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# Seismic Design of Underground Structures using the Free-field Method and other Misconceptions



(Chuto Industrial Inc., 1997)

**Antonio Bobet**  
**PGS 2011**

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## Misconceptions

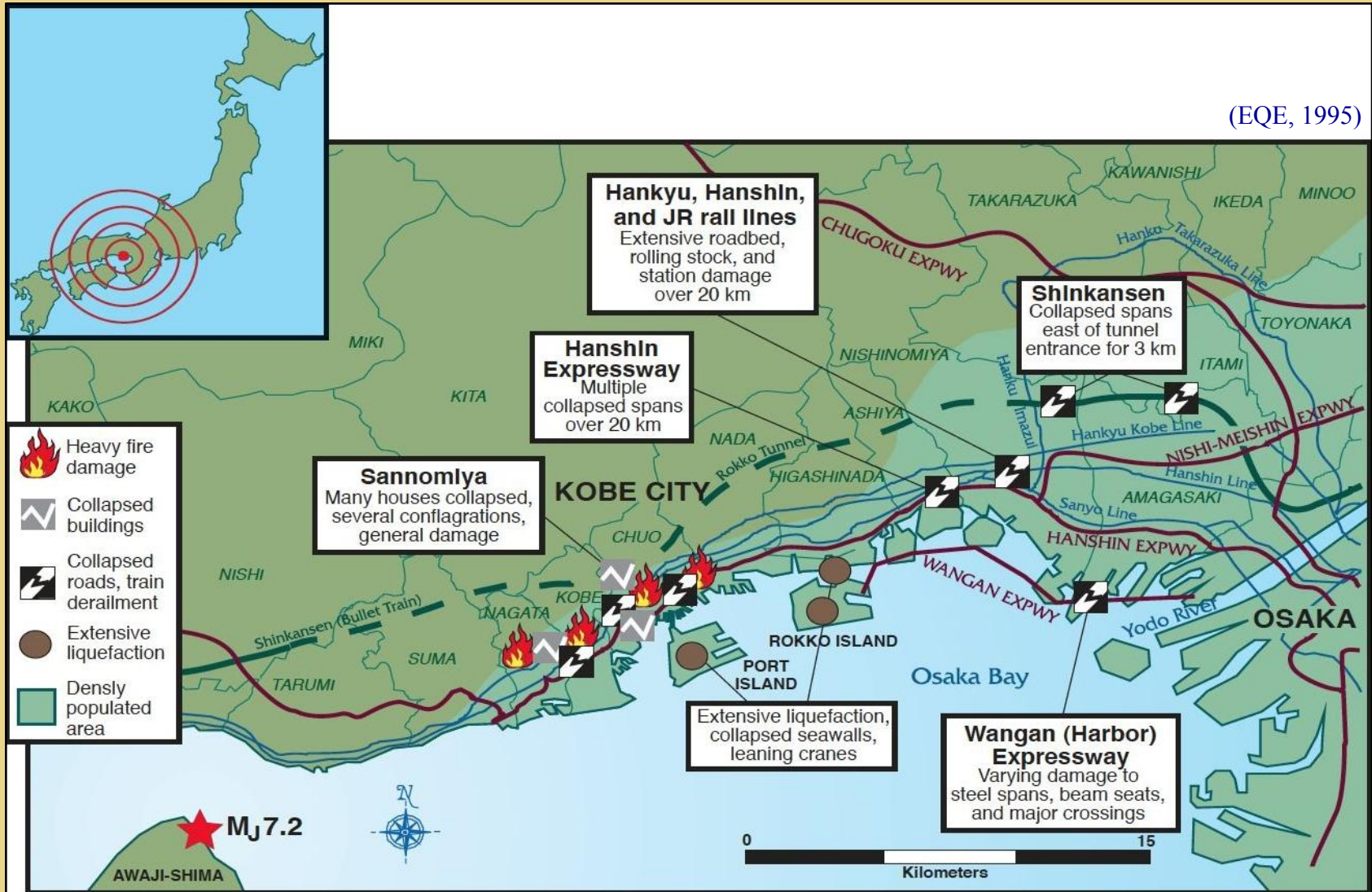
- 1.Underground structures are safe against earthquakes**
- 2.Underground structures deform with surrounding ground**
- 3.Deep structures are safer than shallow structures**
- 4.Use Mononobe-Okabe method to estimate loads**

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# Outline

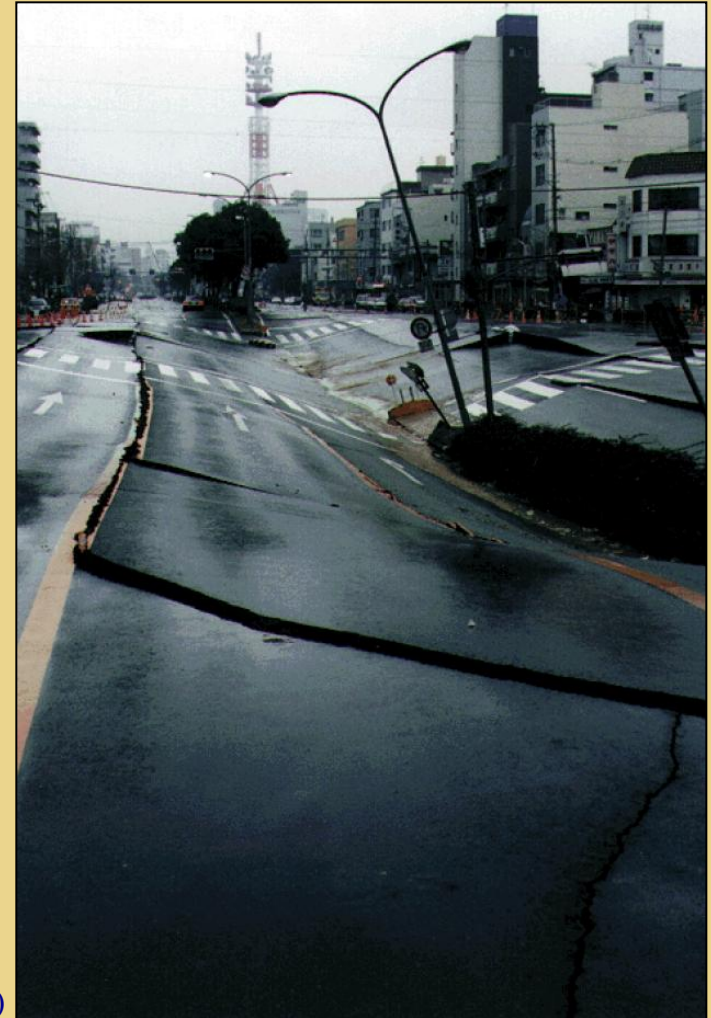
- 1. Motivation**
- 2. Current Design**
- 3. Design of Underground Structures**
- 4. Misconceptions**

(EQE, 1995)



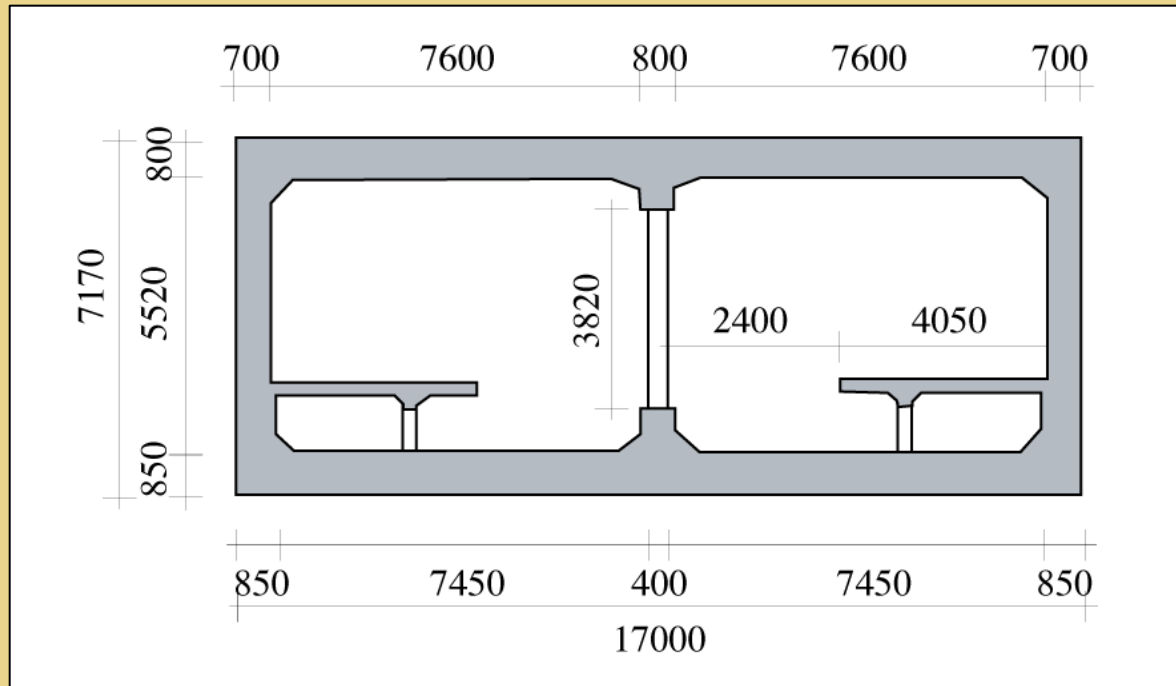
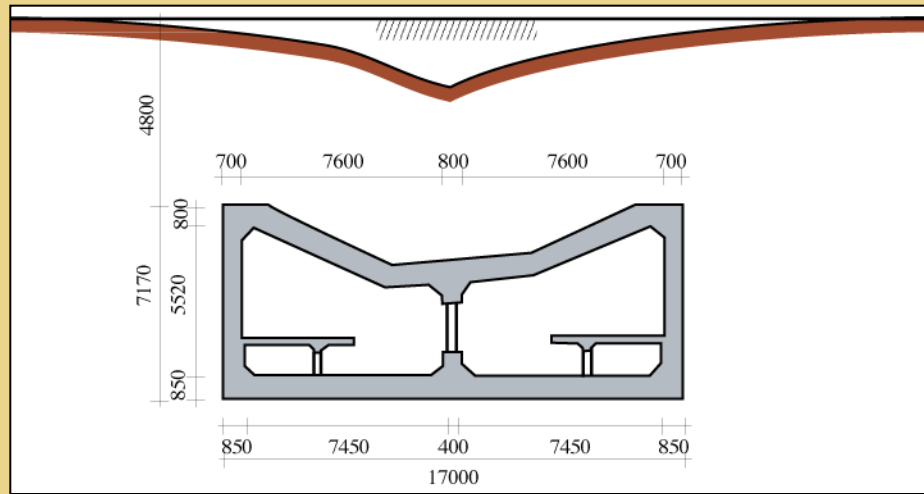


(Chuto Industrial Inc., 1997)



(EQE, 1995)

## Collapse of the Daikai Station



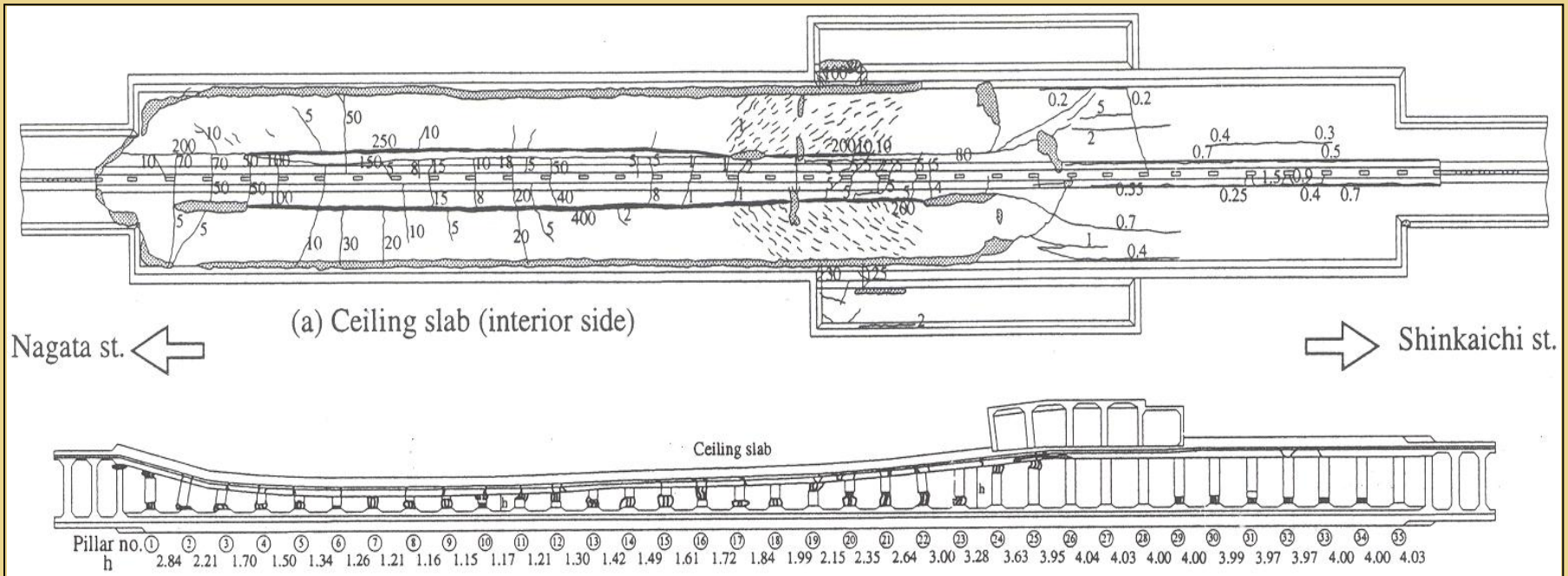
Cross Section





(Chuto Industrial Inc., 1997)

## Damage to the Central Column



(Iida et al., 1996)

## Plan View of the Daikai Station



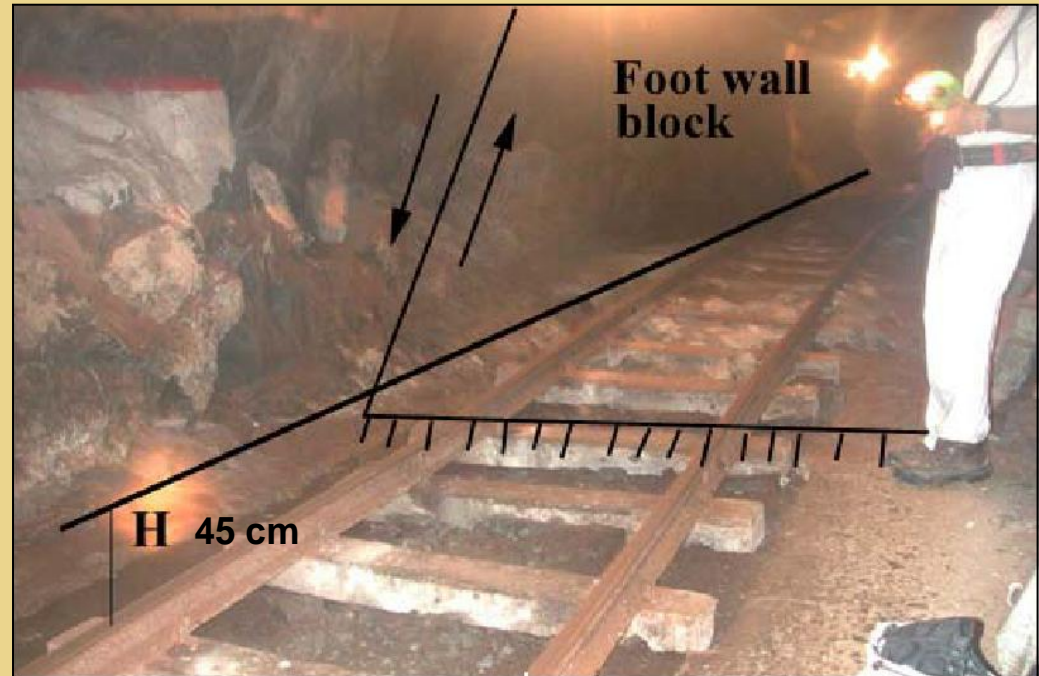
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# Outline

1. Motivation
- 2. Current Design**
3. Design of Underground Structures
4. Misconceptions

## Sources of damage

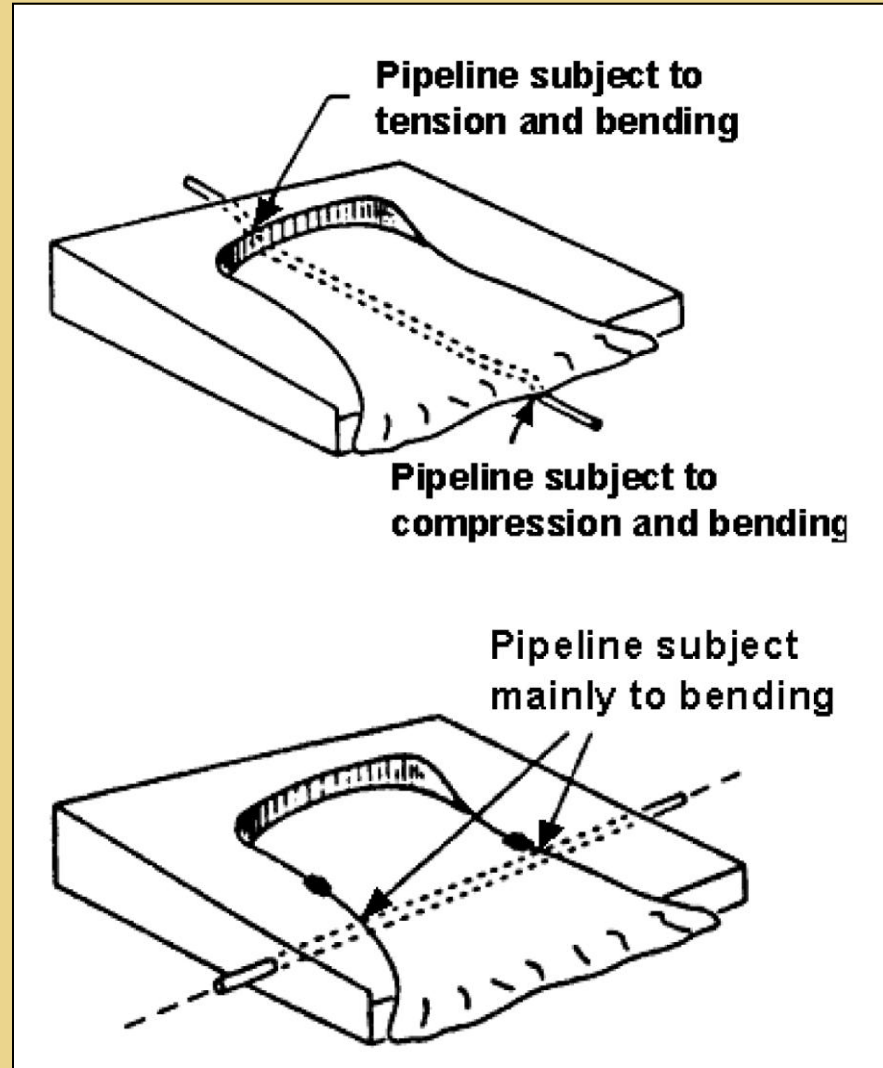
- Fault displacement →
- Ground failure
- Ground Shaking



Dagbreek fault in matjhabeng mine - Israel

## Sources of damage

- Fault displacement
- Ground failure
- Ground Shaking

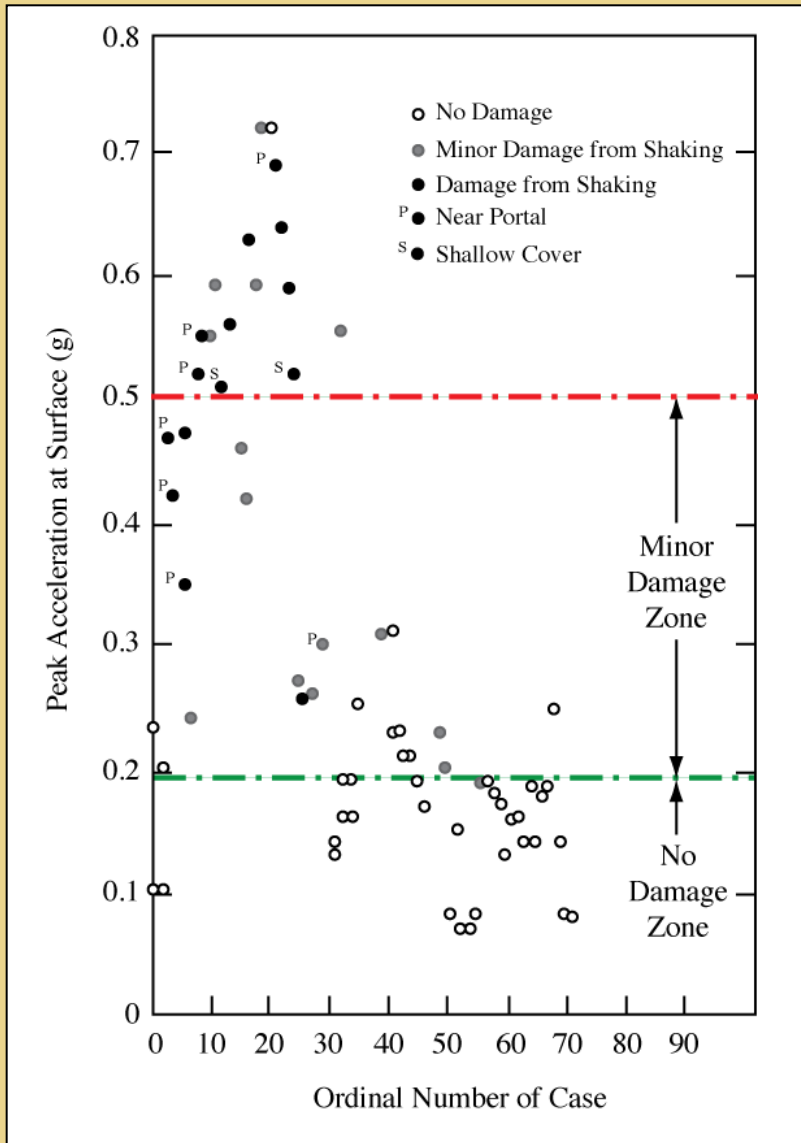


## Sources of damage

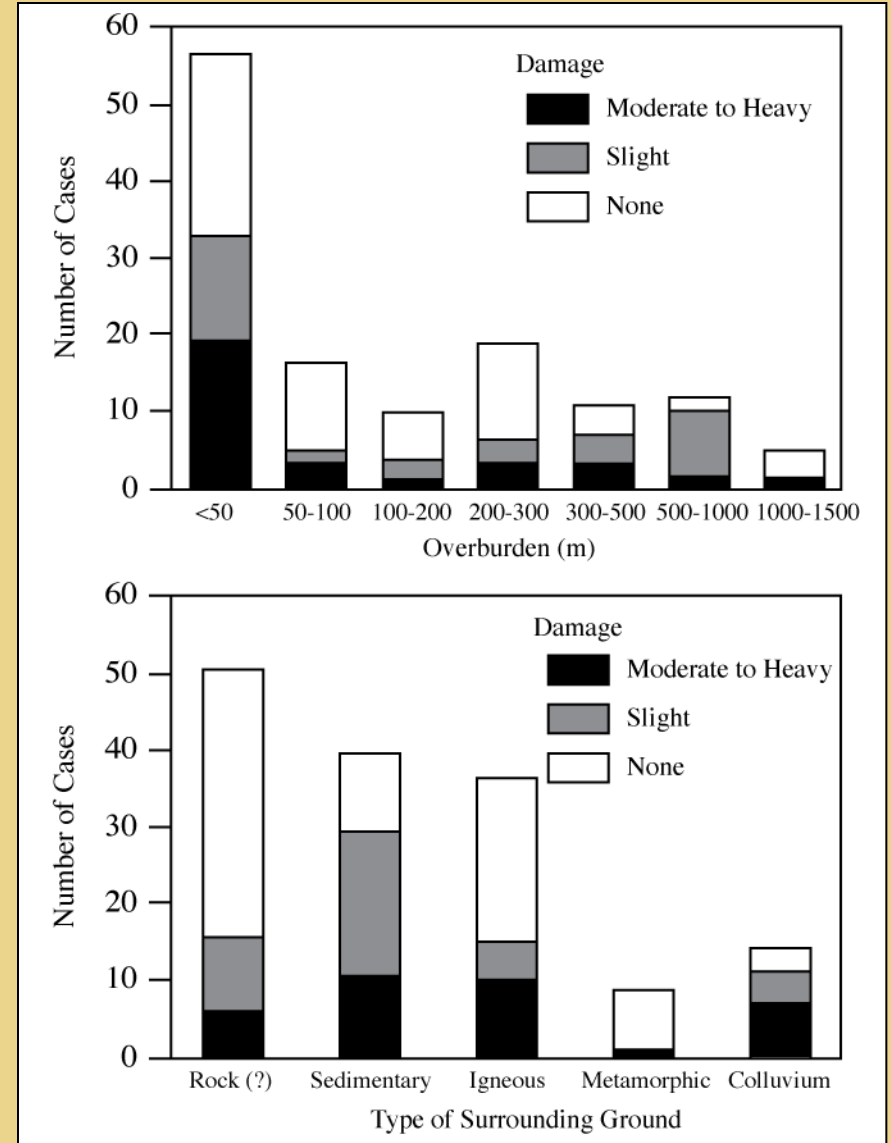
- Fault displacement
- Ground failure
- Ground Shaking



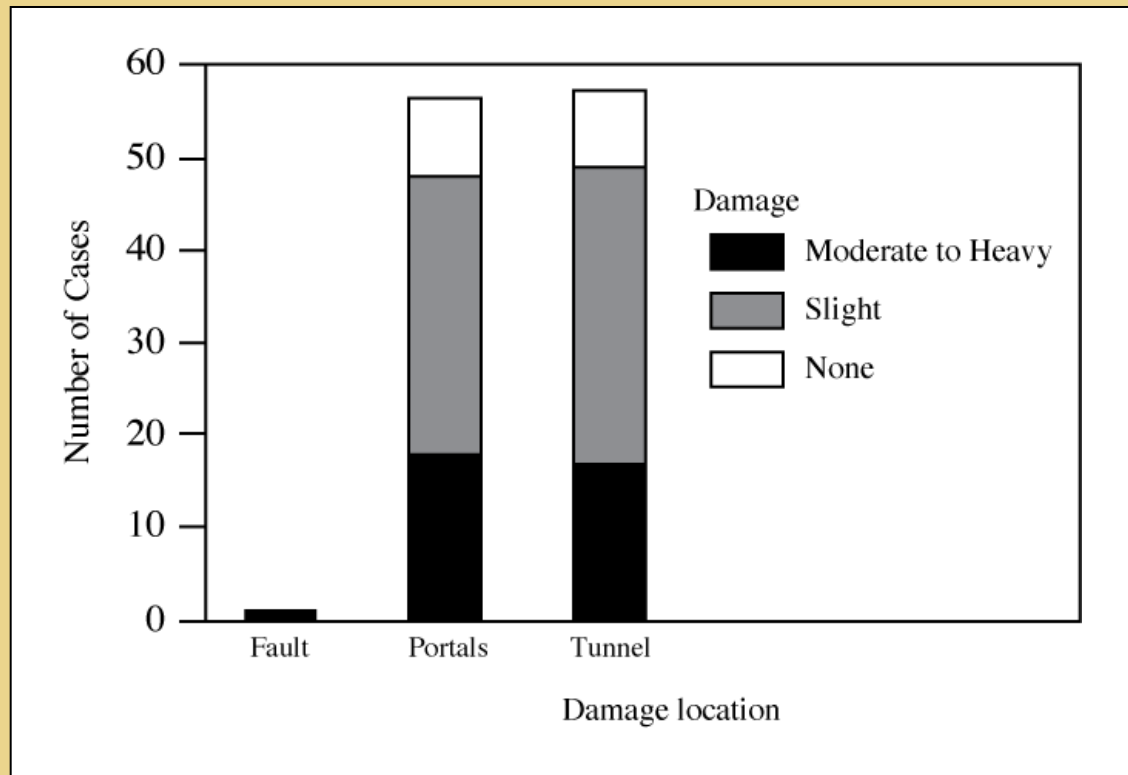




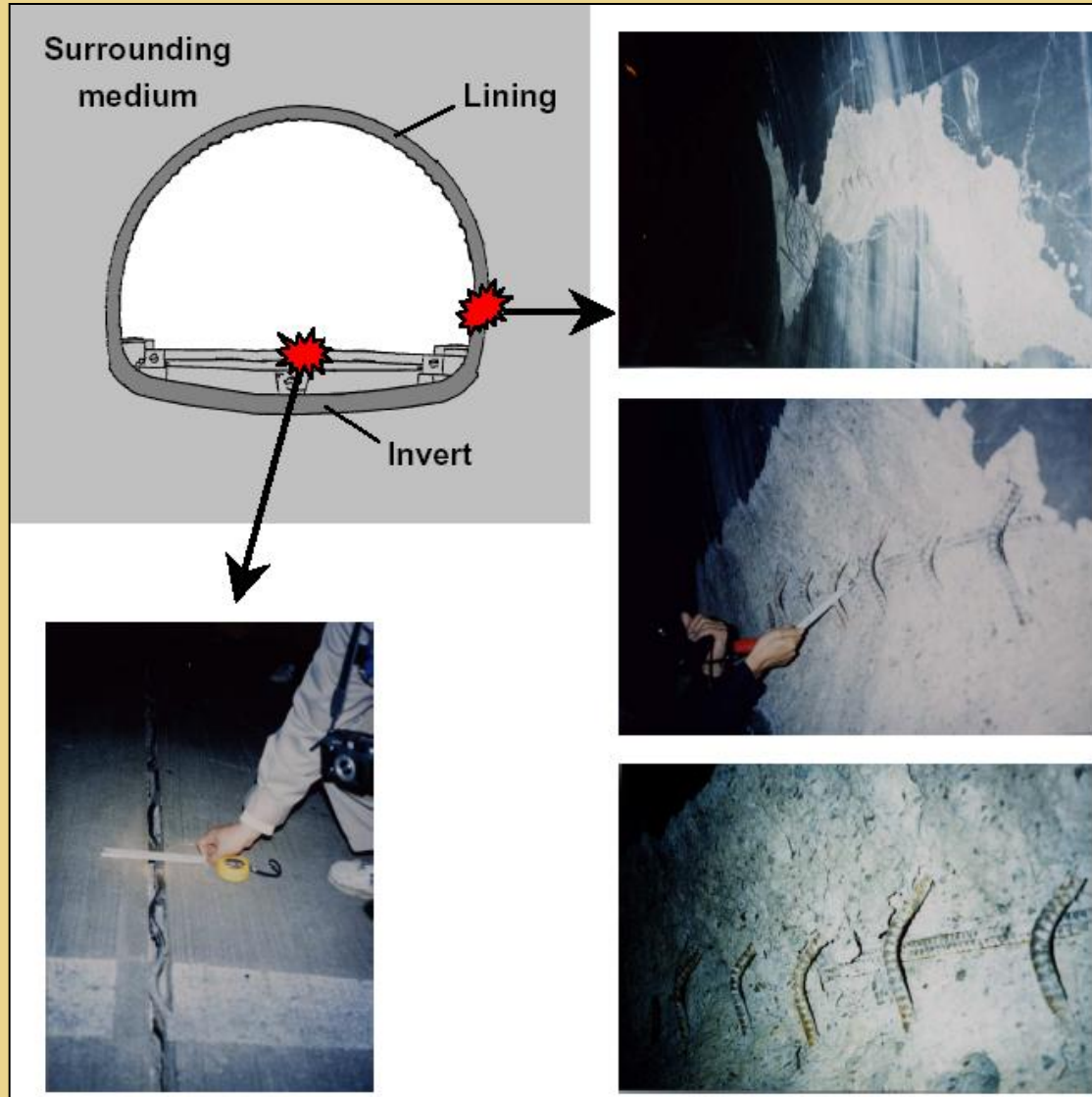
(Dowding, 1977;  
71 cases – 42 damaged)



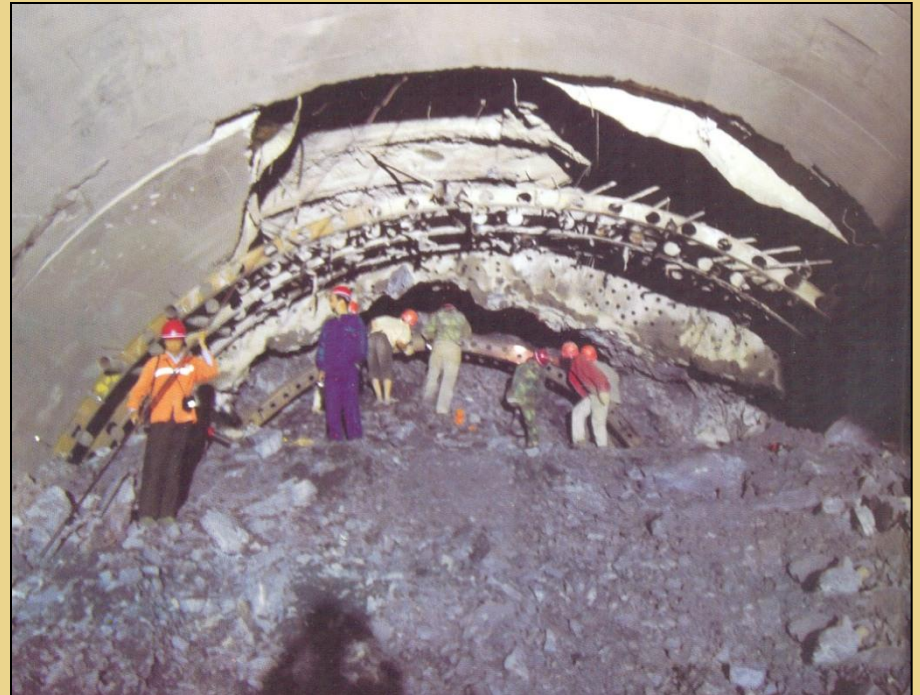
(Sharma and Judd, 1991;  
192 cases – 94 damaged)



Damage to mountain tunnels during the Chi-Chi earthquake, Taiwan, 1999. Data from Wang et al., 2001 (57 cases – 49 damaged)

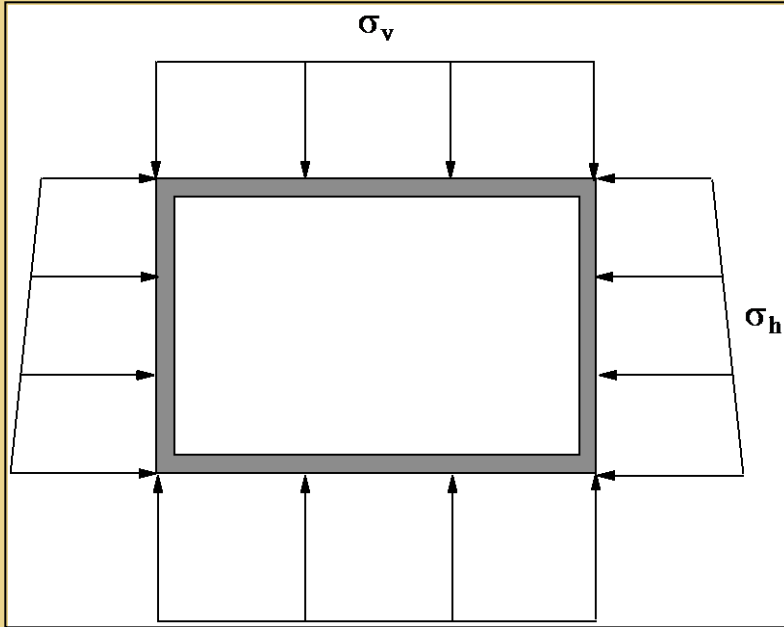


Bantaki Tunnel, after Kobe Earthquake



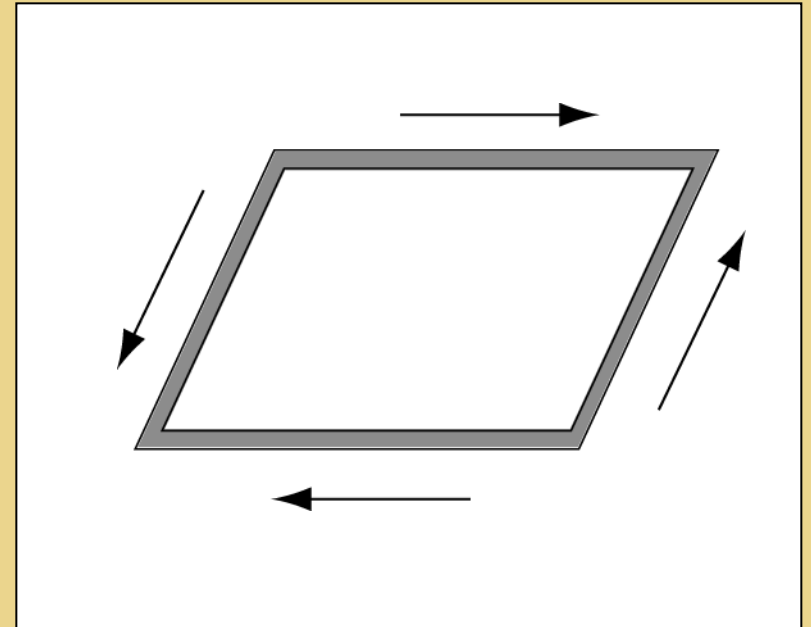
Longxi Tunnel, after 2008 Wenchuan earthquake, China (courtesy of Dr. H. Yu)



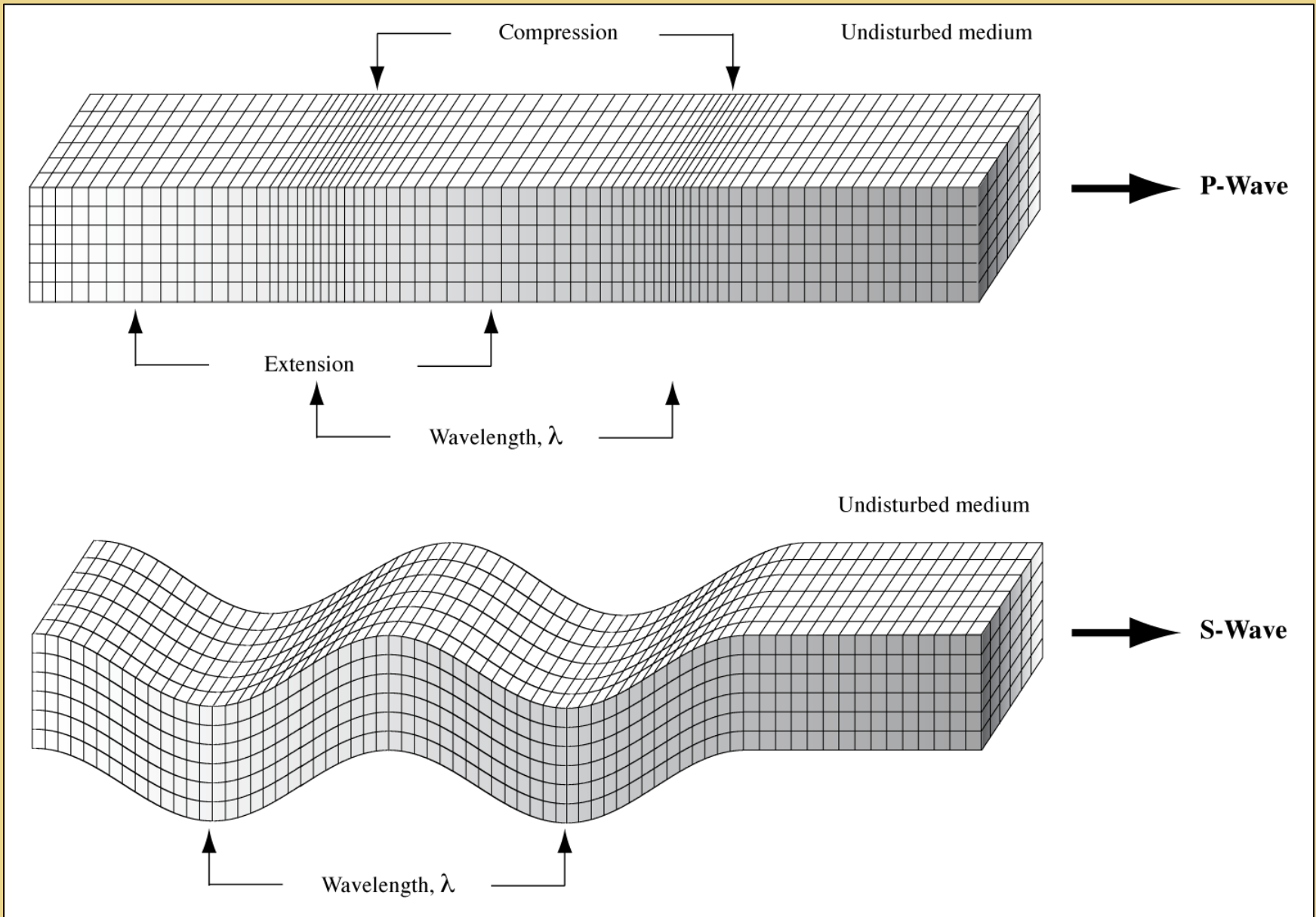


Static

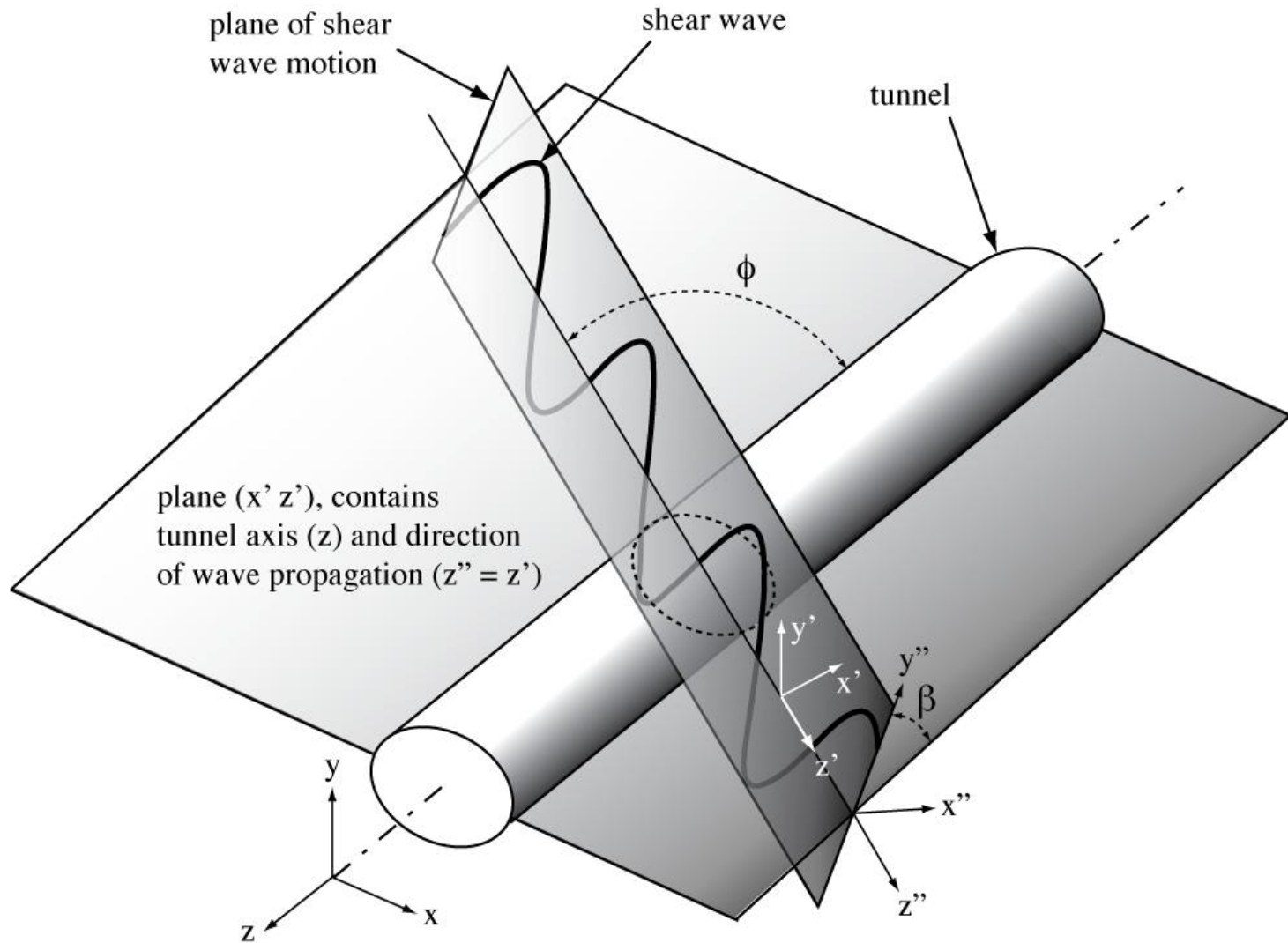
+



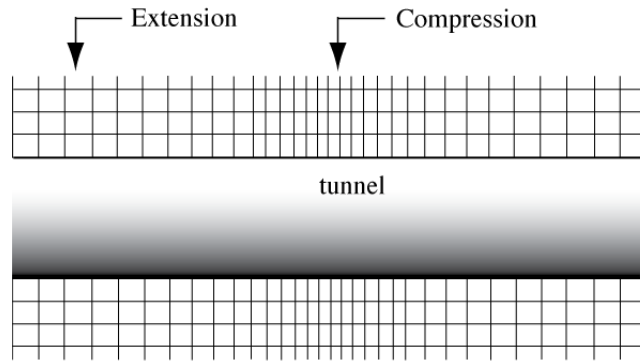
Dynamic



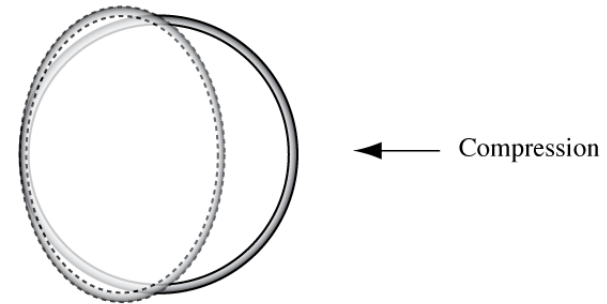
Body Waves



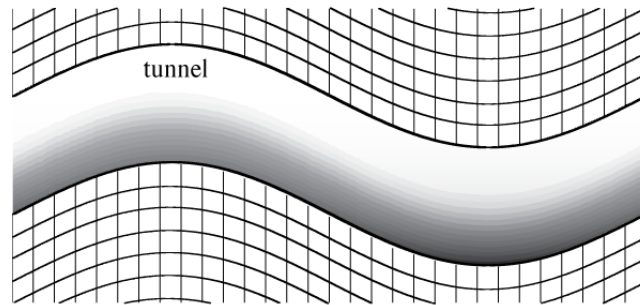
Shear Wave Impinging Tunnel



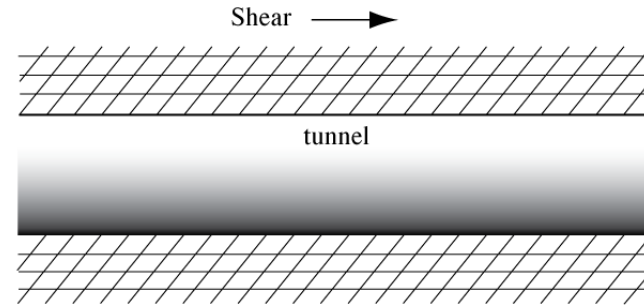
(a) Axial Compression-Extension



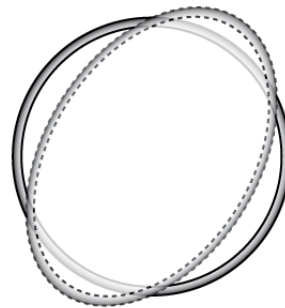
(b) Transverse Compression-Extension



(c) Axial Bending - Snaking



(d) Axial Shear



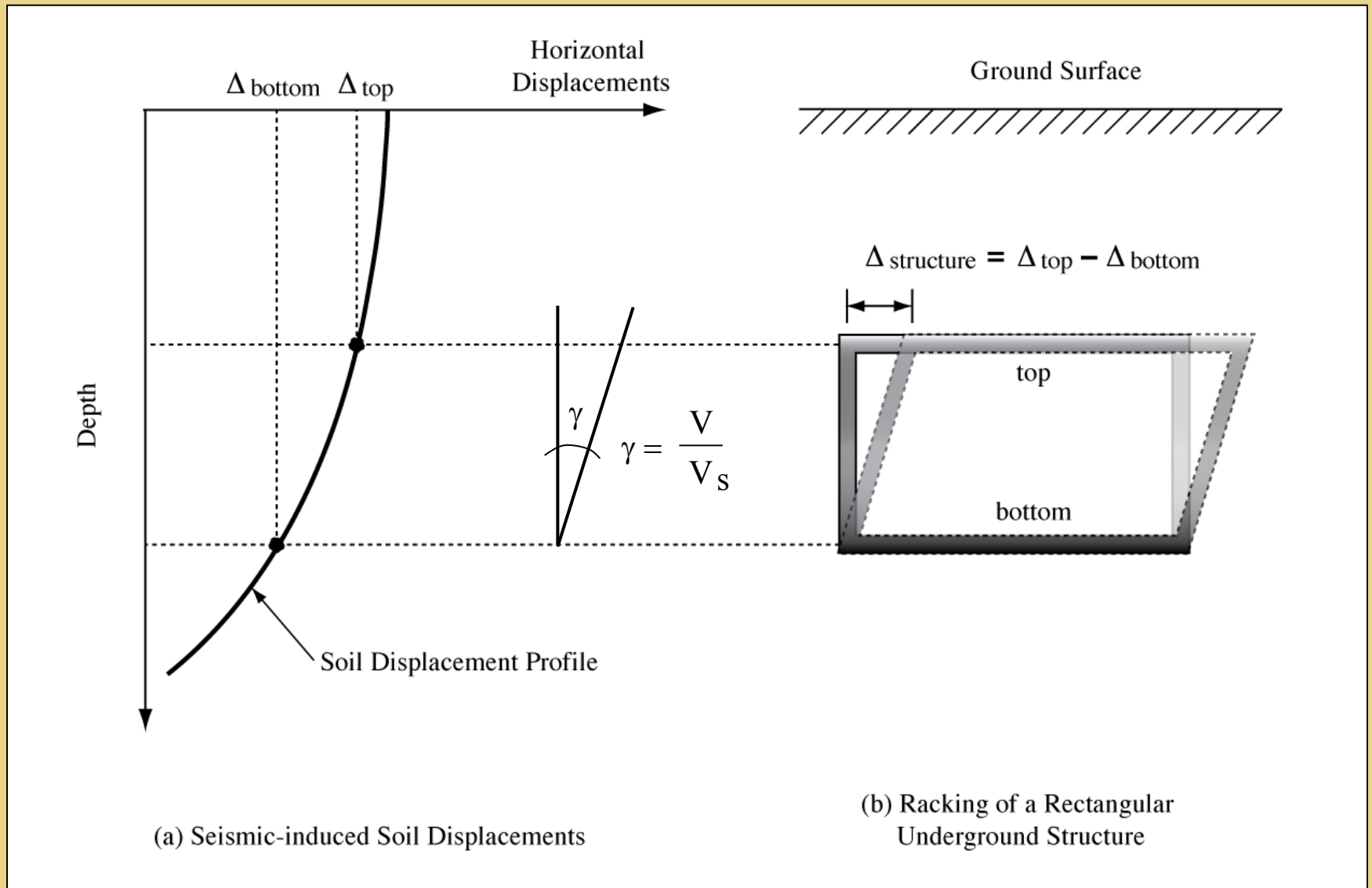
(e) Ovaling



(f) Racking

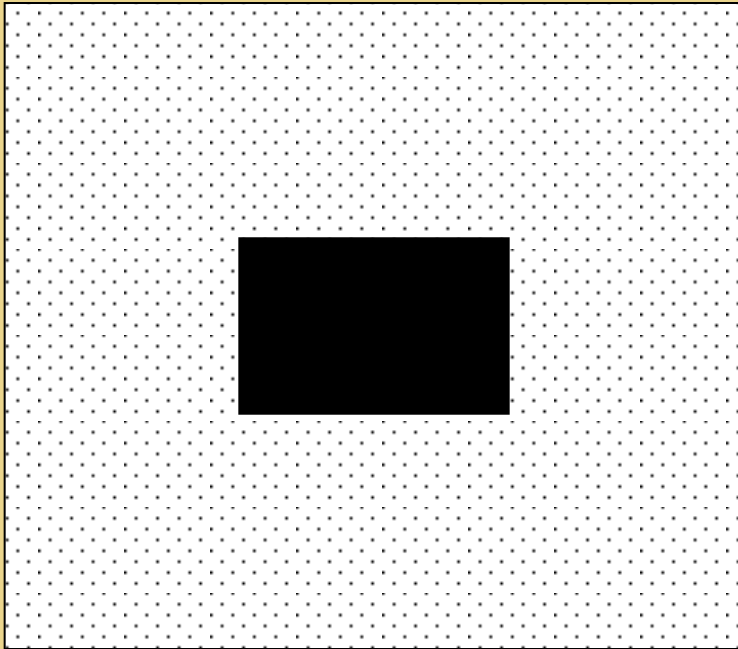
# Tunnel Deformation Modes





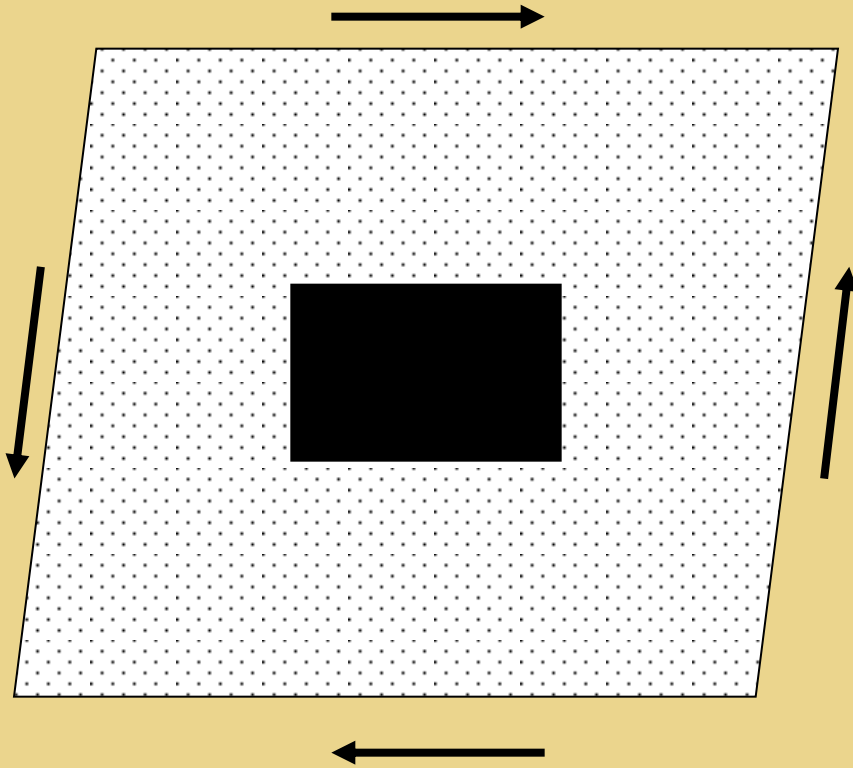
Free-field Method: Racking Deformation

“Thought experiment”



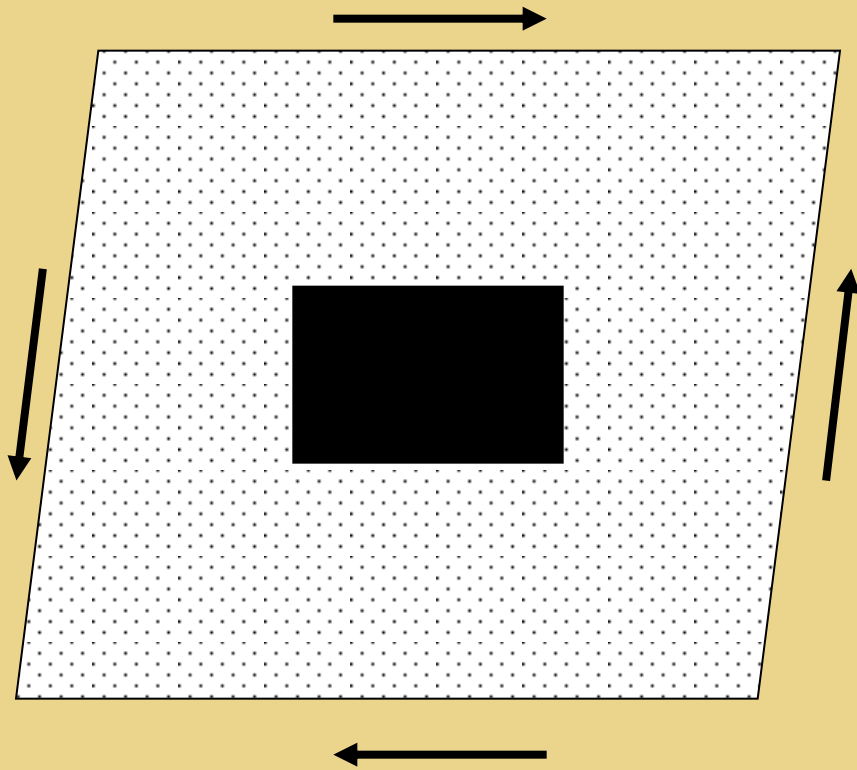
“stiff” tunnel

“Thought experiment”

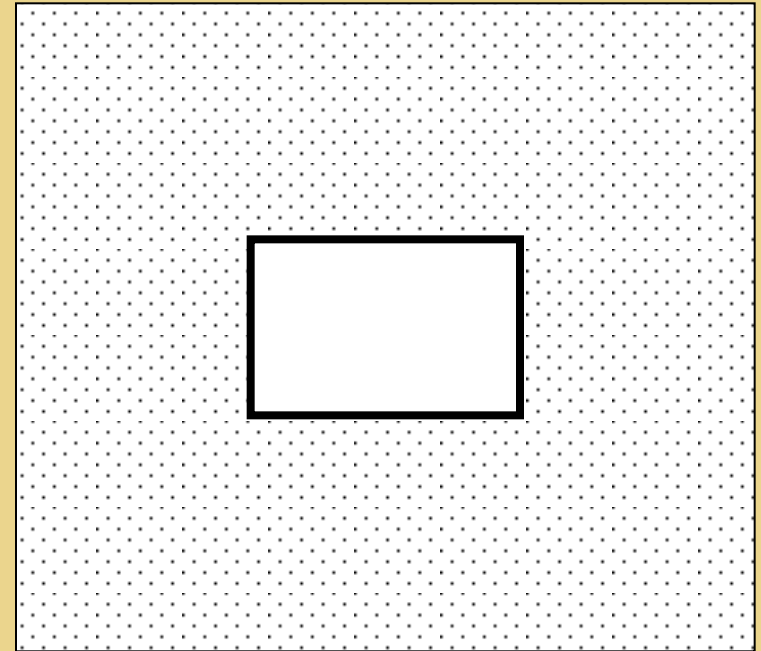


“stiff” tunnel

“Thought experiment”



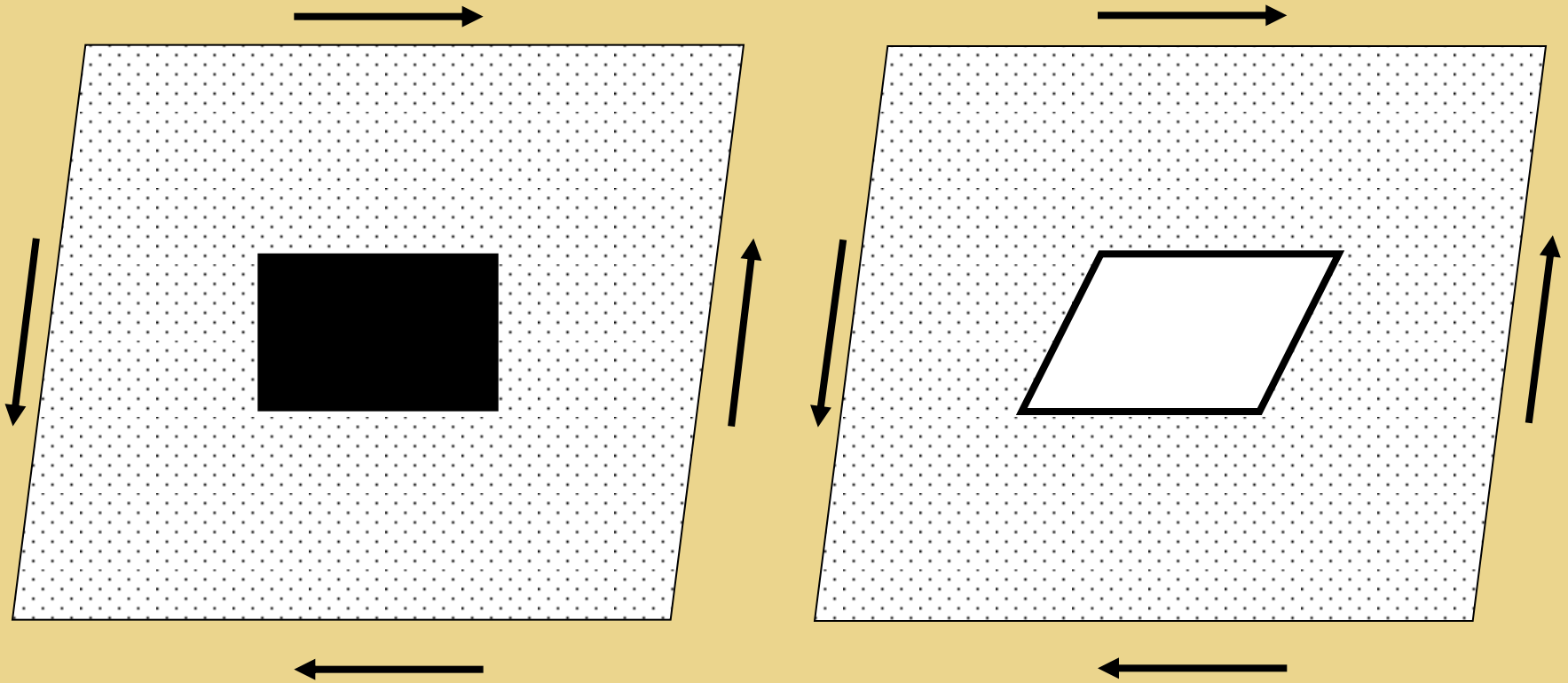
“stiff” tunnel



“soft” tunnel

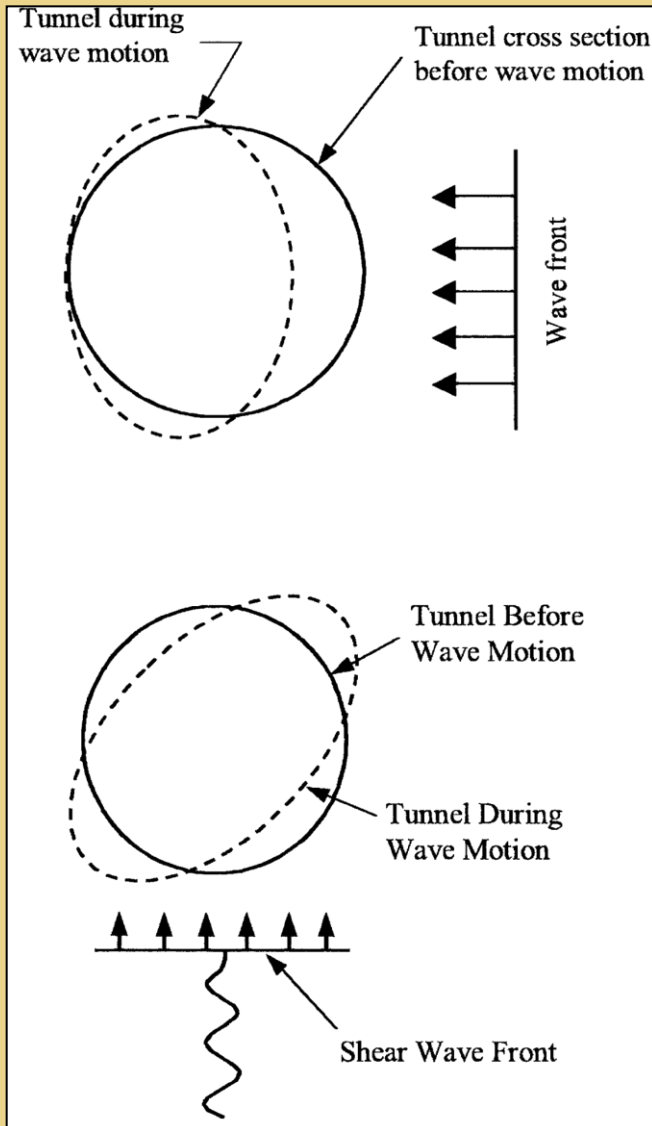


“Thought experiment”



“stiff” tunnel

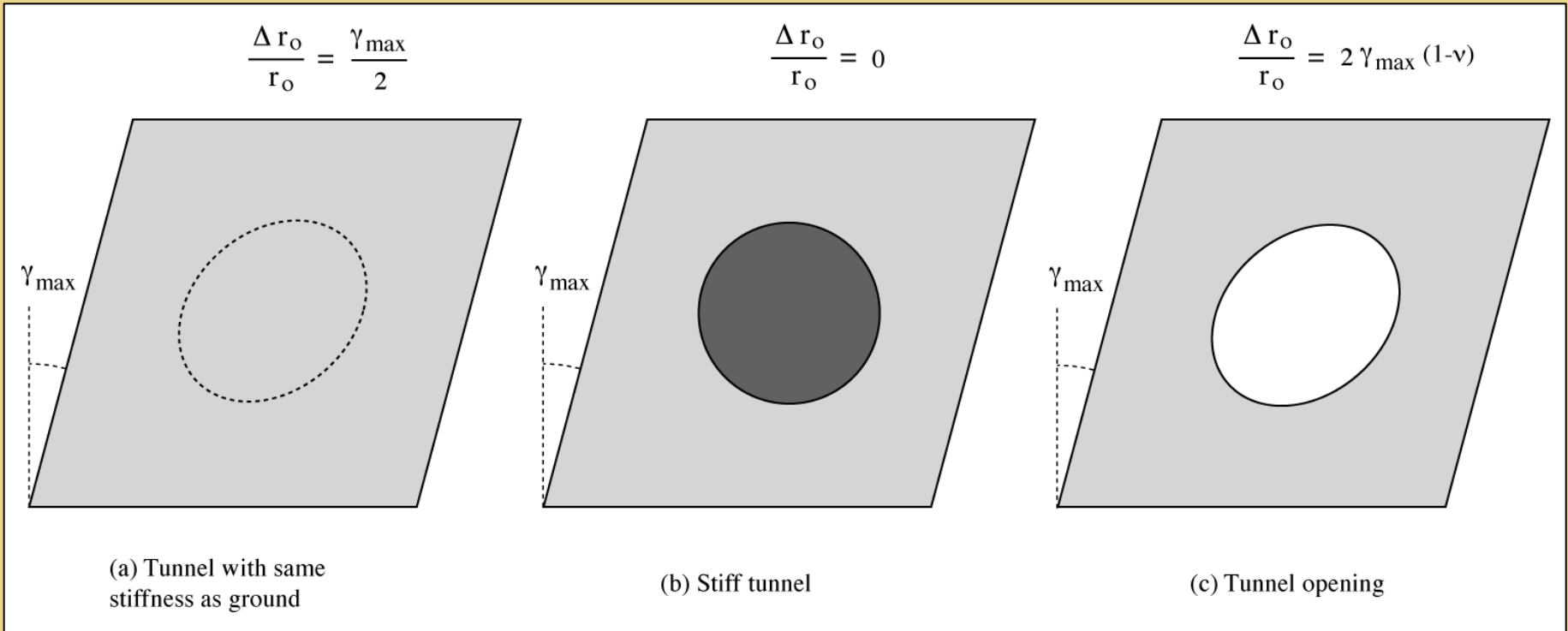
“soft” tunnel



$$\left. \frac{\Delta r_o}{r_o} \right|_{\text{tunnel}} = \frac{4(1-\nu)^2 F}{(1-\nu)(3-2\nu)F + 12(3-4\nu)} \frac{V_{\max}}{V_p}$$

$$F = \frac{E r_o^3 (1-\nu_s^2)}{E_s I_s (1-\nu^2)} \quad C = 0$$

$$\left. \frac{\Delta r_o}{r_o} \right|_{\text{tunnel}} = \frac{4(1-\nu)^2 F}{(1-\nu)(3-2\nu)F + 12(3-4\nu)} \frac{V_{\max}}{V_s}$$



Free Field “errors”



(Benedicto, 2001)

New Station (one year later)



(Benedicto, 2001)

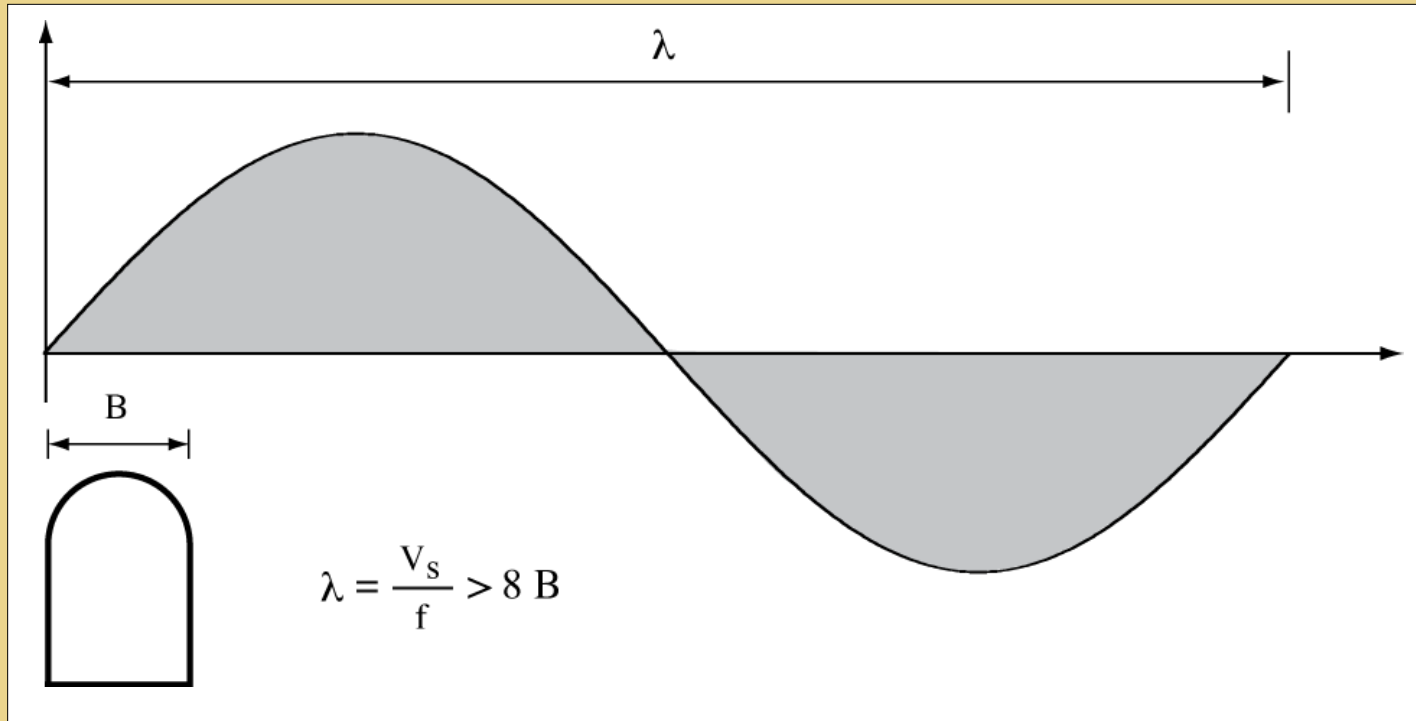


Tunnel

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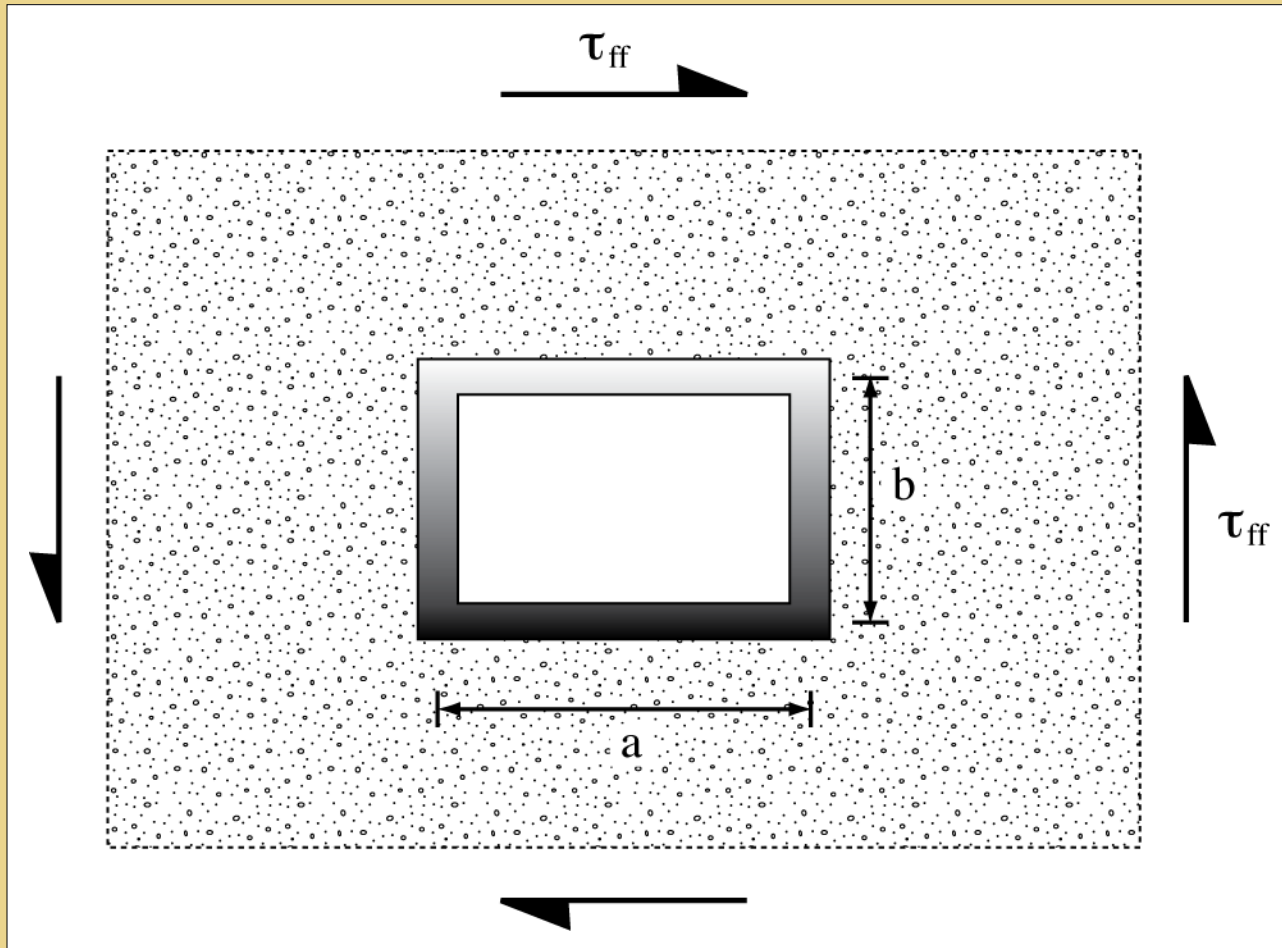
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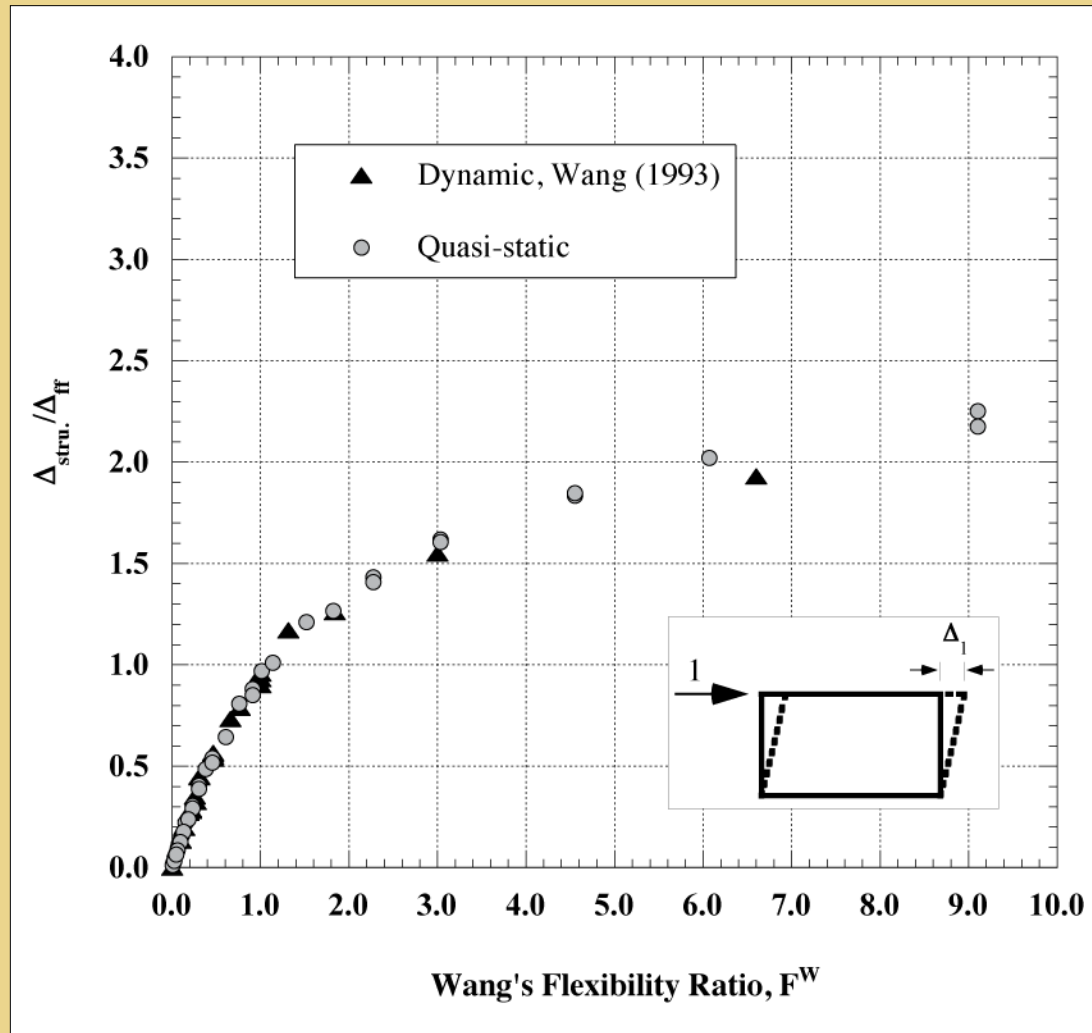


Pseudo-static Analysis (Hendron and Fernández, 1983)

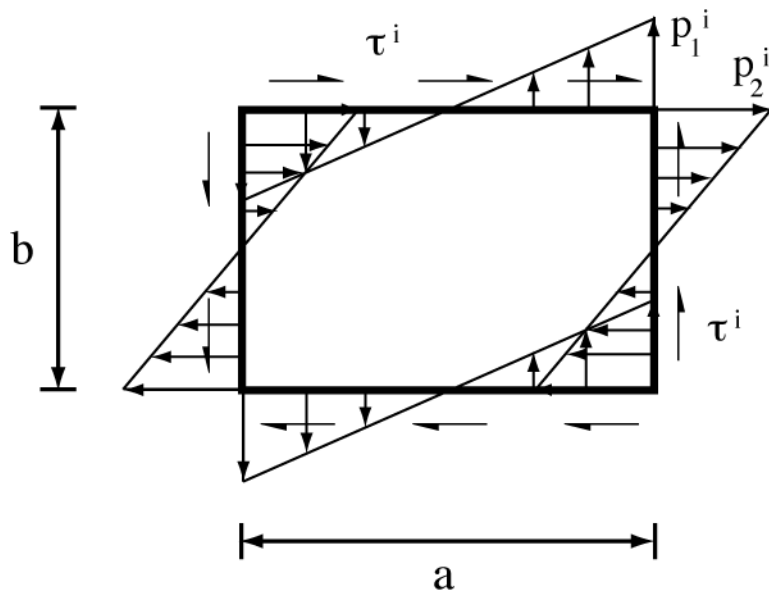




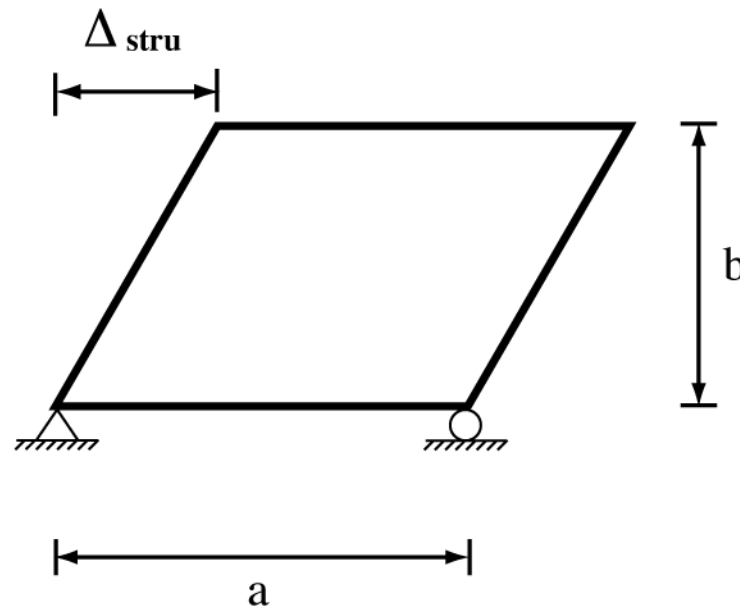
Rectangular Structure in Infinite Elastic Medium



Rectangular Tunnel

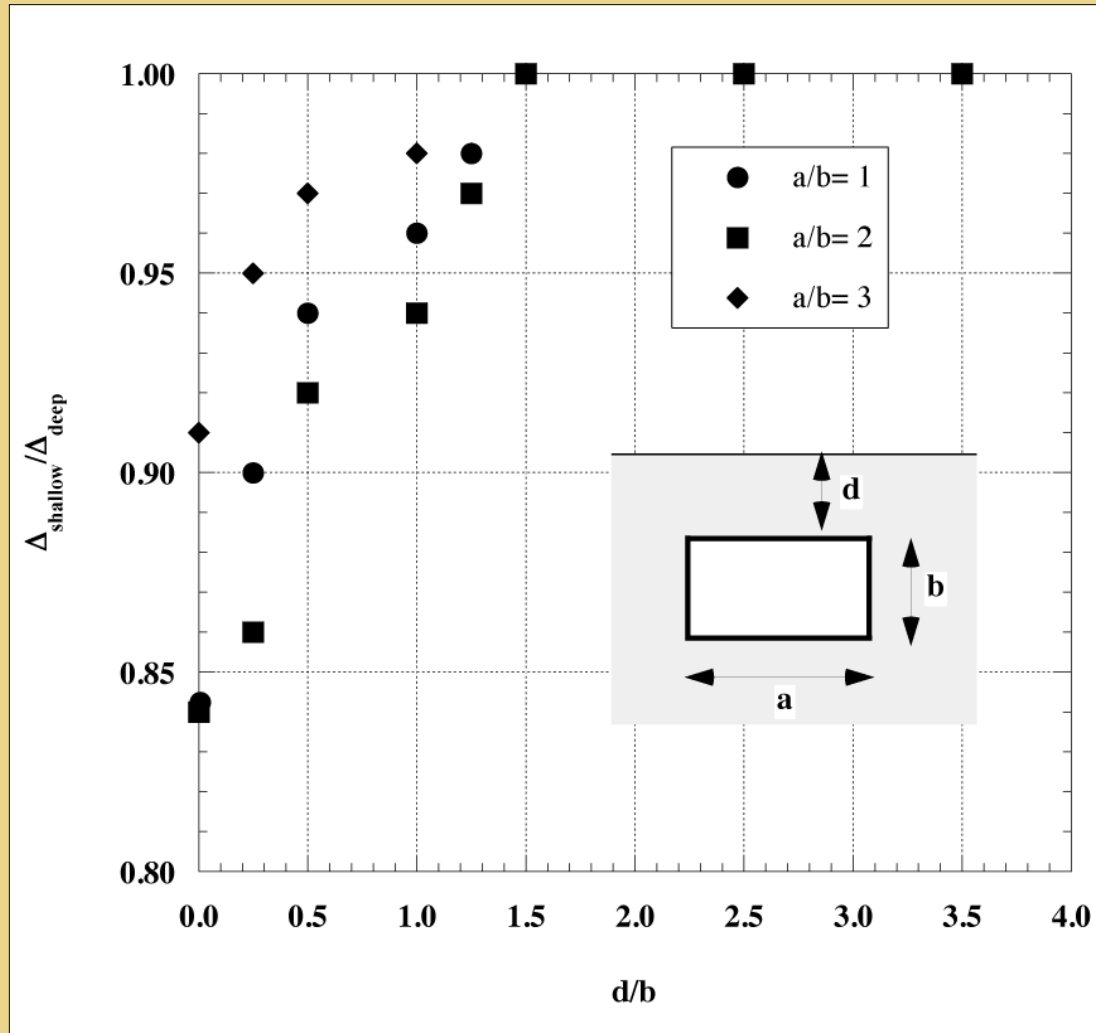


(a) loading



(b) deformations

## Rectangular Structure in Infinite Elastic Medium



Depth Effect

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**Thank you**

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