- Final Conference -

Earthquake engineering
Presentation of the book

"Strategies for reduction of the seismic risk"

Tunnel under seismic loading: a review of damage case histories and protection methods

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Outline

1. *Case histories collection*
2. *Damage to urban tunnels*
3. *Damage classification criterion*
4. *Seismic parameters affecting the damage*
5. *Cracks along the tunnel lining*
6. *Protection methods*

Case histories collection

Before San Fernando earthquake (1971):

- *Damage data available only after strong earthquakes*
- *Difficult distinguish between previous and seismic induced cracks*

After San Fernando earthquake (1971):

- *Damage data from different earthquakes*

- ***ASCE*** *(1974): damage after San Fernando earthquake (1971)*
- ***Dowding & Rozen*** *(1978): 71 cases*
- ***Owen & Scholl*** *(1981): 127 cases*
- ***Sharma & Judd*** *(1991): 191 cases*
- ***Power et al****. (1996): 217 cases*
- ***Wang et al****. (2001): damage after Chi-Chi earthquake (1999)*

Damage to urban tunnels

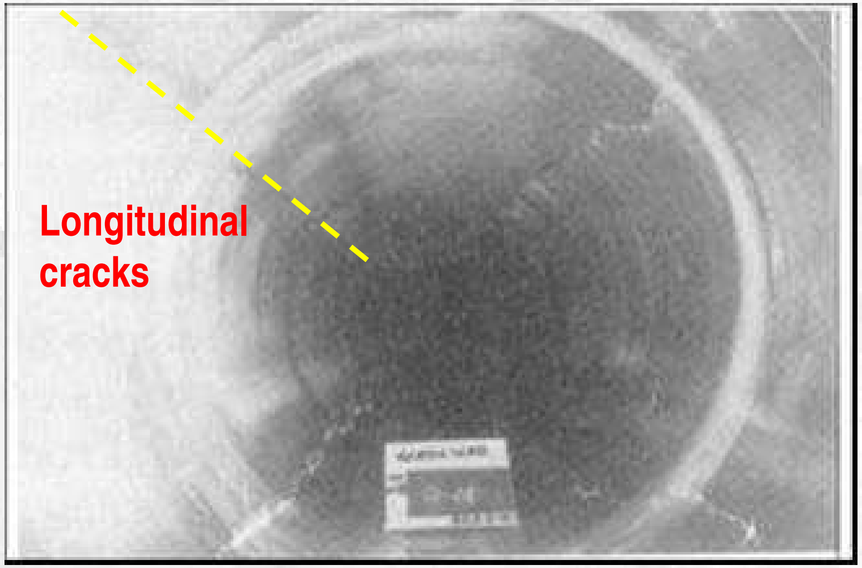
Some Earth's areas suffer strong earthquakes and had severe damage to underground structures:

Nation	Earthquake	Year	M_w	Number of cases
Japan	Kanto	1923	7.9	25
	Kobe	1995	6.9	97
California	San Francisco	1906	7.8	10
	San Fernando	1971	6.6	10
	Loma Prieta	1989	7.1	22
	Northridge	1994	6.7	31
Taiwan	Chi-Chi	1999	7.6	57
Turkey	Duzce	1999	7.2	1
Italy	Irpinia	1980	6.9	1

- *Most of the documented damage cases are referred to Japan, California, China and Taiwan (99%);*
- *Well documented earthquakes increased in time;*
- *Poor damage database for European strong earthquake (absence of monitoring or less vulnerability?)*

Kobe earthquake (1995)

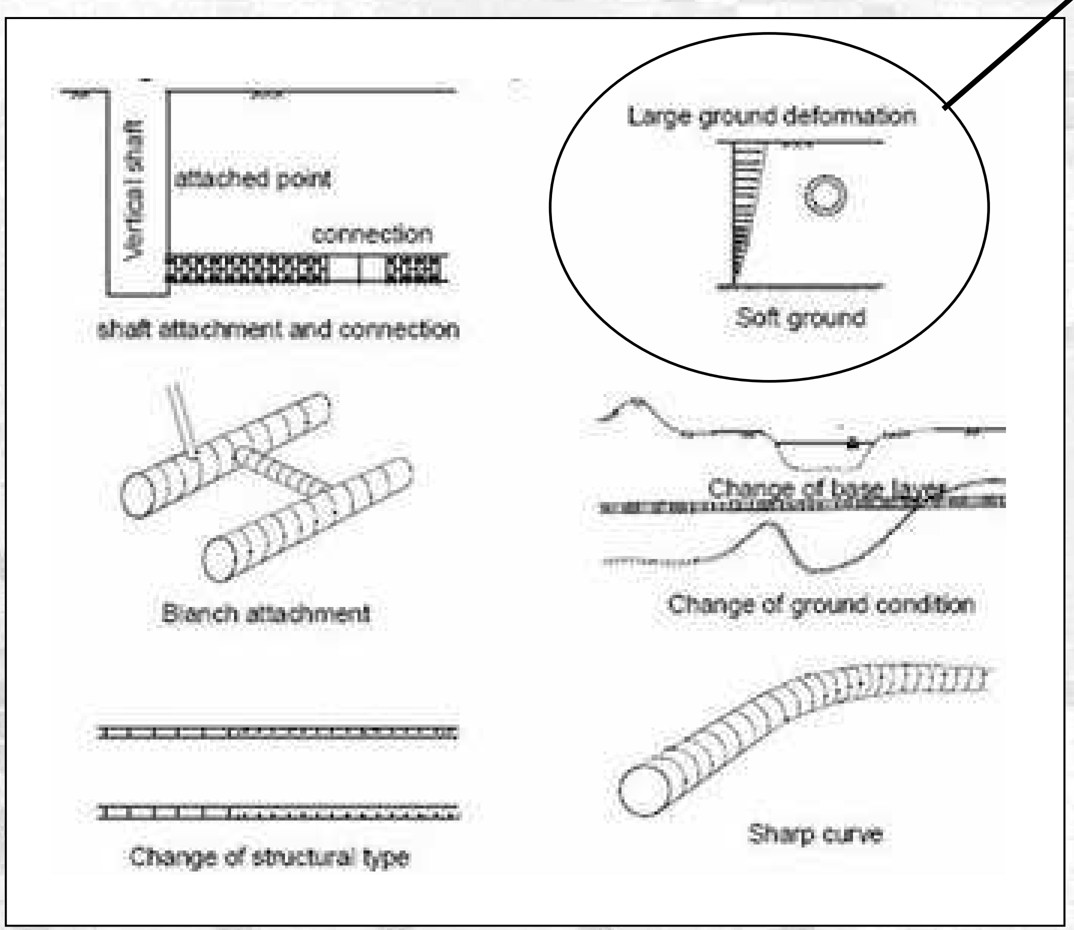
Damage to Metro Lines of Kobe (Iida et al. 1996; Yoshida 1999)



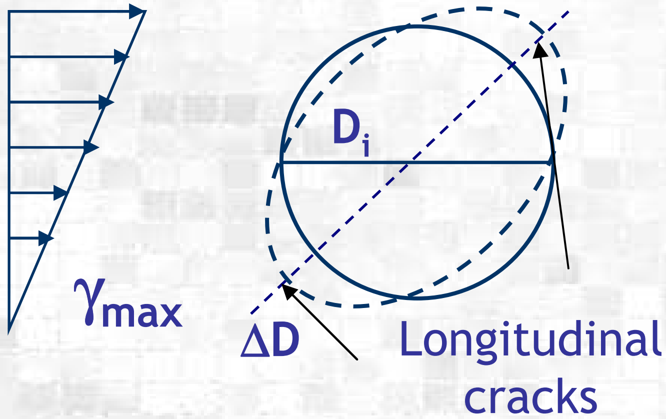
- *Collapse of Daikai Station due to instability of central columns*
- *Longitudinal cracks on the lining at $\theta = \pi/4 + n\pi/2$ (n=0,1,2,3)*

Possible unfavourable conditions

Typical condition inducing tunnel cracks or collapse (Yoshida, 1999)



Damage in a homogeneous soft medium due to ground shaking (ovalization)

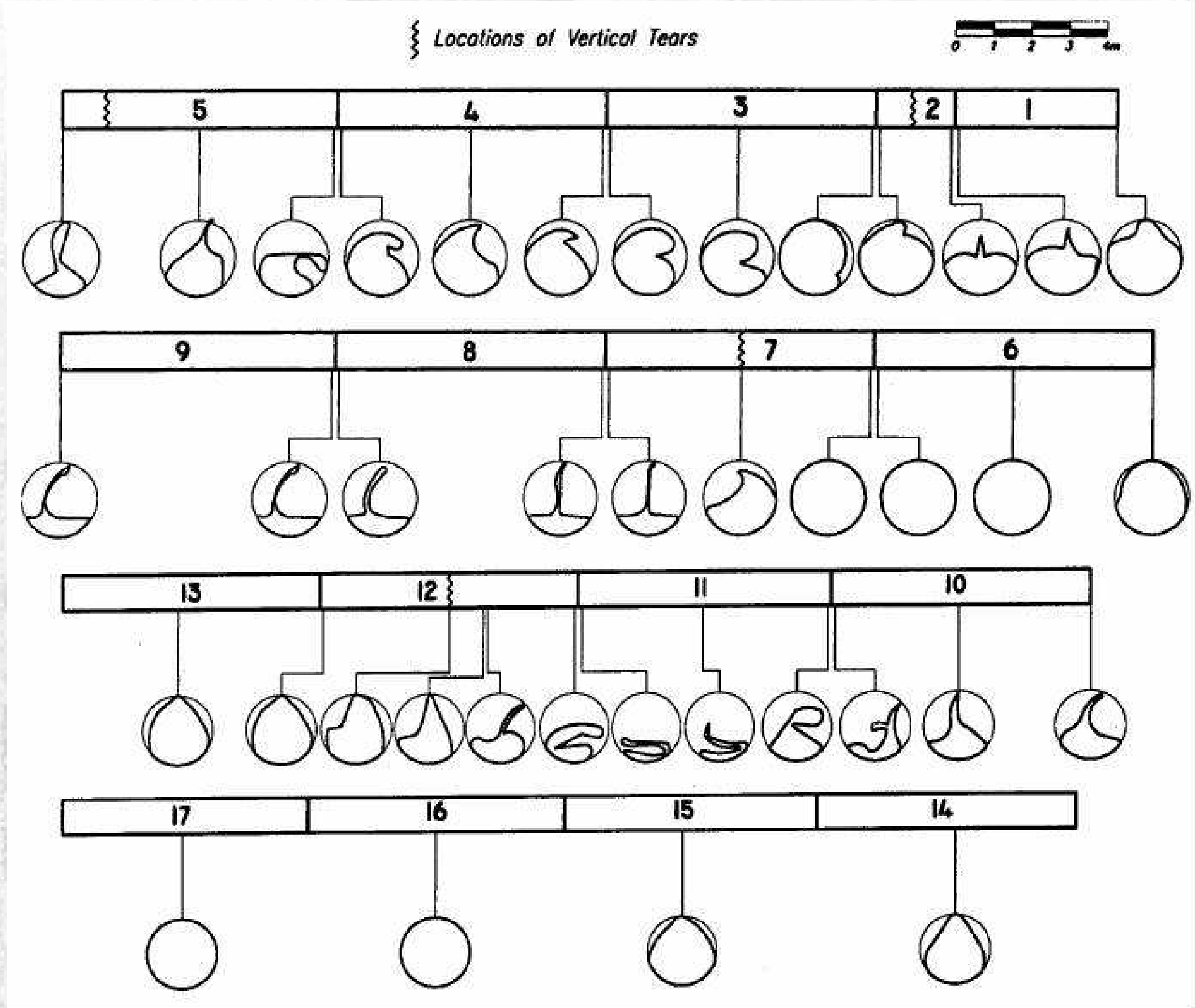


Damage for <u>abrupt changes</u> in structural stiffness or ground conditions:

- ***Connections between tunnels and buildings or transit stations;***
- ***Junctions of tunnels of different structural material;***
- ***Passing through distinct geologic media of varying stiffness;***
- ***Local restraint on tunnels from movements of any type.***

Northridge earthquake (1994)

Drawings of damaged tubes (Bardet & Davis 1999)



- *Water and gas transmission pipelines was severely damaged*
- *Failure mechanism for steel pipes is lateral buckling due to confinement reduction (also shown in shaking table tests by Madabhushi et al. 2007)*
- *Railway and roadway tunnels had no damage because of the a-seismic joints installed on Los Angeles Metro and San Francisco BART (Bay Area Rapid Transit)*

Damage classification criteria

- ***Damage type***
  - *Ground failure, such as liquefaction or landslides at tunnel portals*
  - *Fault displacement*
  - *Ground shaking or ground vibrations*
- ***Structure type***
  - *Bored tunnels*
  - *Cut-and-cover structures*
  - *Steel and plastic pipelines*
- ***Damage levels (Dowding & Rozen 1978)***

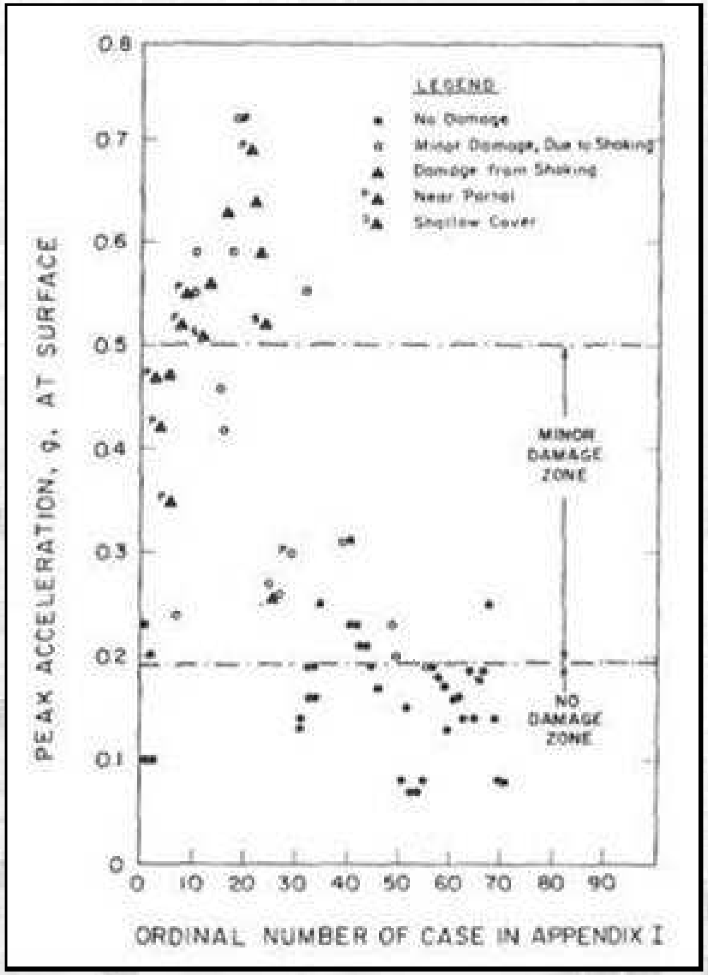
  Classification based on length L and width W of cracks and serviceability after earthquake
  - *Class A: Slight damage. L<5m W<3mm. Full functionality.*
  - *Class B: Moderate damage. L>5m W>3mm. Compromised functionality.*
  - *Class C: Severe damage. Structural (partial) collapse. Service stop without any possible restoration;*

Seismic parameters affecting the damage (1/4)

- *Seismic signal parameters:*
  - *Peak ground acceleration and velocity (PGA & PGV)*
  - *Frequency content*
  - *Magnitude*
  - *Duration*
  - *Epicentral distance*
- *Soil/Structure parameters:*
  - *Tunnel depth*
  - *Ground type (stiffness…)*
  - *Lining support (type, shape, thickness, material)*

Seismic parameters affecting the damage (2/4)

Dowding & Rozen (1978)

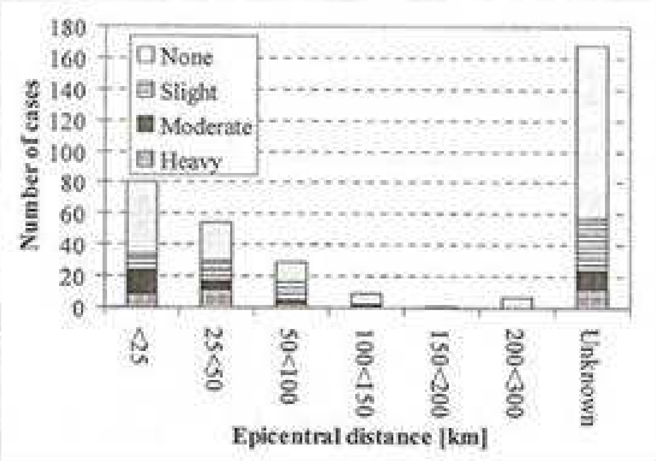


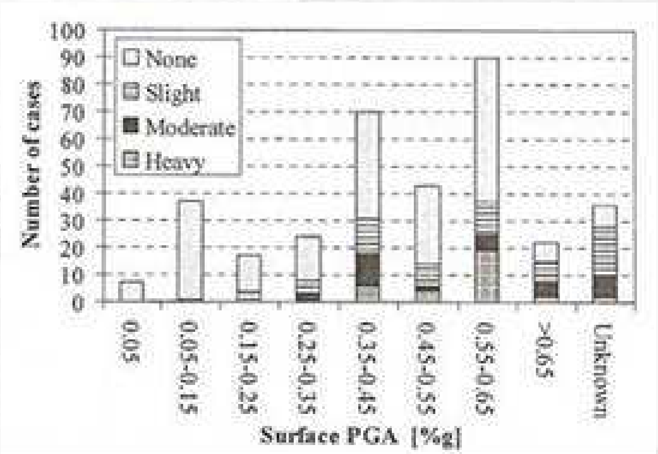
- *72 cases of damage to tunnels*
- *3 damage levels (class A, class B, class C)*
- *Link between tunnel damage and peak ground acceleration PGA (or velocity PGV)*
- *0.2g is the limit between class A and B*
- *0.5g is the limit between class B and C*
- *Severe damage occurred only during strong earthquakes*
- *The underground structures are safer than above-ground structure during a seismic event (lateral confinement)*

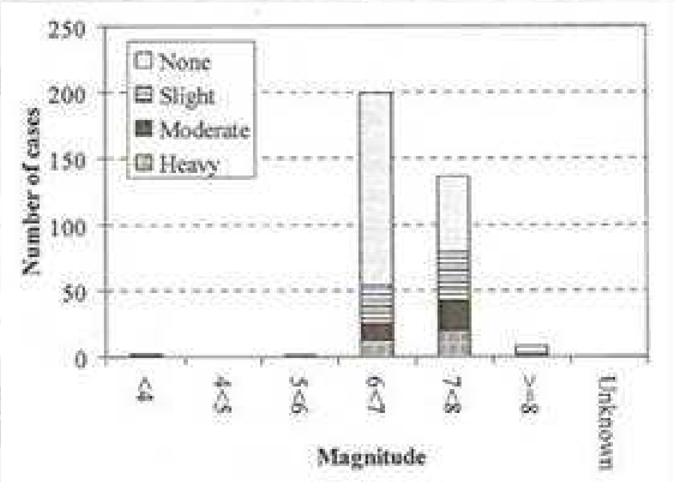
Seismic parameters affecting the damage (3/4)

Sharma & Judd (1991)

- *191 cases of damage to tunnels*
- *4 damage levels (none, slight, moderate and heavy)*
- *Three parameters of seismic signal were used to classify all the cases (PGA, epicentral distance, magnitude)*
- *Severe damage occurred when the magnitude is higher than 6 and for epicentral distance lower than 25 km*
- *Severe damage occurs for PGA value higher than 0.55g (severe earthquake)*



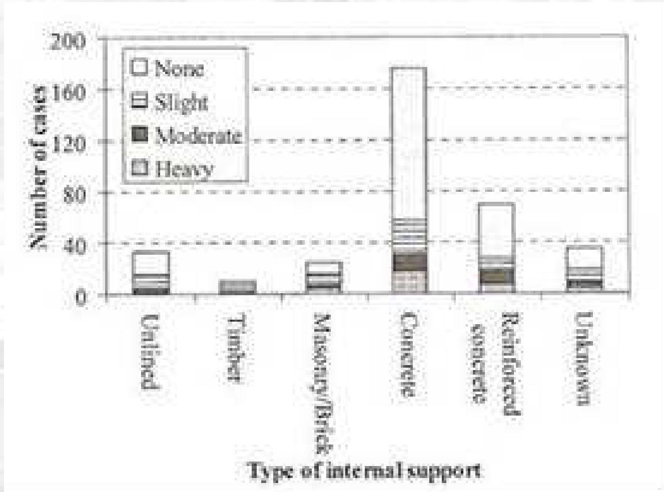


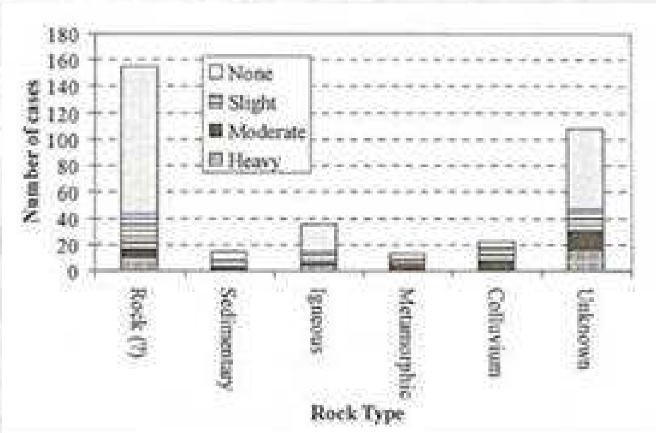


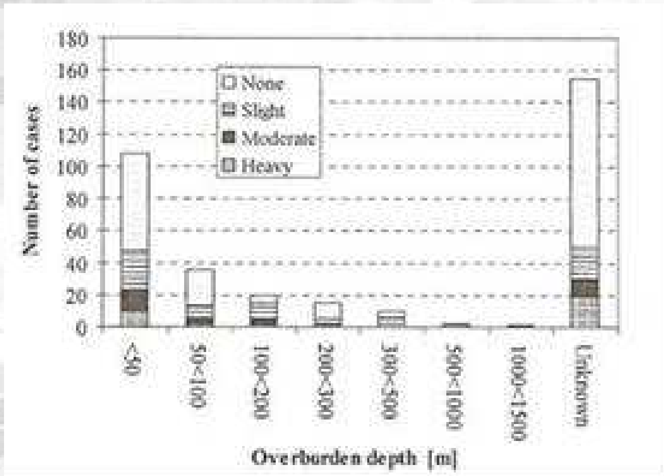
Seismic parameters affecting the damage (4/4)

Sharma & Judd (1991)

- *191 cases of damage to tunnels*
- *4 damage level (none, slight, moderate and heavy)*
- *Three soil/structure parameters were used to classify all the cases (type of internal support, soil type, overburden depth)*
- *Severe damage occurred for shallow tunnels (under 50m)*
- *The graphs relative to rock and lining type do not clarify the influence of relative stiffness between soil and lining*







Type of cracks (1/9)

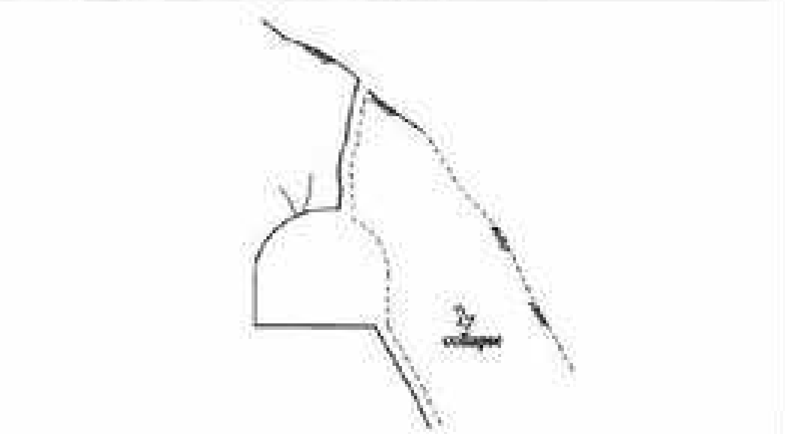
a) Sheared off lining

Possible factors
Passing through fault zones
Unfavourable ground conditions
Interface hard-soft ground
Nearby slope surface and portals
Collapse during construction
Lining cracks before earthquake
Poor structural arrangements
Un-reinforced concrete lining
Deteriorated lining material
Cavity existed behind lining

Wang et al. (2001)

Type of cracks (2/9)

b) Slopes failure induced tunnel collapse



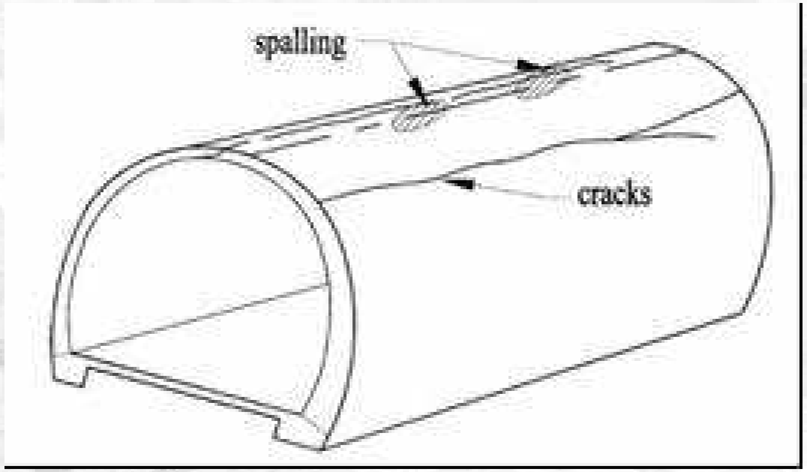
Possible factors

- *Passing through fault zones*
- *Unfavourable ground conditions*
- *Interface hard-soft ground*
- ***Nearby slope surface and portals***
- *Collapse during construction*
- *Lining cracks before earthquake*
- *Poor structural arrangements*
- *Un-reinforced concrete lining*
- *Deteriorated lining material*
- *Cavity existed behind lining*

Wang et al. (2001)

Type of cracks (3/9)

c) Longitudinal cracks



Possible factors

Passing through fault zones

Unfavourable ground conditions

Interface hard-soft ground

Nearby slope surface and portals

Collapse during construction

Lining cracks before earthquake

Poor structural arrangements

Un-reinforced concrete lining

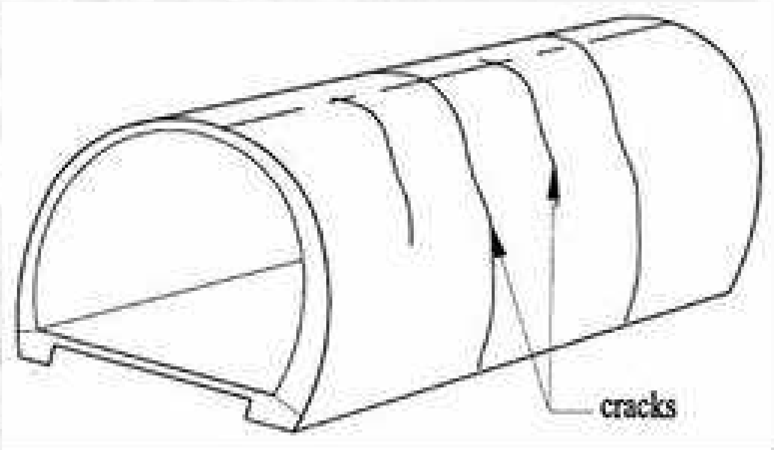
Deteriorated lining material

Cavity existed behind lining

Wang et al. (2001)

Type of cracks (4/9)

d) Transverse cracks



Possible factors

Passing through fault zones

Unfavourable ground conditions

Interface hard-soft ground

Nearby slope surface and portals

Collapse during construction

Lining cracks before earthquake

Poor structural arrangements

Un-reinforced concrete lining

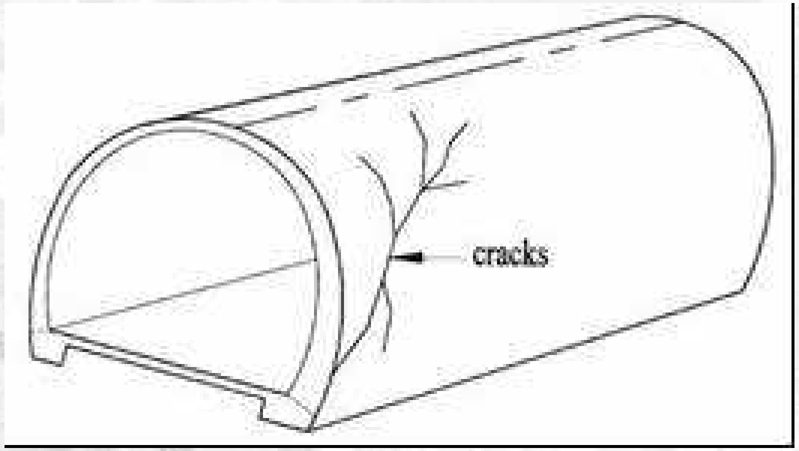
Deteriorated lining material

Cavity existed behind lining

Wang et al. (2001)

Type of cracks (5/9)

e) Inclined cracks



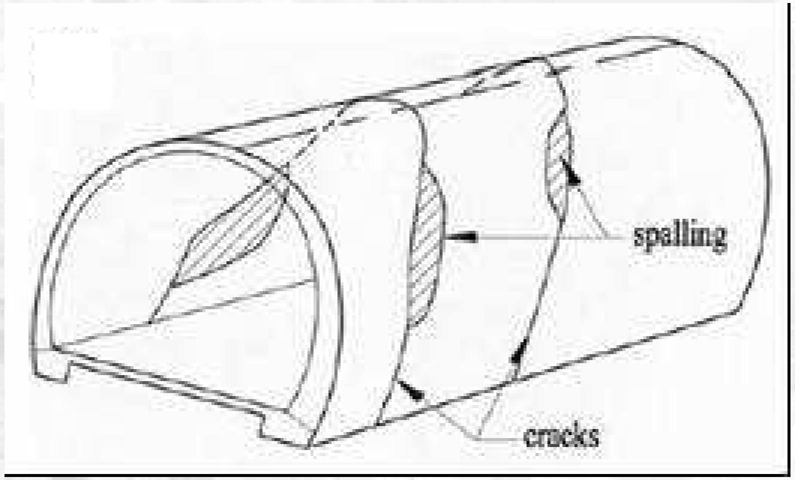
Possible factors

Possible factors
Passing through fault zones
Unfavourable ground conditions
Interface hard-soft ground
Nearby slope surface and portals
Collapse during construction
Lining cracks before earthquake
Poor structural arrangements
Un-reinforced concrete lining
Deteriorated lining material
Cavity existed behind lining

Wang et al. (2001)

Type of cracks (6/9)

f) Extended cracks



Possible factors

Possible factors
Passing through fault zones
Unfavourable ground conditions
Interface hard-soft ground
Nearby slope surface and portals
Collapse during construction
Lining cracks before earthquake
Poor structural arrangements
Un-reinforced concrete lining
Deteriorated lining material
Cavity existed behind lining

Wang et al. (2001)

Type of cracks (7/9)

g) Wall deformation

Possible factors

Passing through fault zones

Unfavourable ground conditions

Interface hard-soft ground

Nearby slope surface and portals

Collapse during construction

Lining cracks before earthquake

Poor structural arrangements

Un-reinforced concrete lining

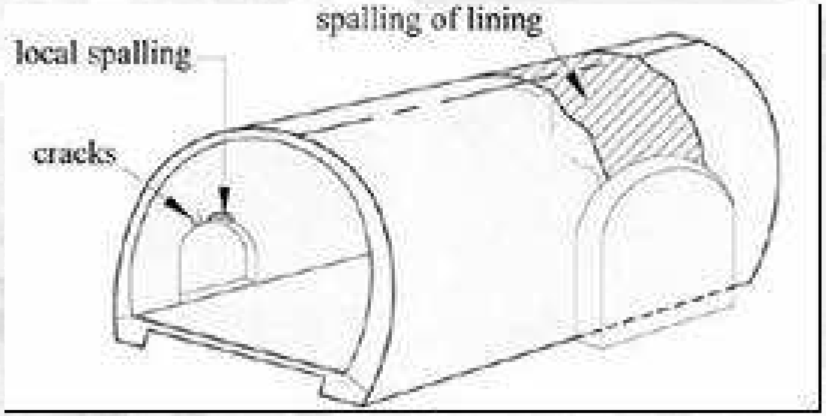
Deteriorated lining material

Cavity existed behind lining

Wang et al. (2001)

Type of cracks (8/9)

h) Spalling of lining



Possible factors
Passing through fault zones
Unfavourable ground conditions
Interface hard-soft ground
Nearby slope surface and portals
Collapse during construction
Lining cracks before earthquake
Poor structural arrangements
Un-reinforced concrete lining
Deteriorated lining material
Cavity existed behind lining

Wang et al. (2001)

Type of cracks (9/9)

Possible factors	a	b	c	d	e	f	g	h
Passing through fault zones	decisive							
Unfavourable ground conditions				decisive		decisive		
Interface hard-soft ground						decisive		
Nearby slope surface and portals		decisive		decisive	decisive	decisive		
Collapse during construction			weak		weak		weak	
Lining cracks before earthquake			weak	weak				
Poor structural arrangements				weak	weak			decisive
Unreinforced concrete lining	weak	weak		weak	weak	weak	weak	decisive
Deteriorated lining material			weak	weak				
Cavity existed behind lining			decisive		weak			

Summary of crack types:

a) *Sheared off lining*

b) *Slopes failure induced tunnel collapse*

c) ***Longitudinal cracks***

d) ***Tranverse cracks***

e) ***Inclined cracks***

f) ***Extended cracks***

g) ***Wall deformation***

h) ***Spalling of lining***

● *decisive link*

● *weak link*

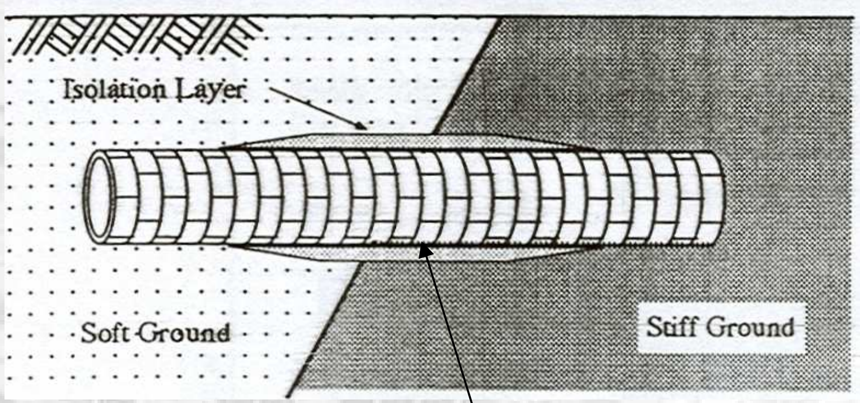
Wang et al. (2001)

Seismic protection methods against damages due to ground shaking

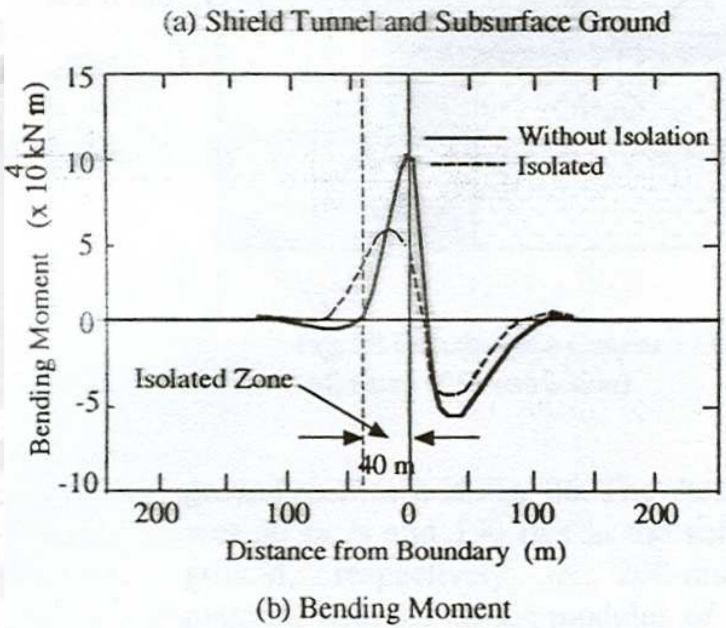
Seismic flexible joints

Joint design:

1. *Differential movement allowed*
2. *Static and dynamic loads*
3. *Water tightness*



Steel or rubber plate



Bending moment reduction (Kawashima, 2000)

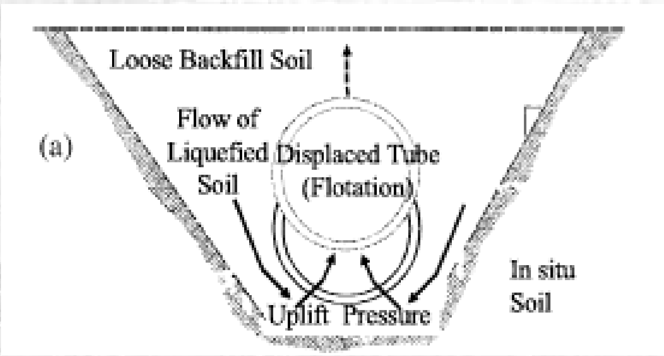
Seismic protection methods

GROUND FAILURE

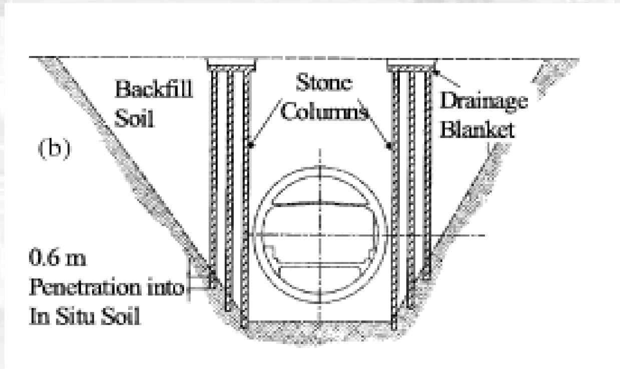
Ground conditions:
- ***Tunnel and tubes in liquefiable soils;***
- ***Tunnel and tubes near slopes***

Solutions against seismic action:
- ***Tunnel relocation***
- ***Stabilization, drainage, soil reinforcements, earth retaining (for slopes)***
- ***Cut-off walls (sheet piles, stone or jet grout columns)***

Flotation mechanism due to liquefaction



Isolation with stone columns



Barrier walls reduce the rise of excess pore pressure in the ground and make the underground structure wider and the uplift more difficult (Schmidt & Hashash, 1999)

Summary of seismic tunnel behaviour

1. *Underground structures suffer minor damage compared to above-ground structures.*
2. *Deep tunnels are safer compared to shallow tunnels;*
3. *Tunnels in soft soils suffer higher damage compared to structure in rock;*
4. *Damage degree increases with magnitude and peak ground acceleration and decreases with epicentral distance;*
5. *Water and gas supply system are more vulnerable compared to metro and road tunnels,*
6. *Most of the metro lines and roadway tunnels are only damaged by extremely severe earthquakes.*
7. *The flexible joints are an useful solution to accommodate differential movements and reduce the stress concentration at interface of material with different stiffness*

Thank you!