{sta\,i} = S_v \sigma_v K_a = S_v \gamma z K_a$

Tensile strength limit state

$T_{sta\,i} =< T_{allow}$

Pullout strength limit state

$T_{sta\,i} =< T_{pullout} = 2\alpha\ F^*\ \sigma_v\ L_{ai}$

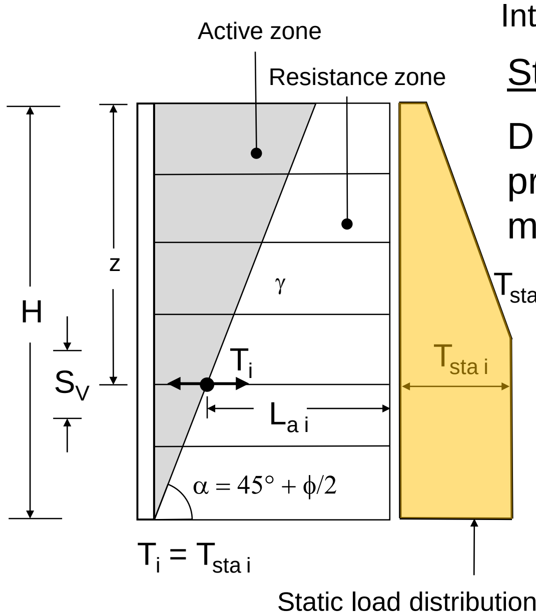
Connection strength limit state

$T_{sta\,i} =< T_{con}$

r.j. bathurst 144

Internal distribution of reinforcement loads

## Static loading




Distribution of lateral earth pressure using the Stiffness method (AASHTO 2020)

$$T_{sta\,i} = S_v\,(\gamma H D_{tmax})\,K_{avh}\,\Phi_{fb}\,\Phi_g\,\Phi_{fs}\,\Phi_{local}\Phi_c$$

Tensile strength limit state

$$T_{sta\,i} =< T_{allow}$$

Pullout strength limit state

$$T_{sta\,i} =< T_{pullout} = 2\alpha\,F^*\,\sigma_v\,L_{ai}$$

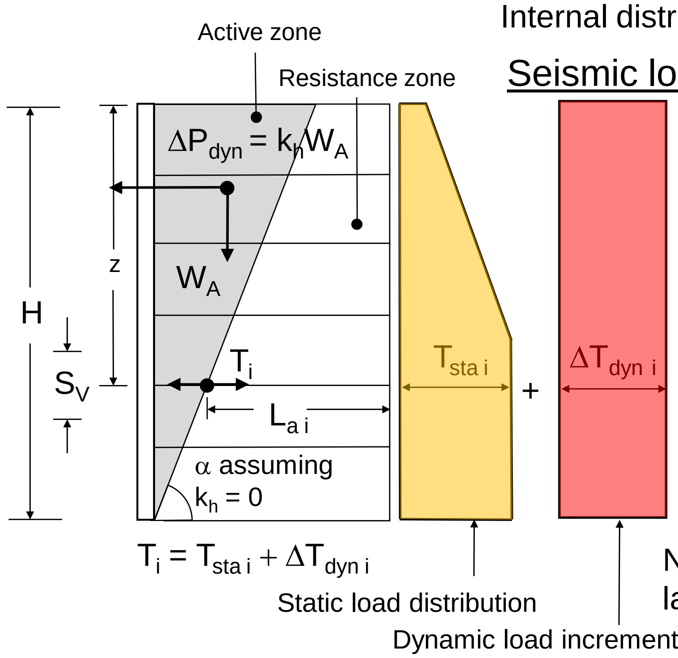
Connection strength limit state

$$T_{sta\,i} =< T_{con}$$

r.j. bathurst 145

Internal distribution of reinforcement loads

## Seismic loading

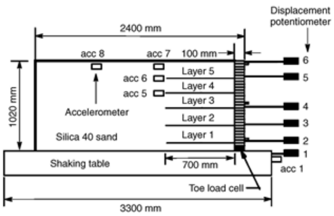



AASHTO (2020)

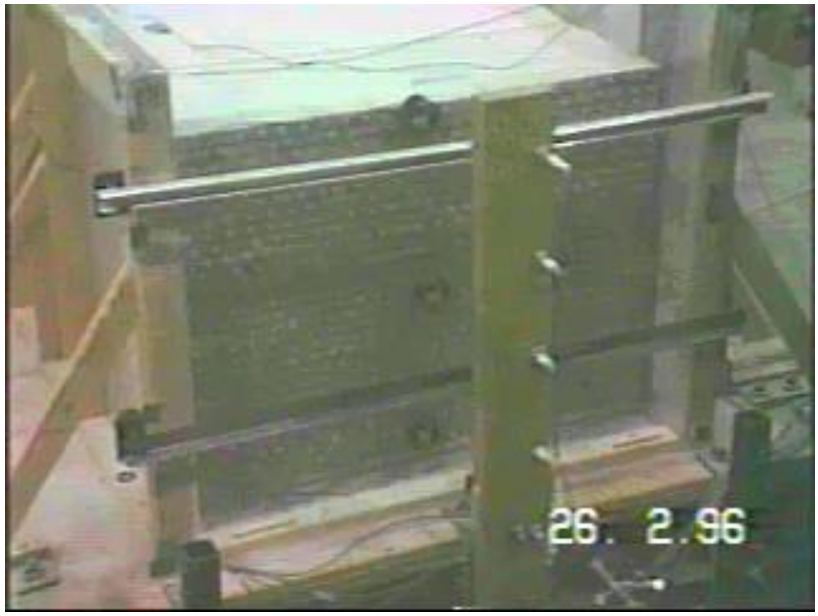
$$\Delta T_{dyn\,i} = \frac{\Delta P_{dyn}}{N}$$

N = number of reinforcement layers

r.j. bathurst 146

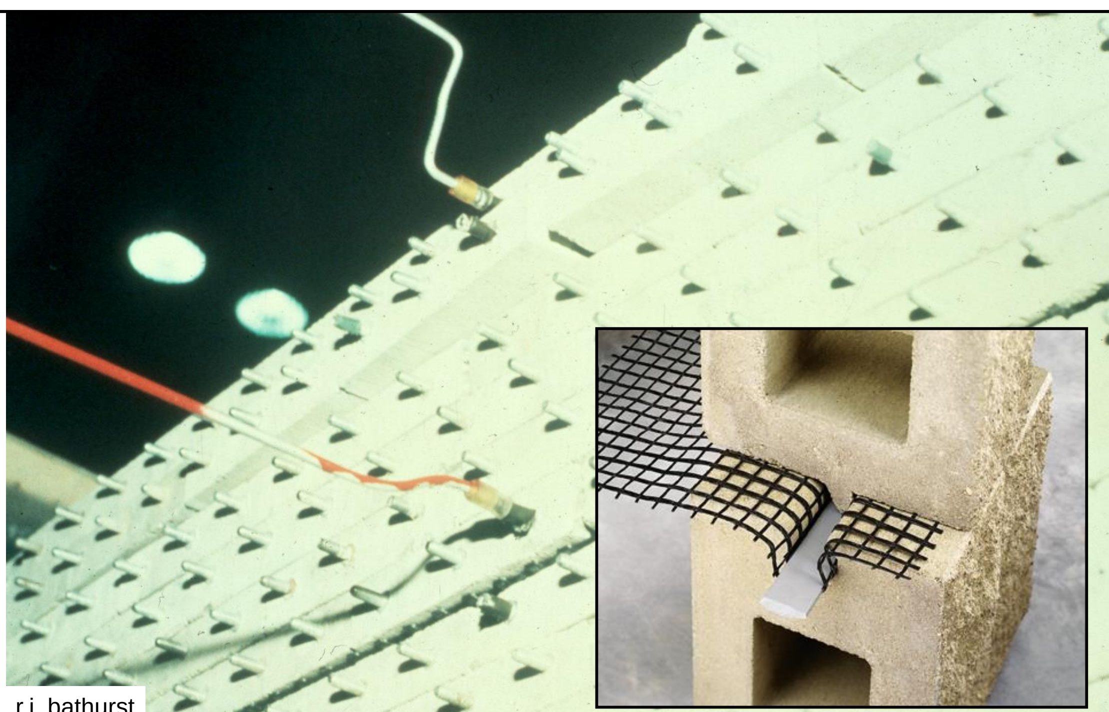







r.j. bathurst

147



r.j. bathurst

148