Nickolas Ambraseys Memorial Symposium

Deep Immersed Tunnel Subjected to Fault Rupture Deformation + Strong Seismic Shaking

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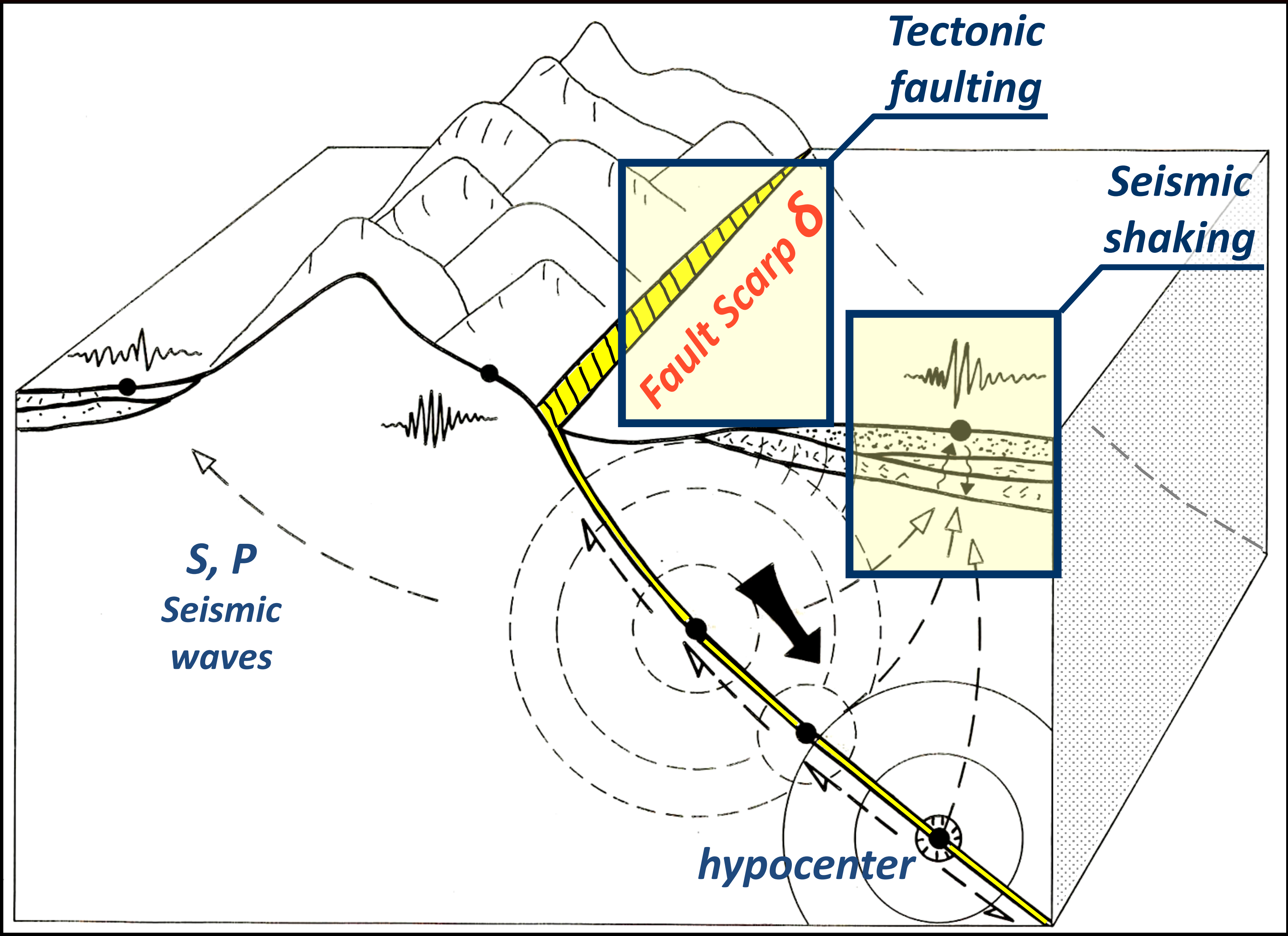
The two components of an Earthquake



The main question:

Can Immersed Tunnels be Designed to withstand a sequence of:

(a) a fault rupturing underneath

(b) strong seismic shaking

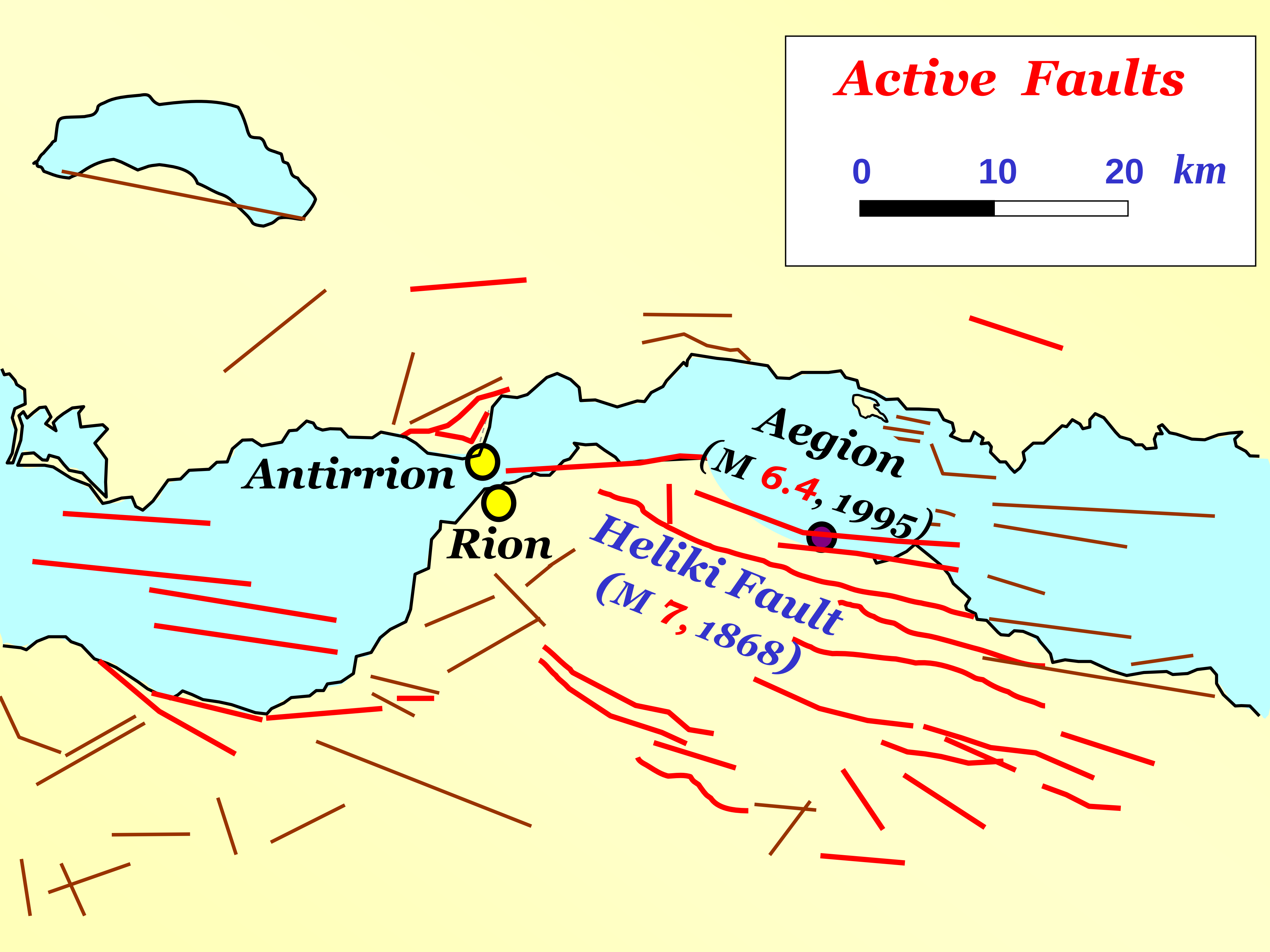

Thessaloniki
Rion–
Antirrion
Rail Link
Athens

The Rion – Antirrion Straits and the Rail Link

UNDER-SEA RAILWAY LINK

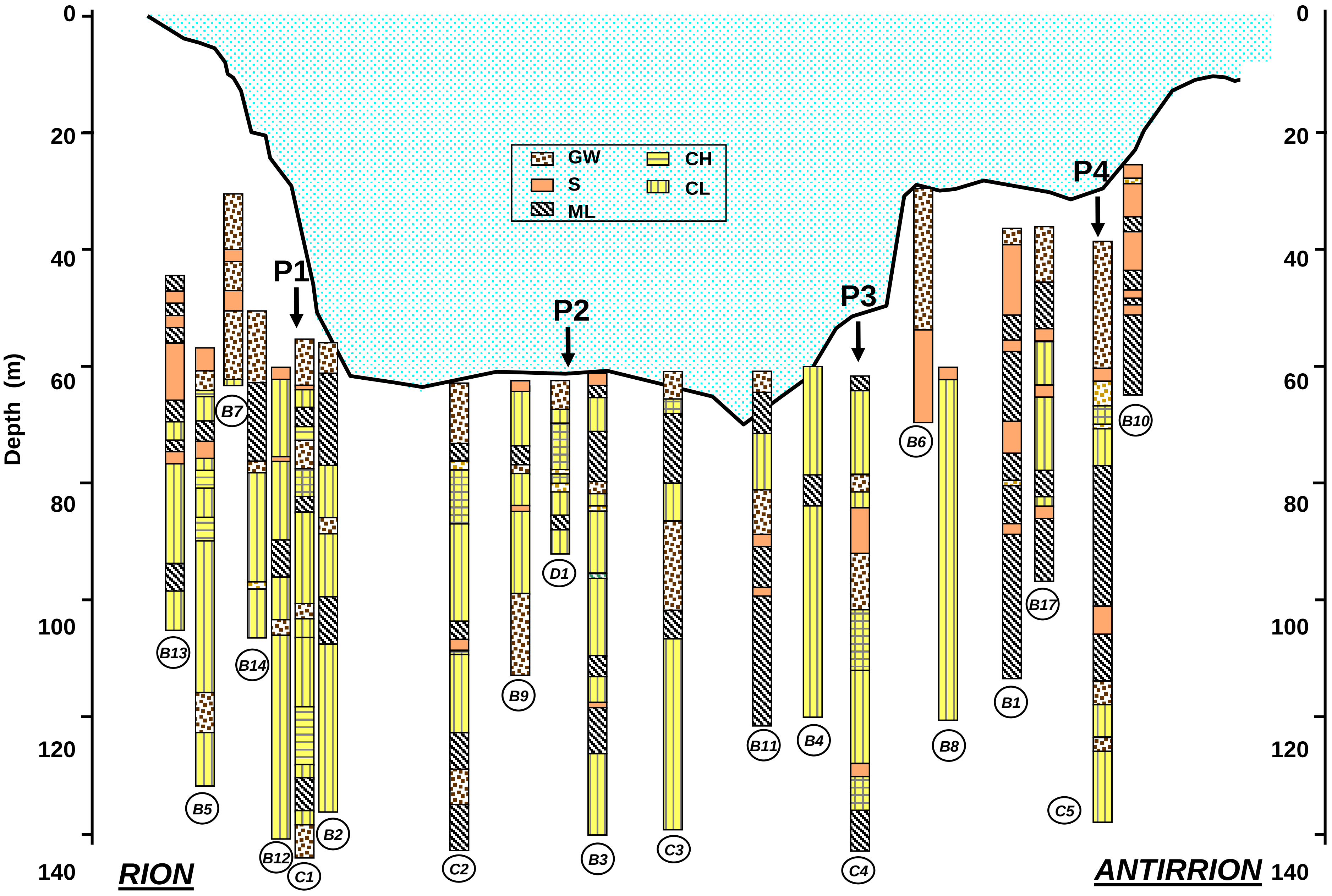
Difficult + Pioneering Project

- ***Great Water Depths: 65 – 70 m***
  for a total length of > 1 km
- ***Very High Seismicity (PGA > 0.50 g)***
- ***Soft Soils to large depths (> 60 m)***

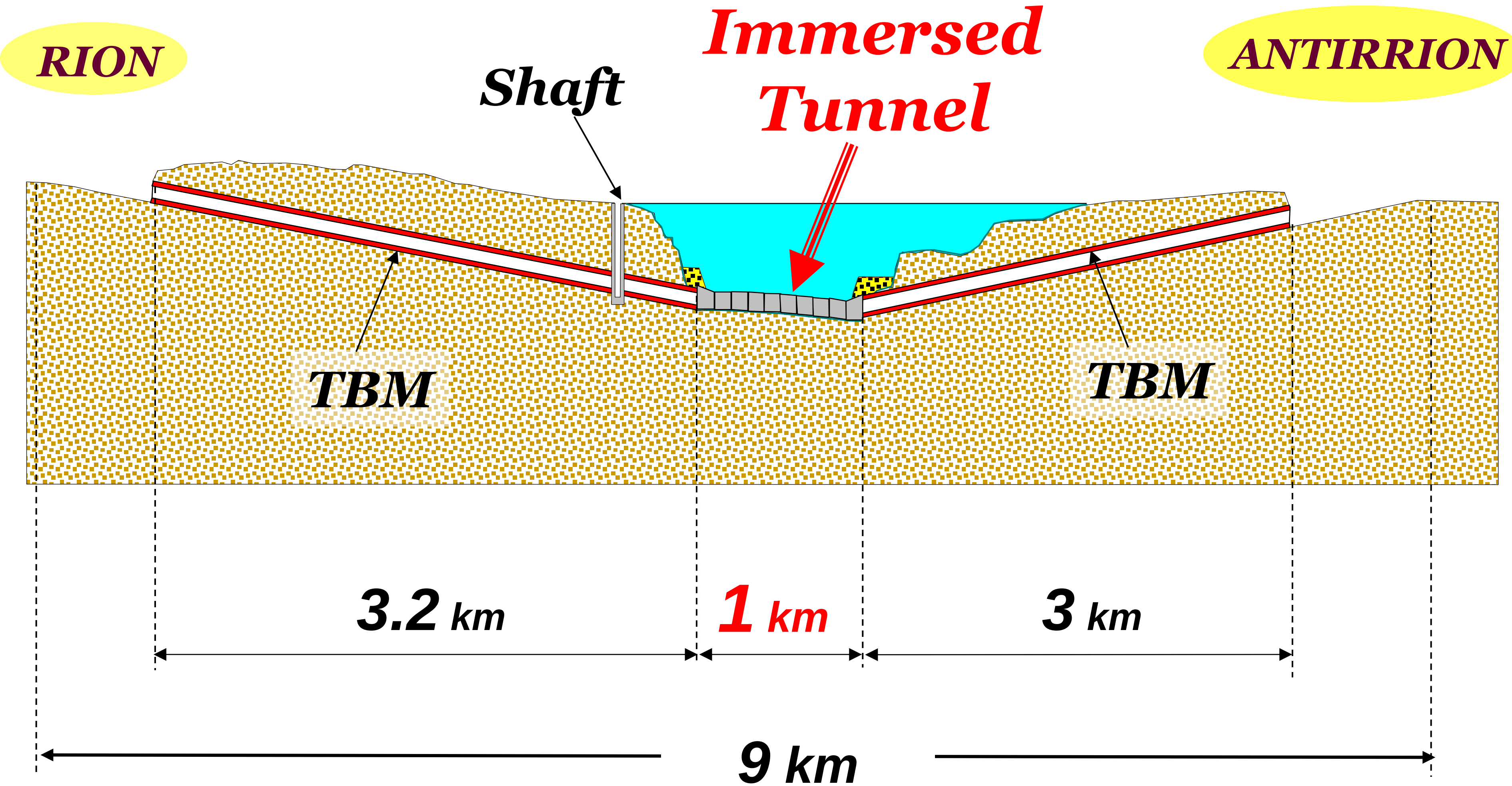


Active Faults
0
10
20
km
Antirrion
Rion
Aegion
(M 6.4, 1995)
Heliki Fault
(M 7, 1868)

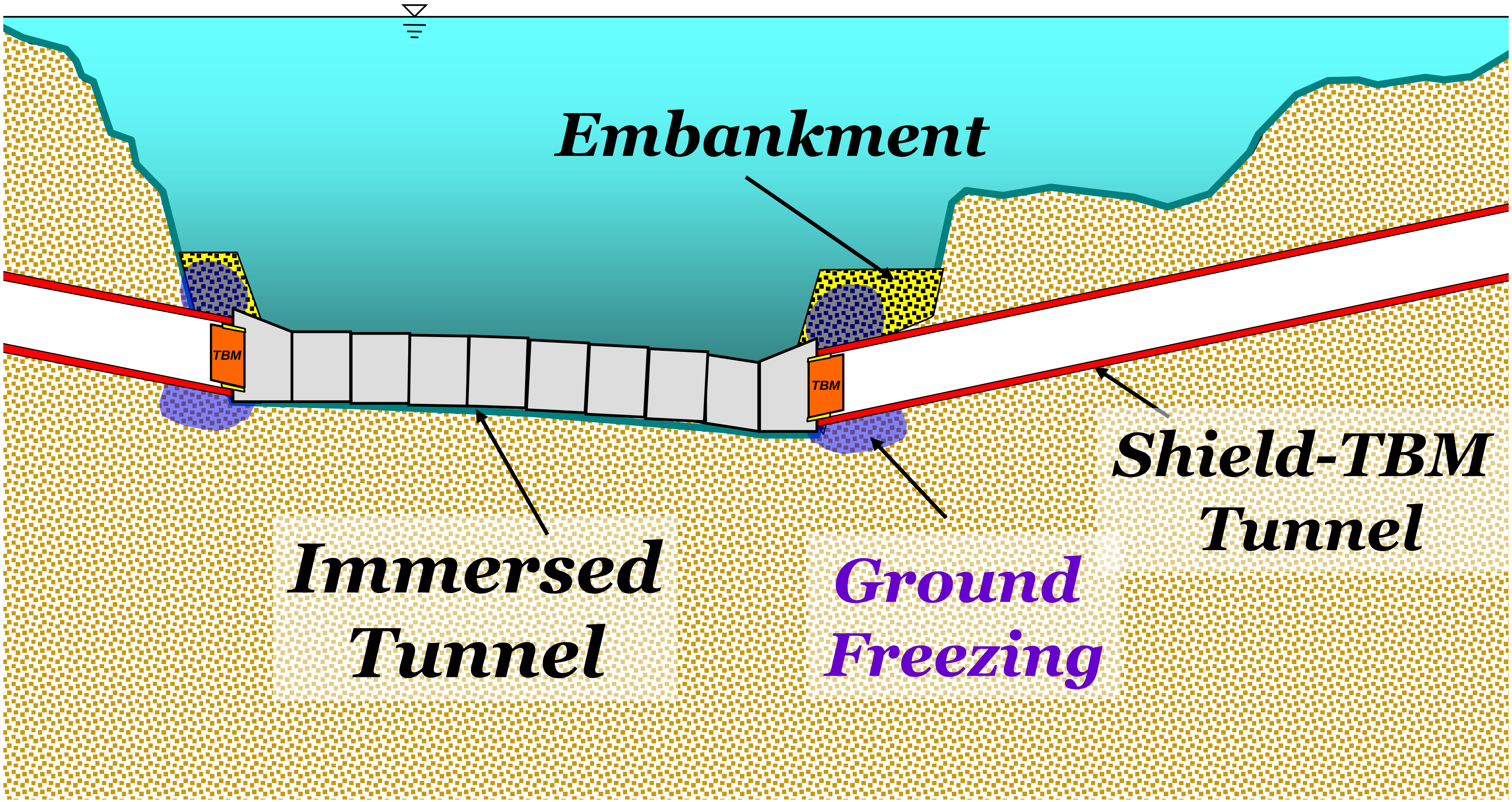
Borings near Tunnel axis



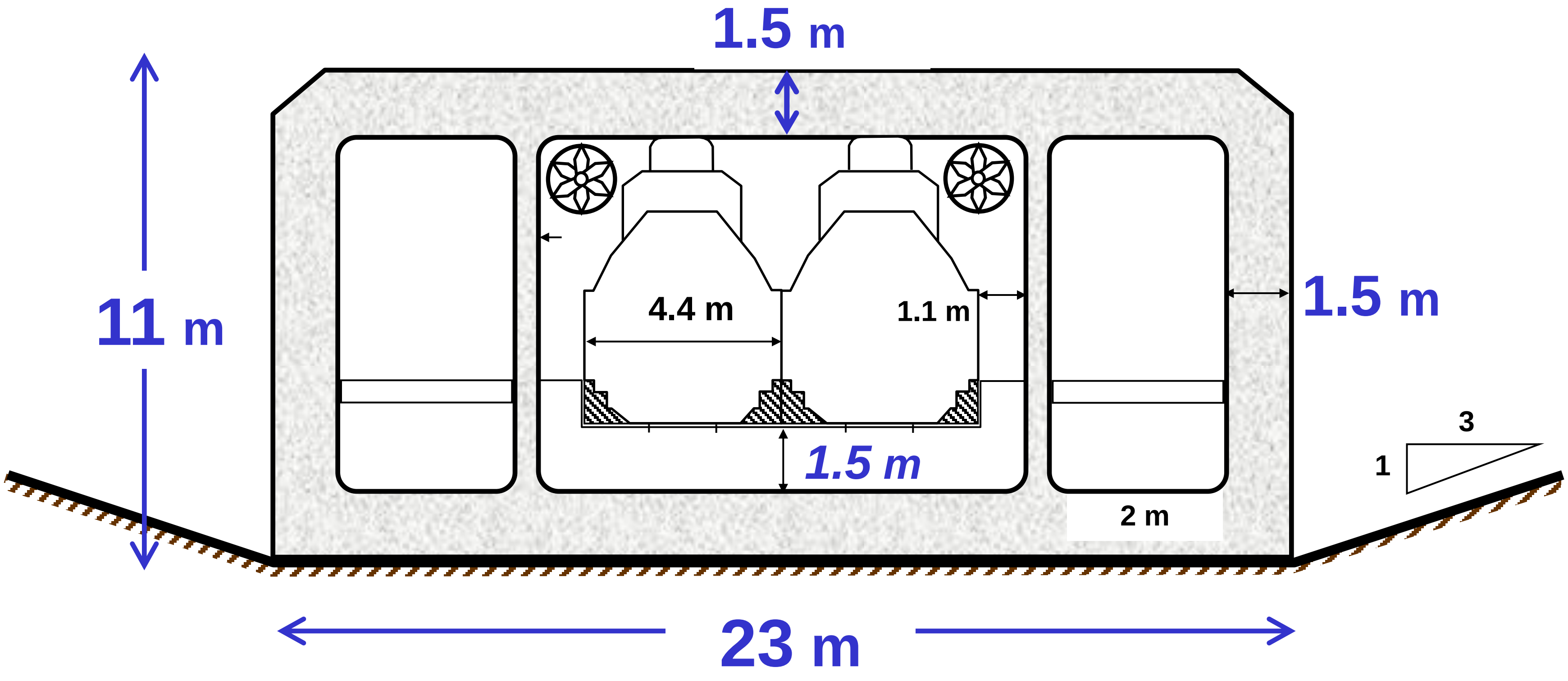
Combination of Immersed and TBM Tunnels



Immersed + TBM Tunnels



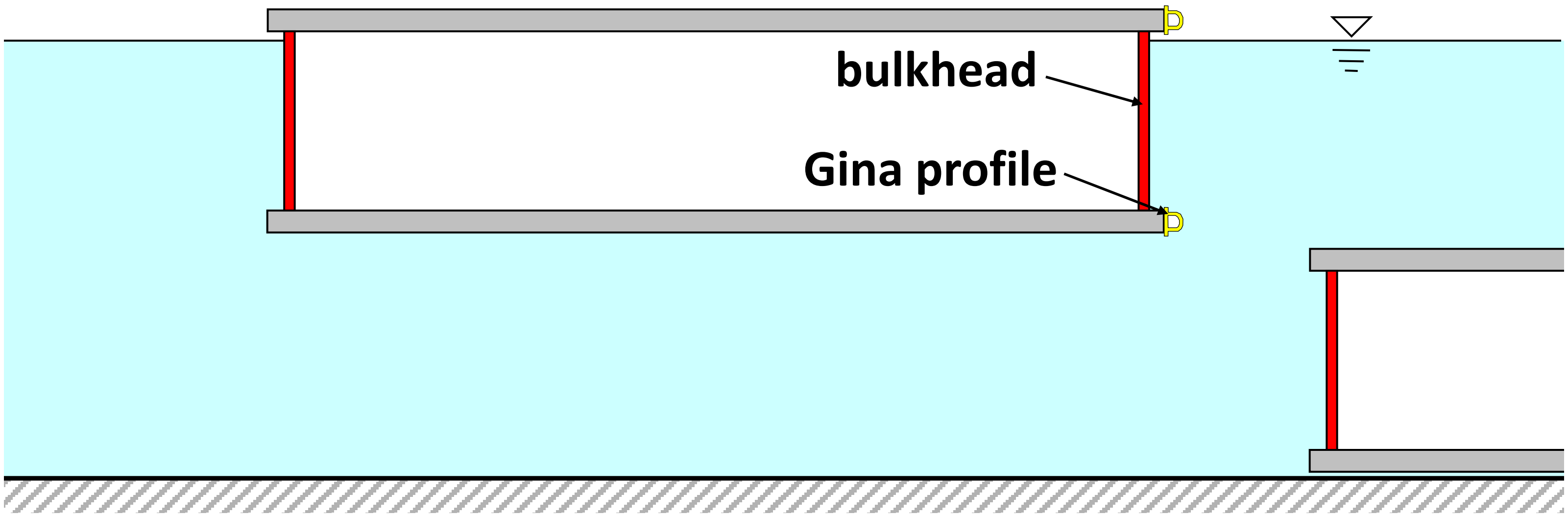
Immersed Tunnel Cross-section



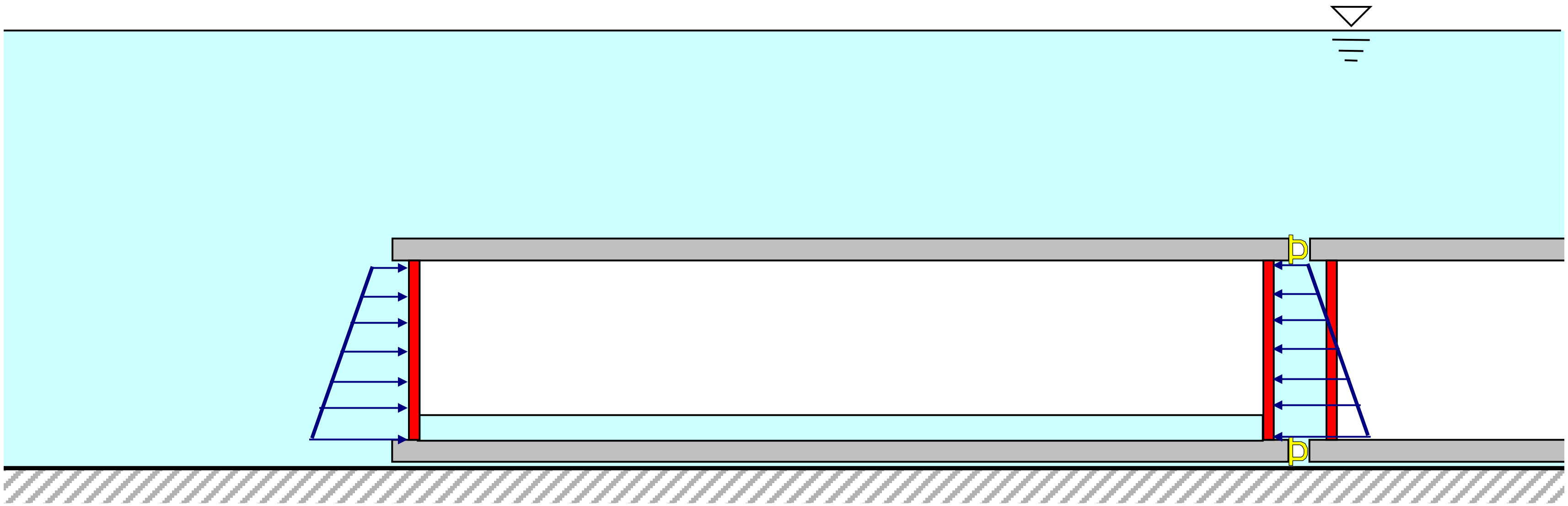
Towing

Immersion

The floating tunnel segment is towed close to the previously installed



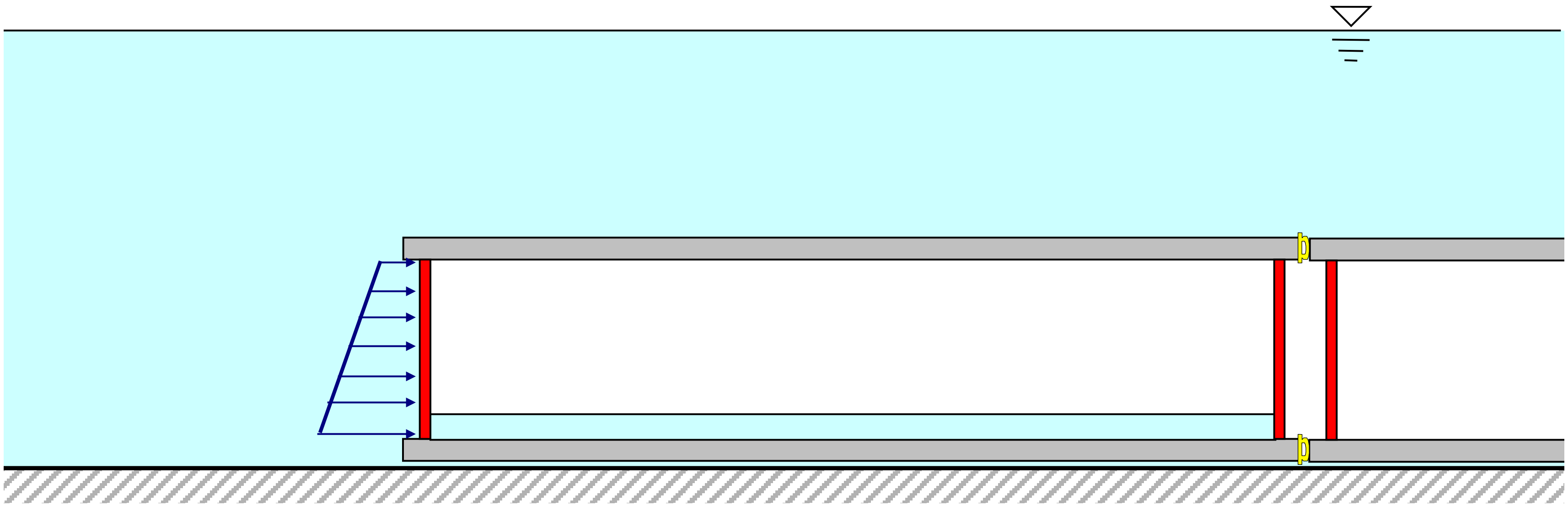
The tunnel segment is filled with water (or other type of ballast) and immersed



The hydrostatic pressures acting on the two bulkheads are equal

The Gina profile is not yet compressed

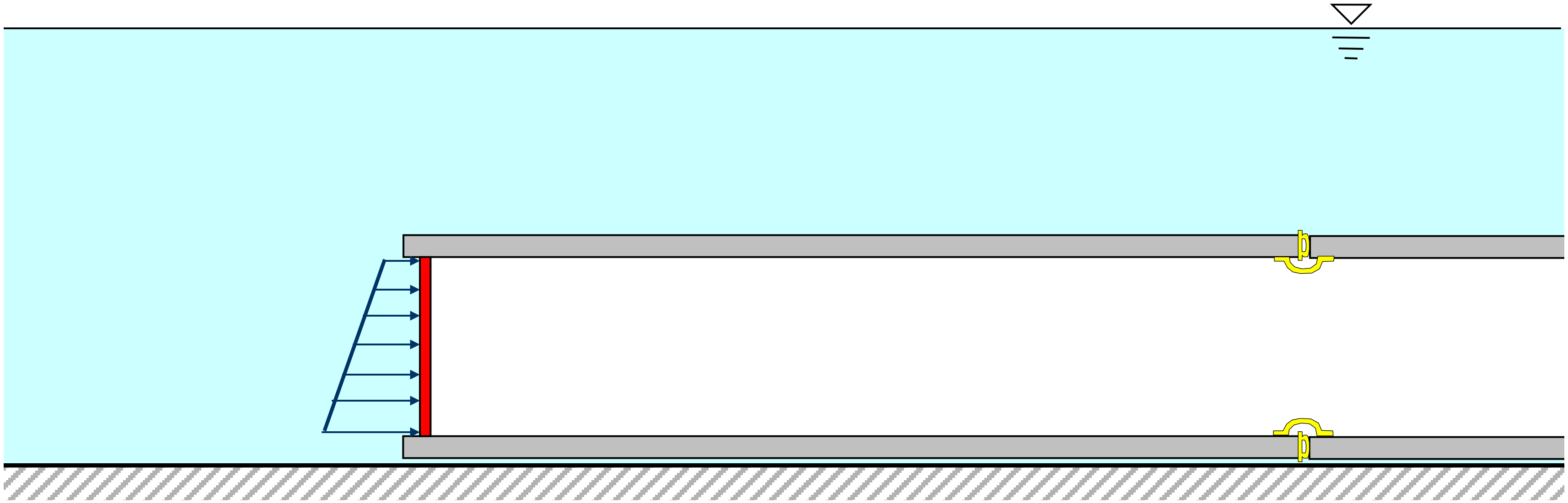
The water between the two bulkheads is pumped out



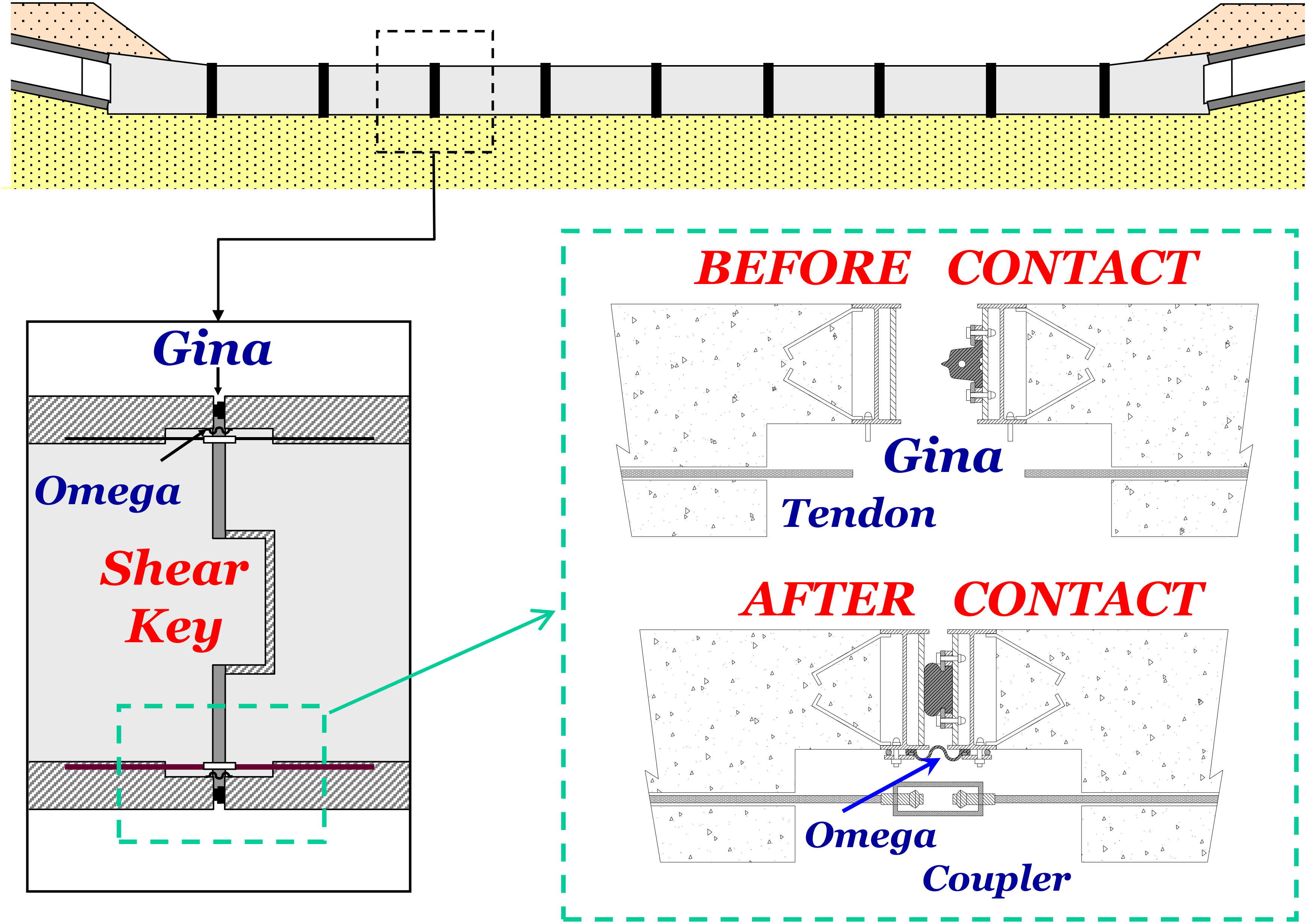
The hydrostatic pressure is now acting only on the left bulkhead

The Gina profile is compressed

The bulkhead is removed and the omega profile is installed



Critical Element: the Joints



Major Concerns:

Behaviour of Joints:

(a) Decompression of Gina Rubber

leading to:

net tension, . . joint opening,

. . . flooding

Behaviour of Joints:

(b) Additional Compression

leading to:

Failure of Rubber

in Lateral Tension

2 Types of Seismic Loading in the life of the tunnel :

(a) Quasi-STATIC:

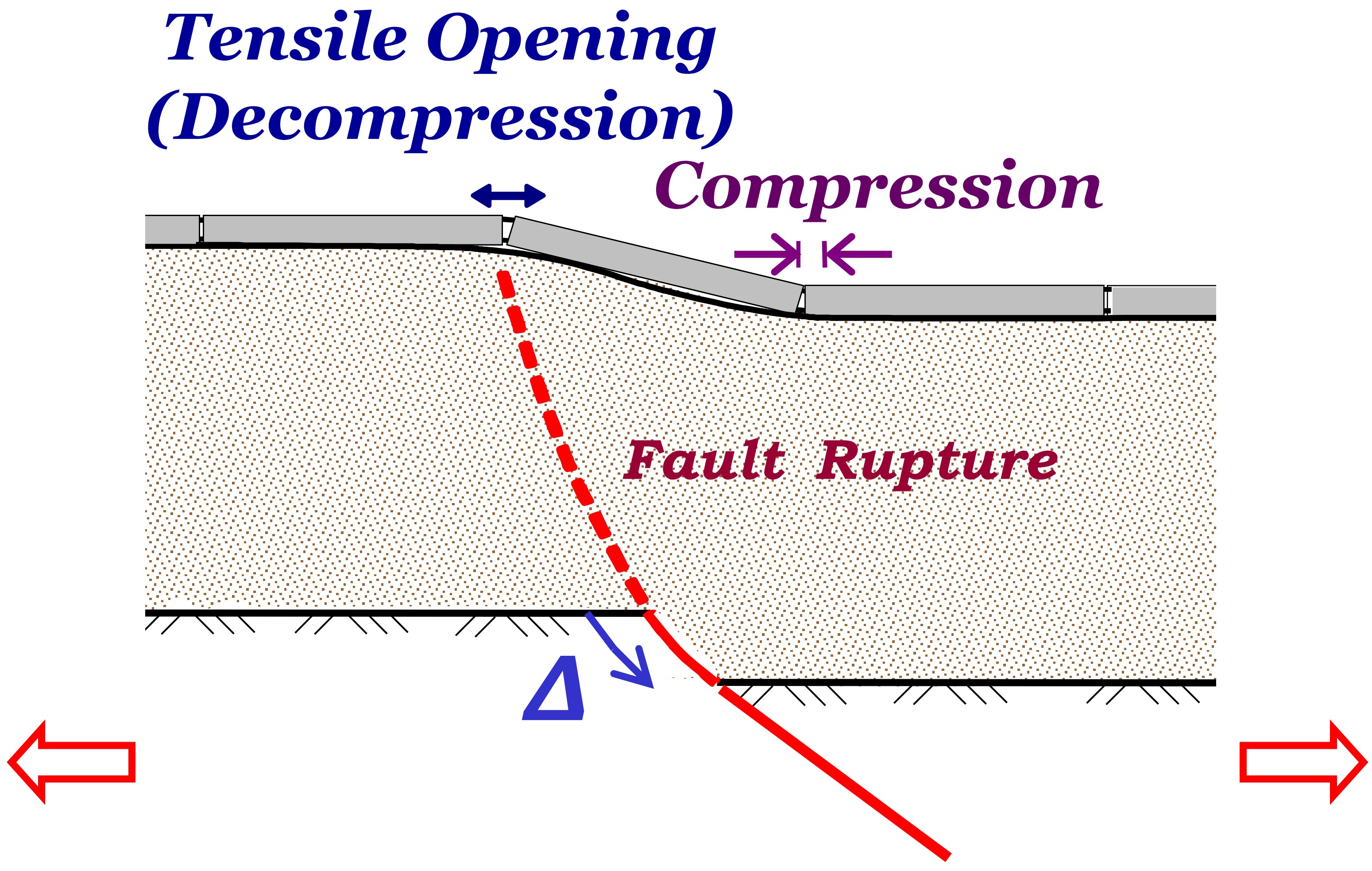
Fault Rupture Underneath , Imposes Deformation on the Surface

(b) DYNAMIC:

Seismic Shaking

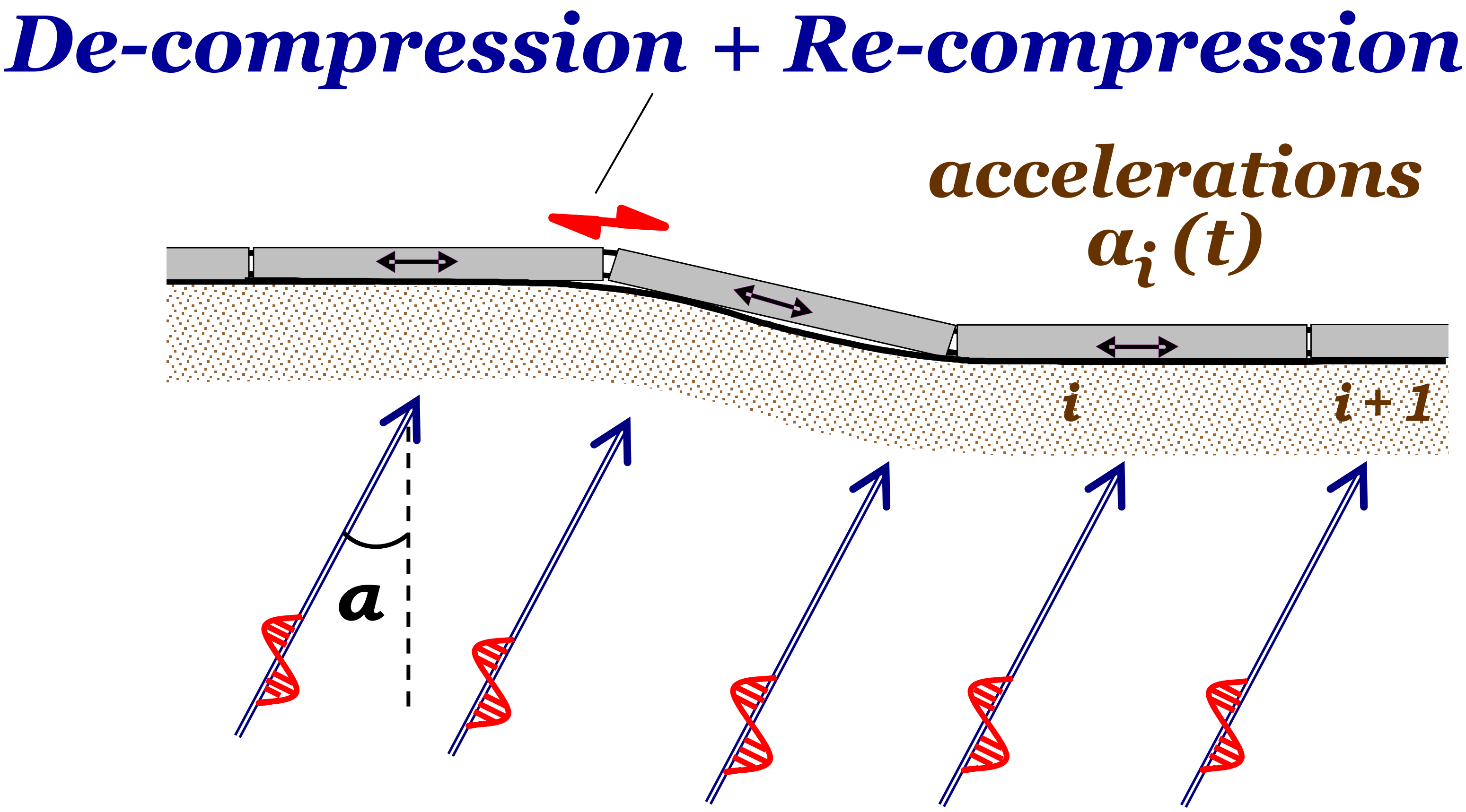
from Waves Propagating through Soil

(a) Quasi-STATIC:
Fault Rupture Imposed Deformation



(b) DYNAMIC:

Seismic Shaking



The two loading situations from
two different seismic events

which may occur many years apart

The Question is:

How will the "injured" tunnel
from the fault rupture
behave during a very strong
seismic shaking ??

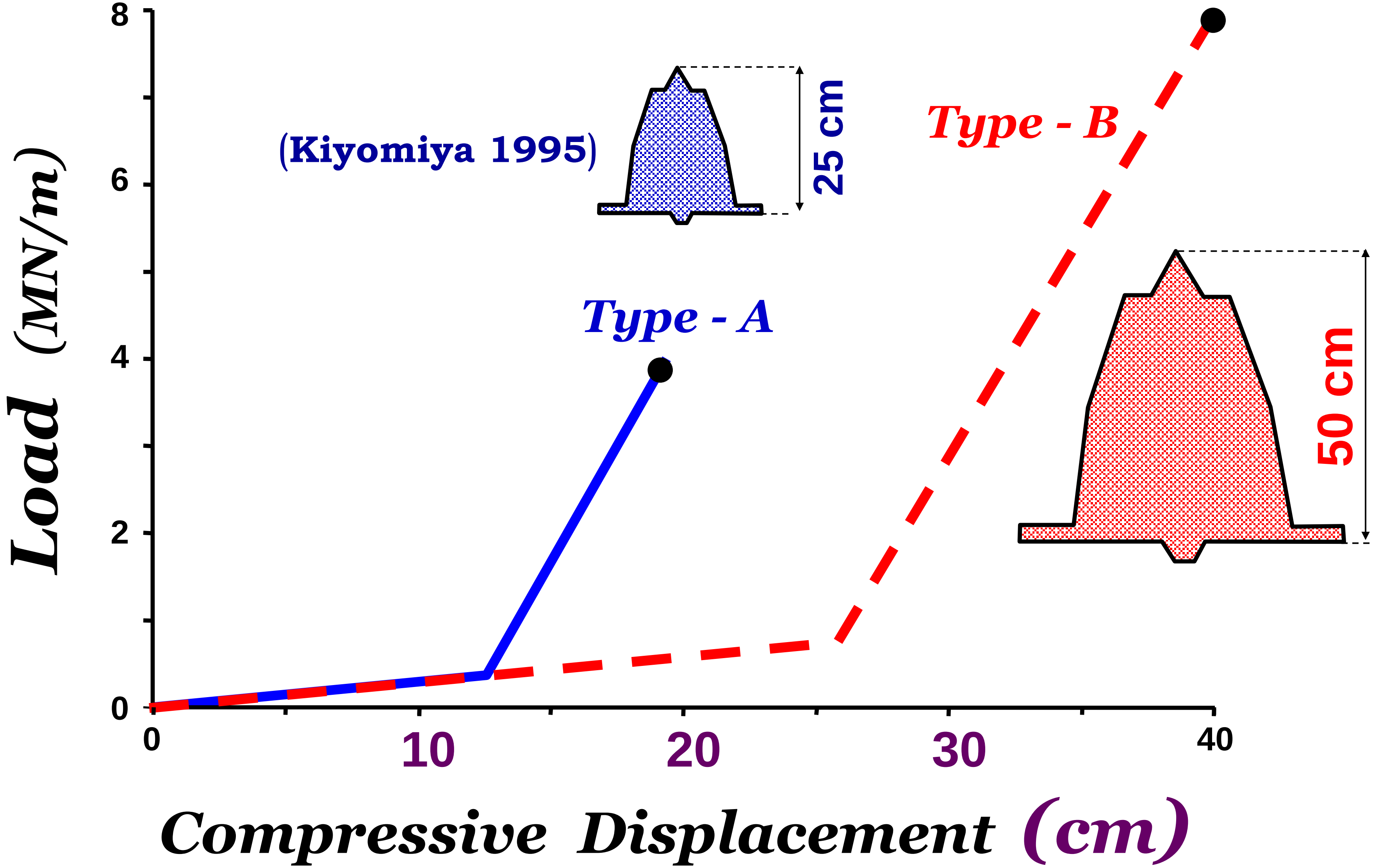
DESIGN SITUATIONS :

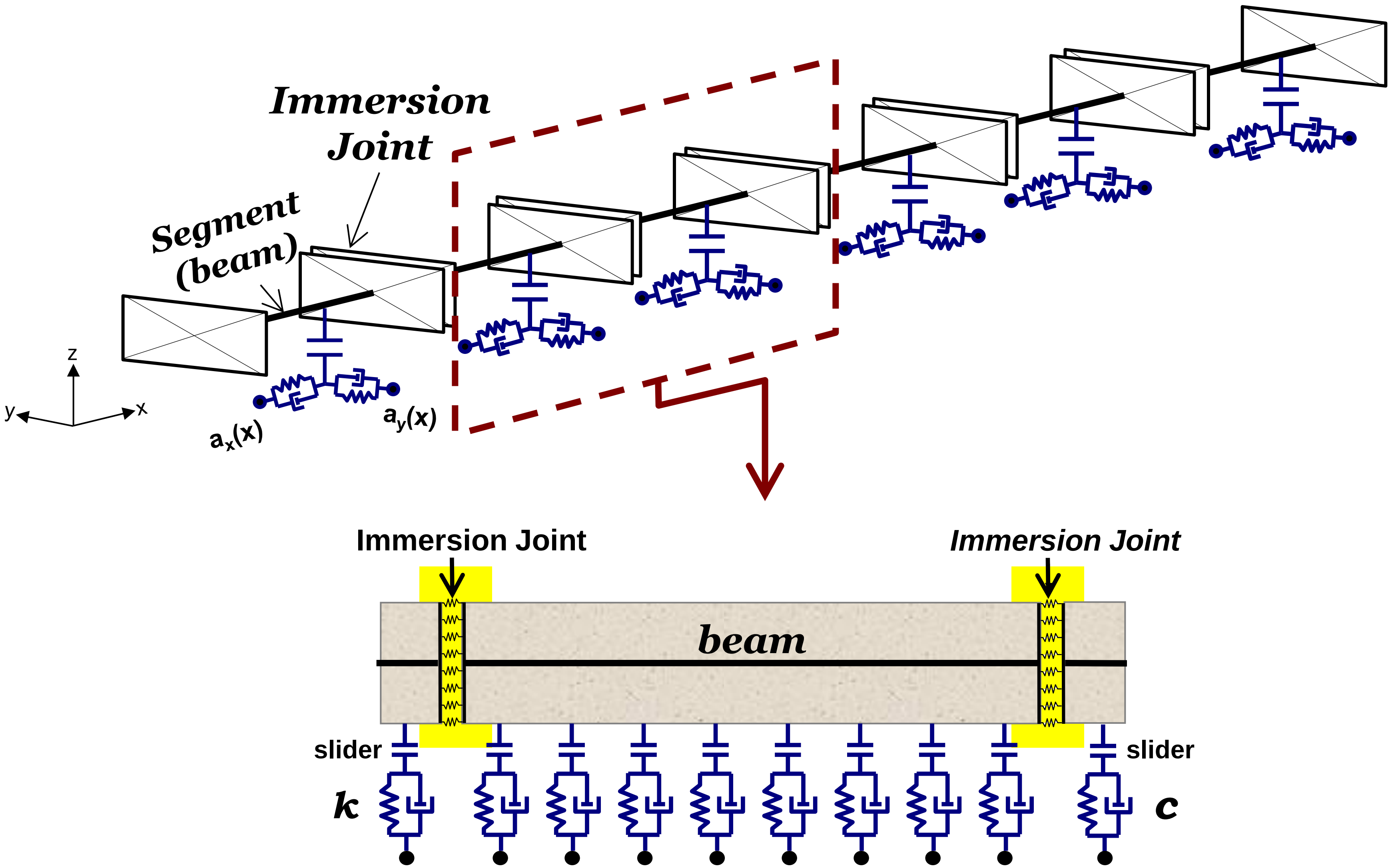
(a) "Dislocation" $\Delta \approx 3$ m at bedrock level

(b) - selected time histories from world-wide records with strong directivity effects (Kobe, Aegion, Rinaldi, Lefkada,…)

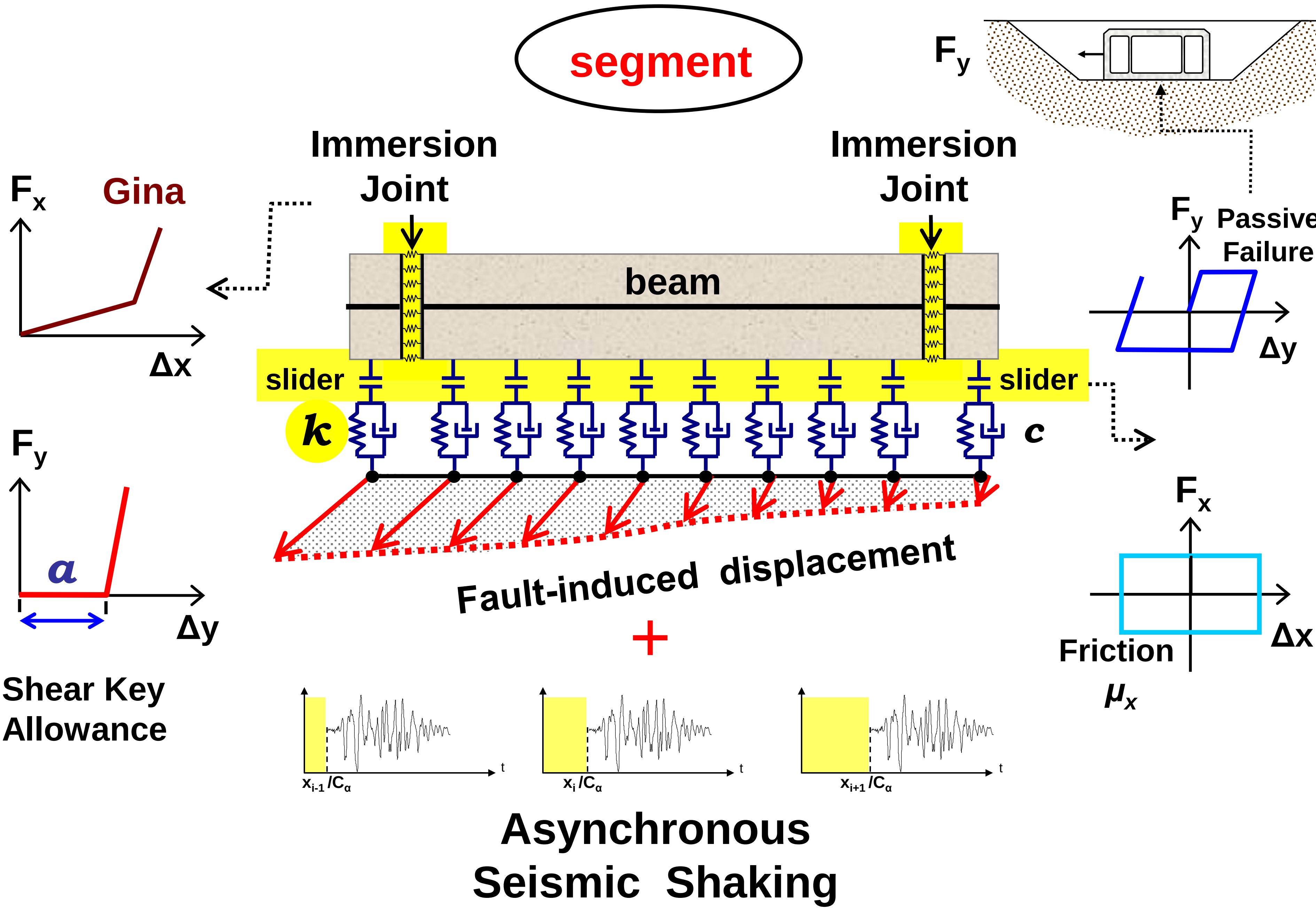
- all scaled to PGA ≈ 0.24 g at bedrock level

GINA Hyperelastic Behaviour





Immersion Joint
Segment (beam)
z
y
x
$a_x(x)$
$a_y(x)$
Immersion Joint
Immersion Joint
beam
slider
slider
k
c



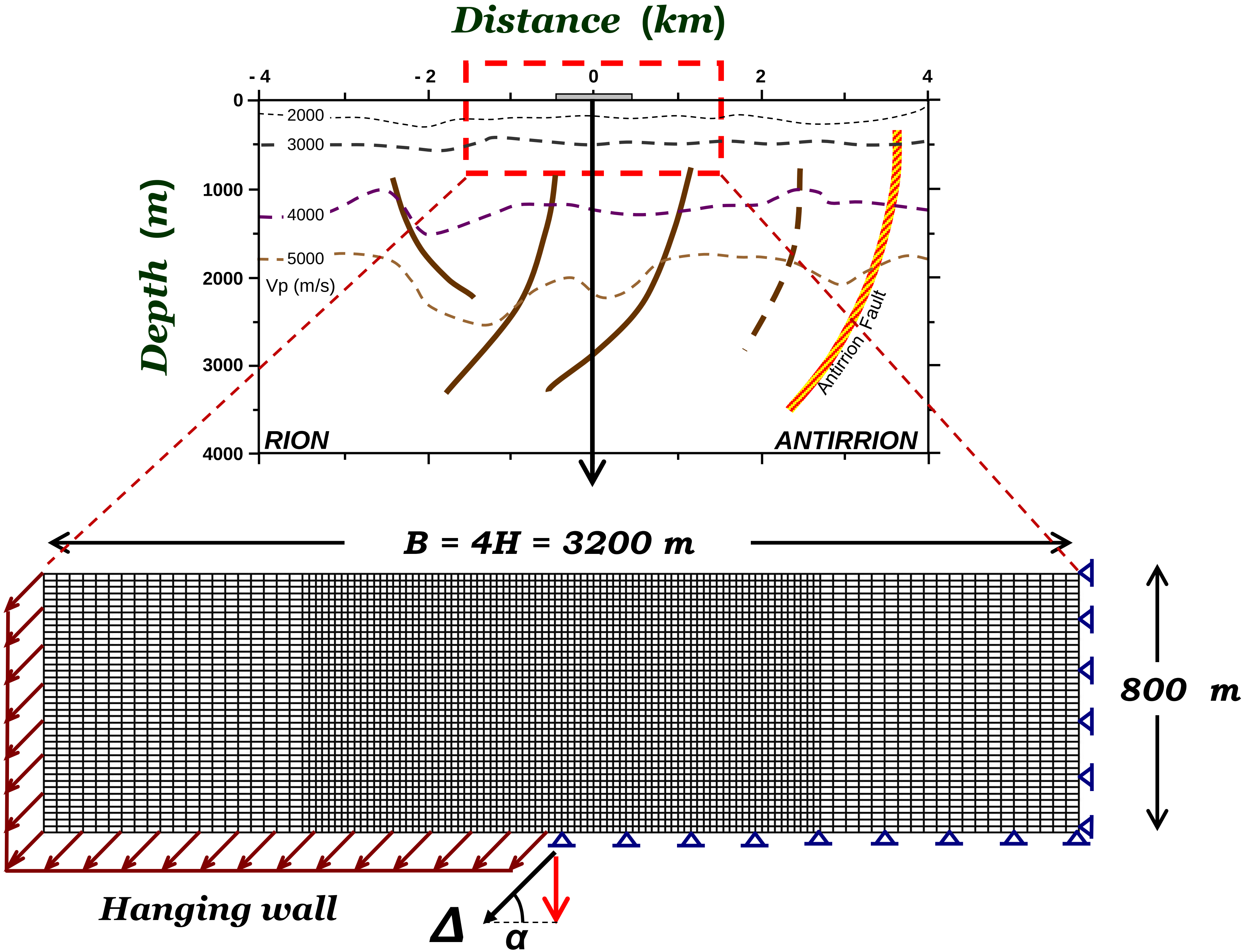
segment
Immersion Joint
Immersion Joint
beam
slider
slider
k
c
Fx
Gina
Δx
Fy
a
Δy
Shear Key Allowance
Fy
Fy
Passive Failure
Δy
Fx
Δx
Friction
μx
Fault-induced displacement
+
x_{i-1}/C_α
x_i/C_α
x_{i+1}/C_α
t
Asynchronous Seismic Shaking

(a)

Dislocation

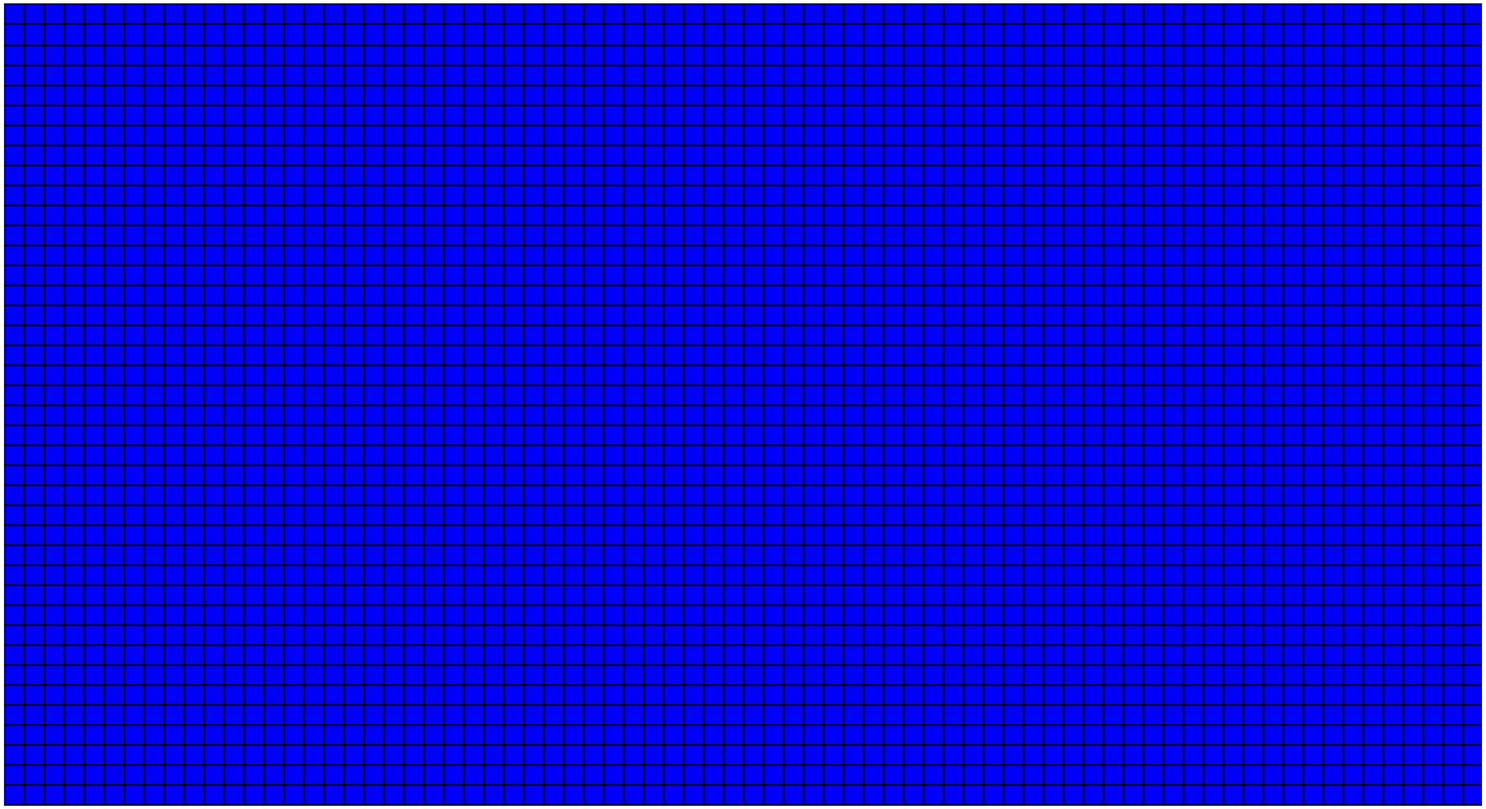
$\Delta \approx 3\ m$

at bedrock level

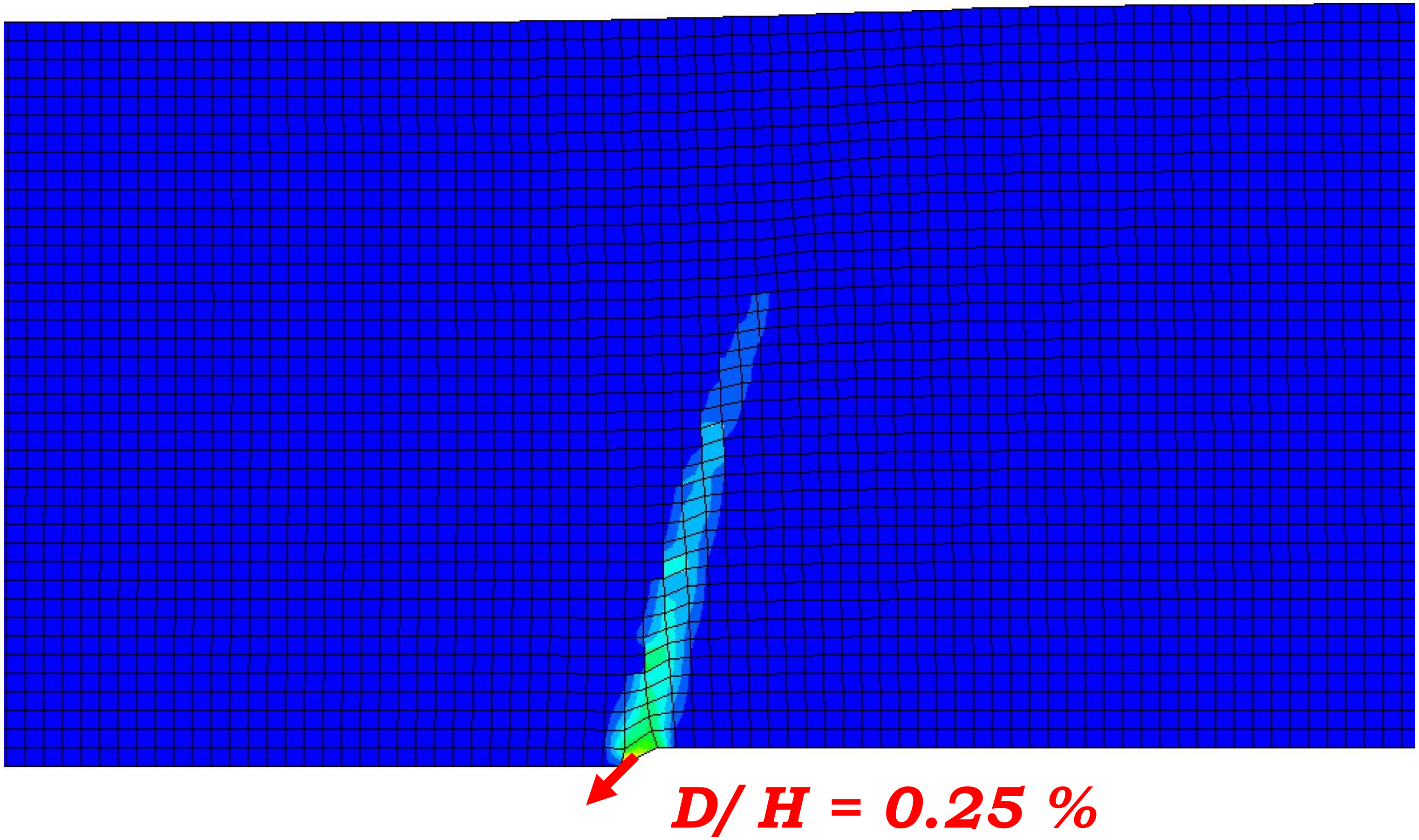


Distance (km)
- 4
- 2
0
2
4
0
1000
2000
3000
4000
Depth (m)
2000
3000
4000
5000
Vp (m/s)
Antirrion Fault
RION
ANTIRRION
B = 4H = 3200 m
800 m
Hanging wall
Δ
α

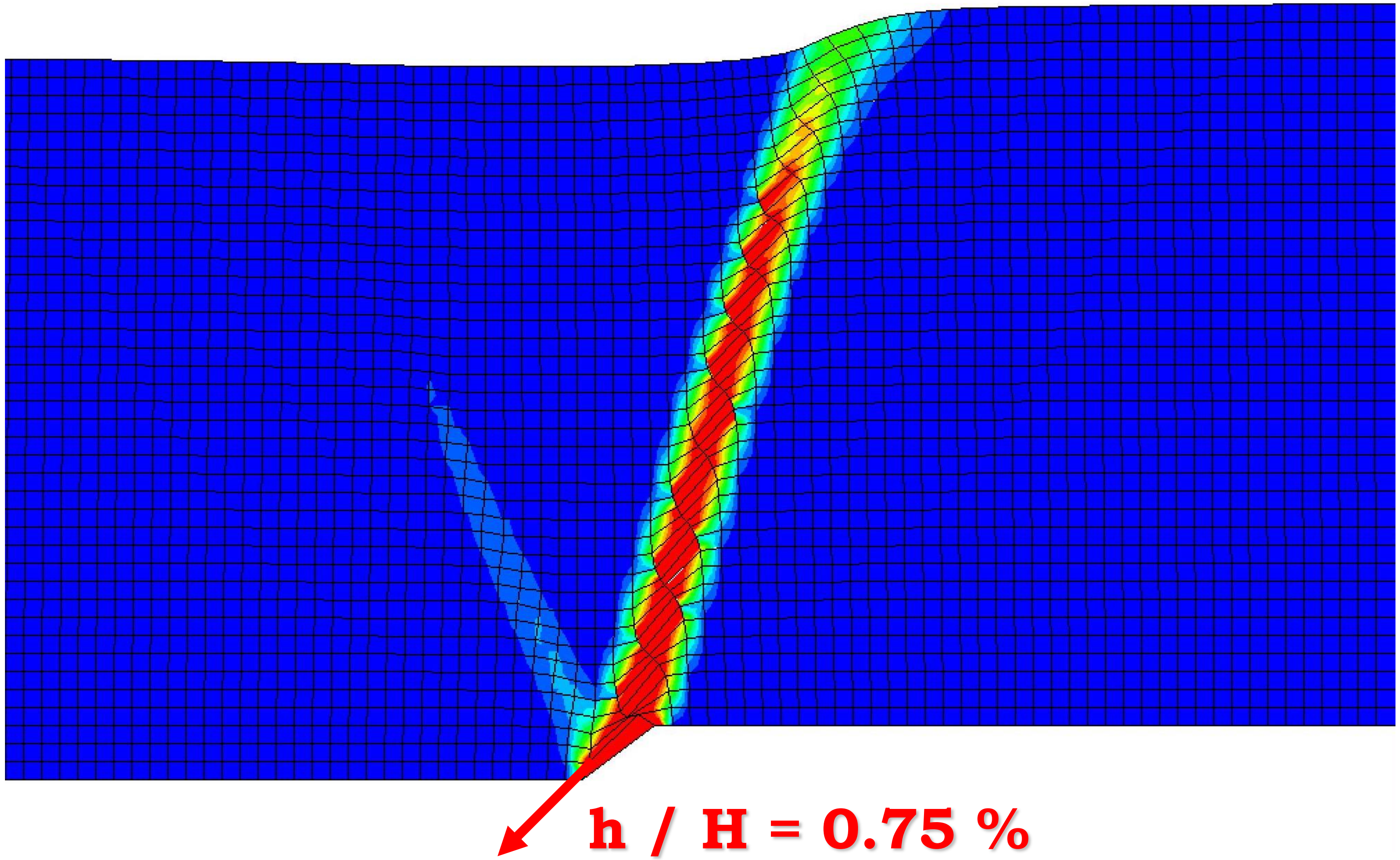
Normal Faulting on Dense Sand , α = 45°



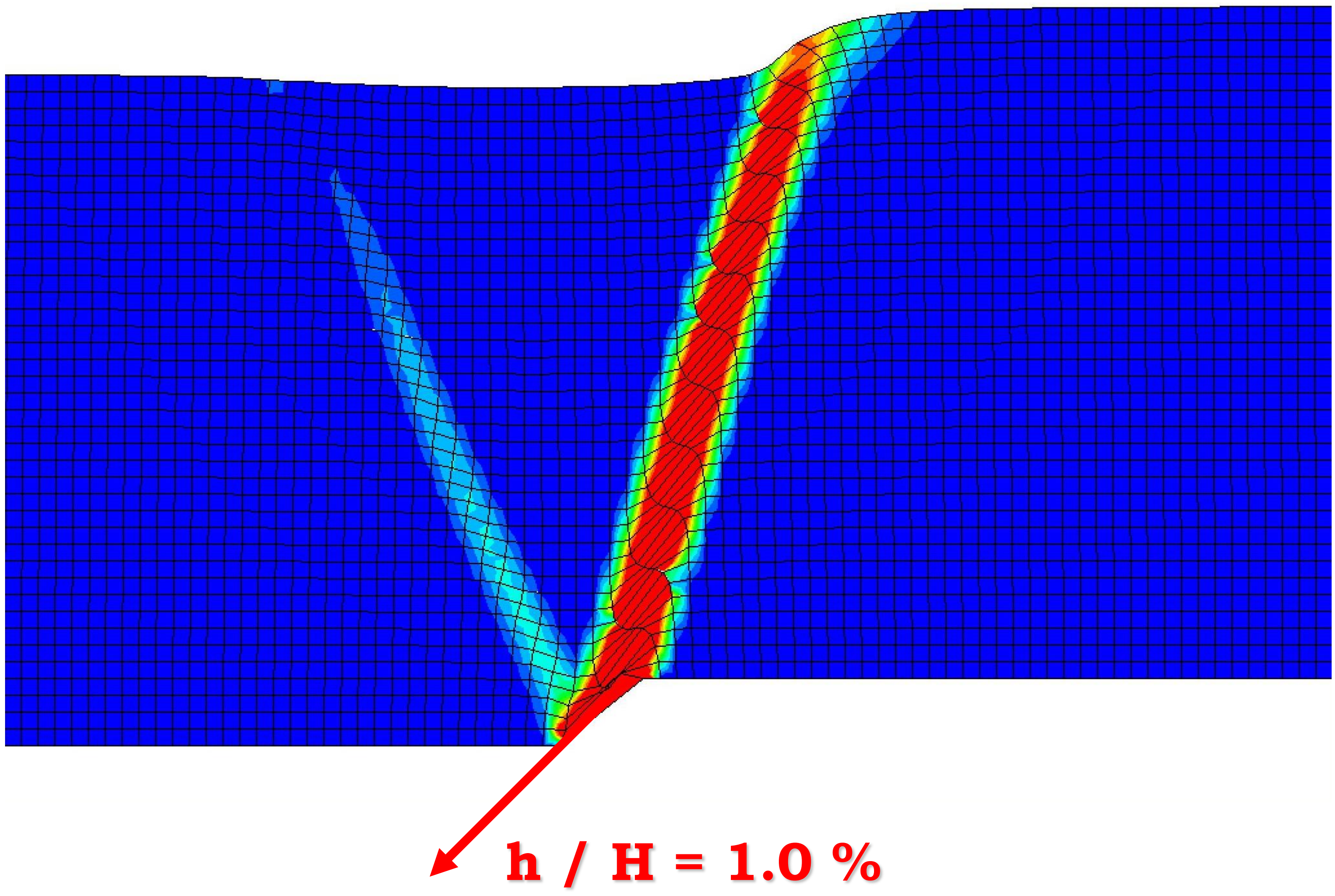
Normal Faulting on Dense Sand , $\alpha = 45^o$

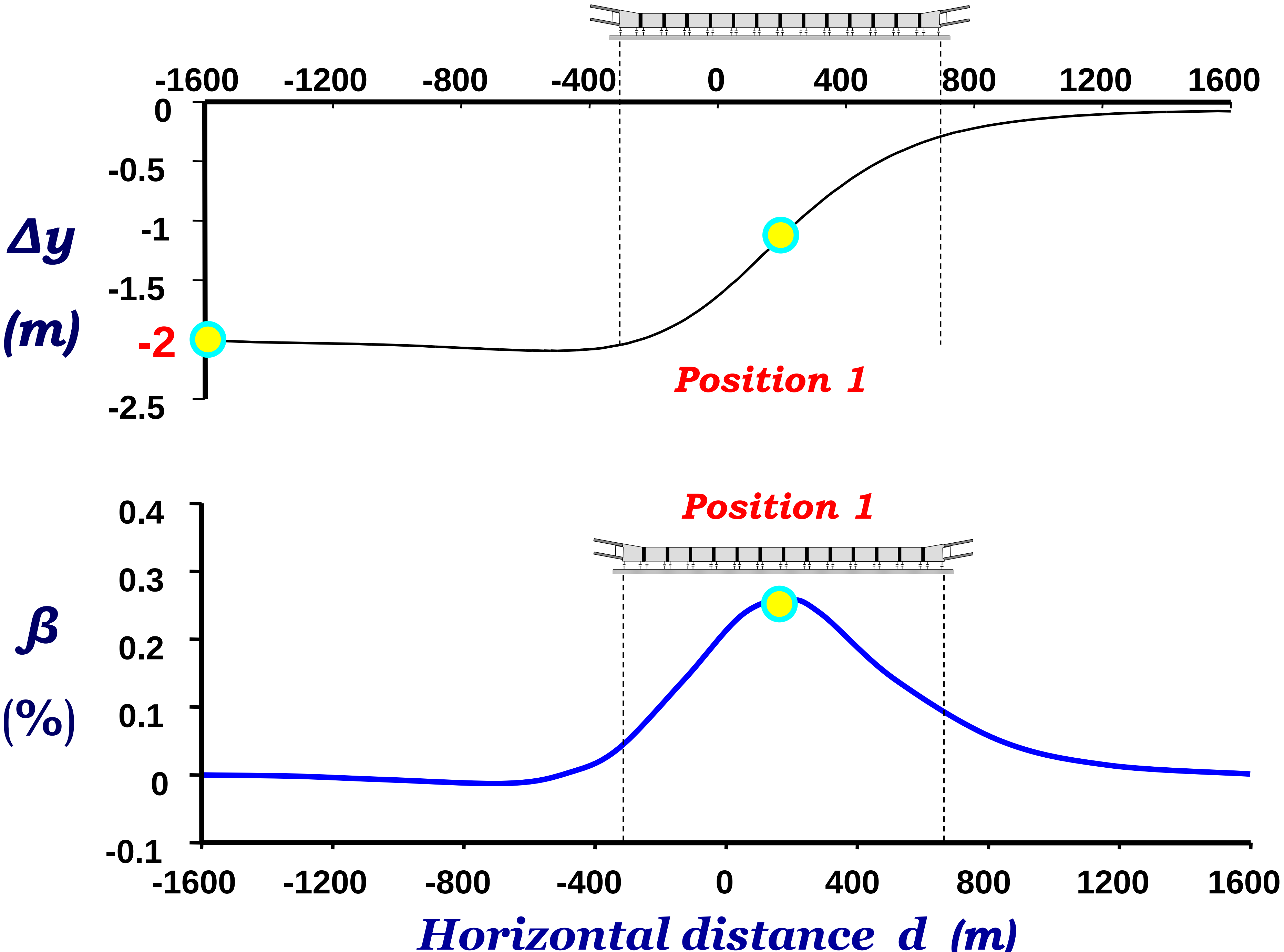


Normal Faulting on Dense Sand , α = 45º



Normal Faulting on Dense Sand , α = 45°

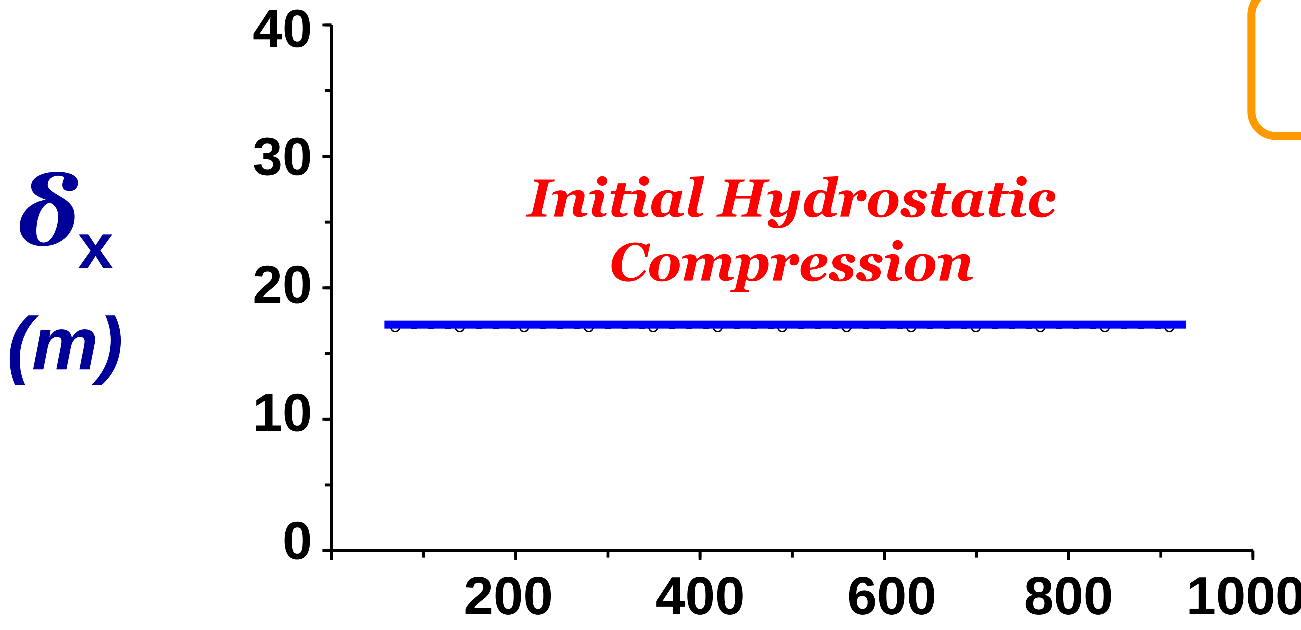




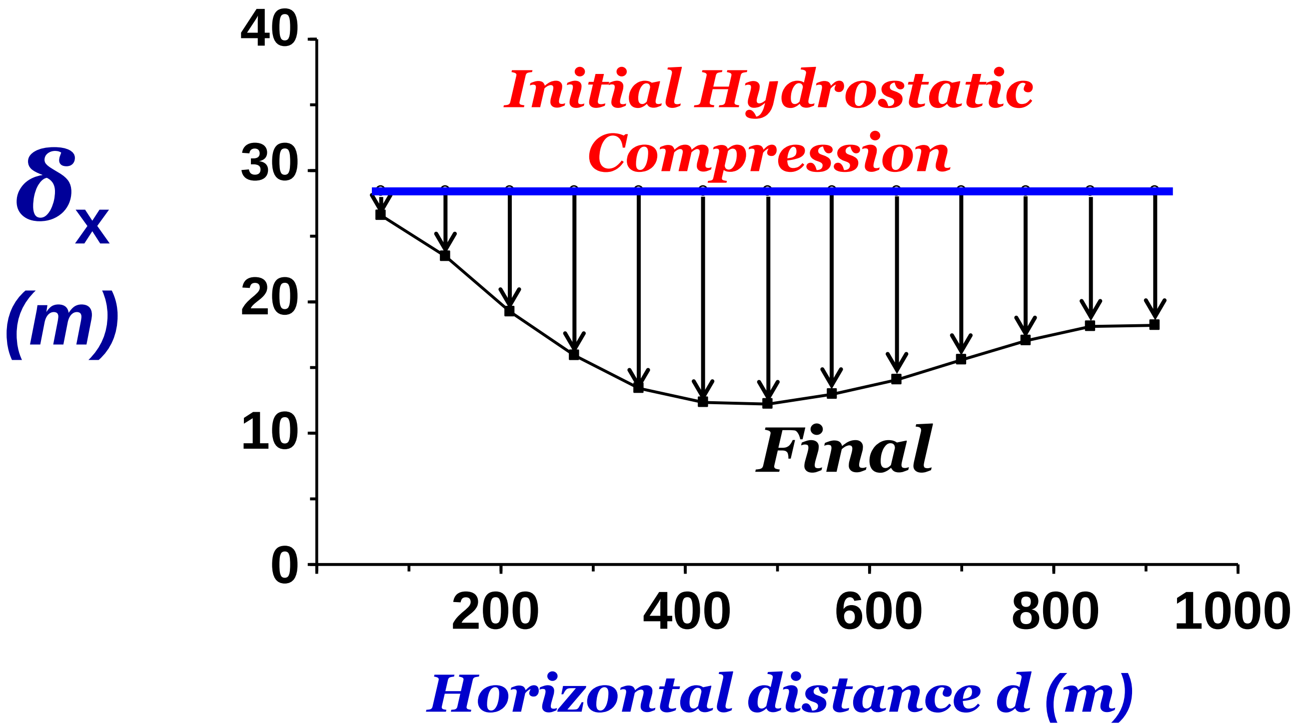
-1600
-1200
-800
-400
0
400
800
1200
1600
0
-0.5
-1
-1.5
-2
-2.5
Δy (m)
Position 1
0.4
0.3
0.2
0.1
0
-0.1
β (%)
Position 1
-1600
-1200
-800
-400
0
400
800
1200
1600
Horizontal distance d (m)

Gina:

Type A



Type B



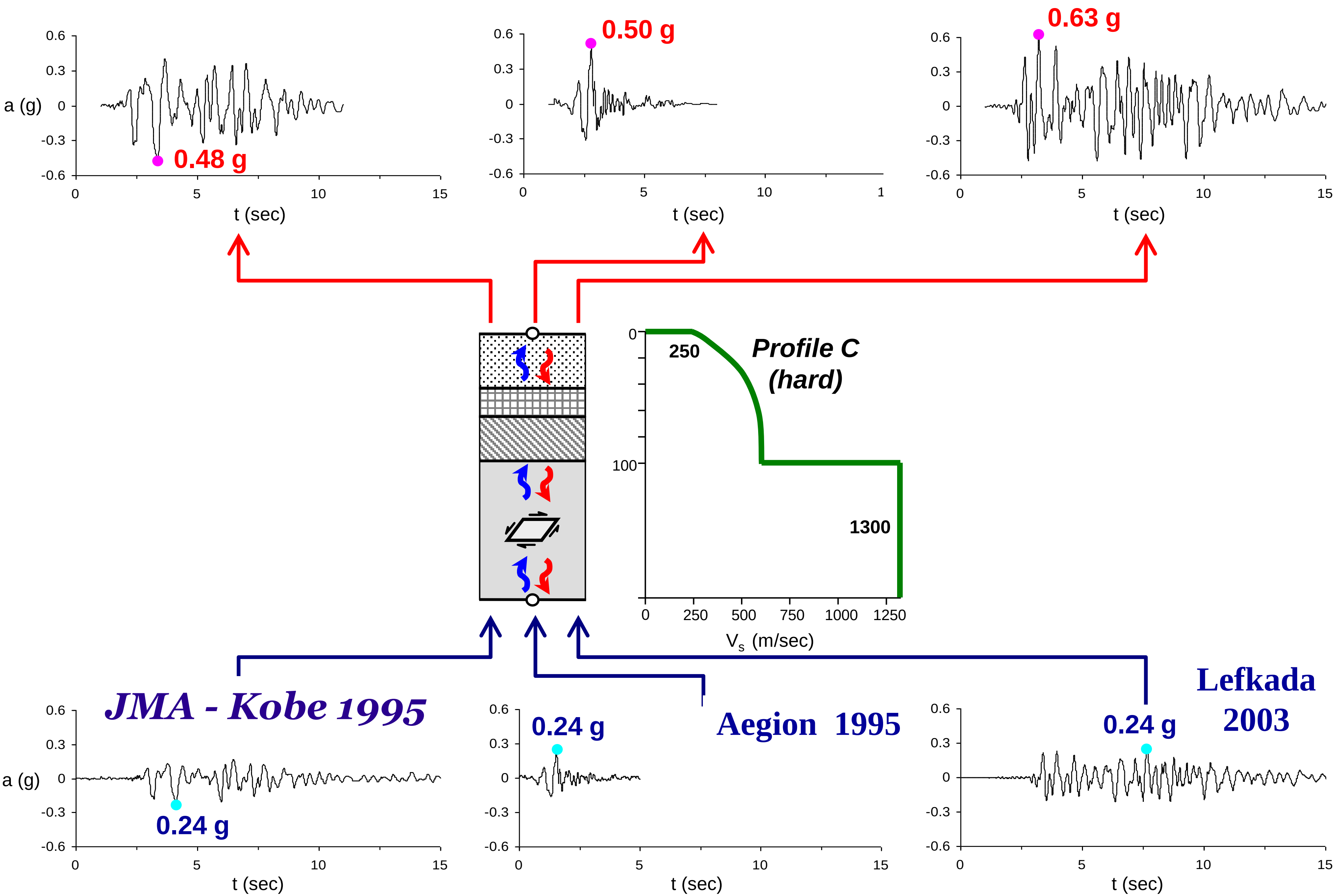
(b)

Seismic Excitation

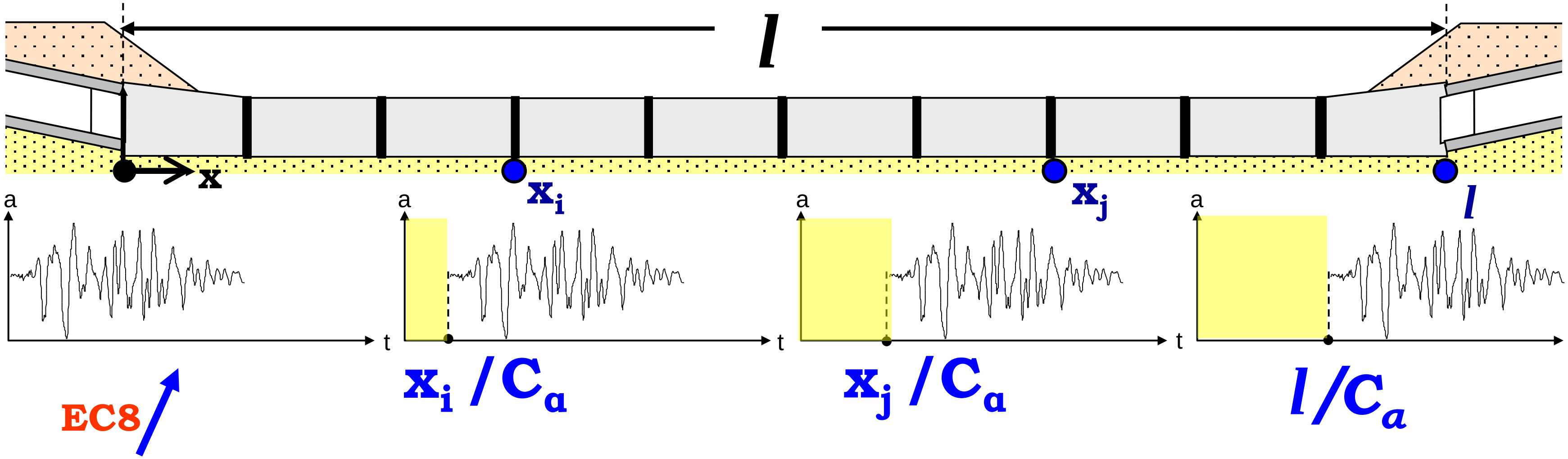
0.24 g

at bedrock level

1-D Dynamic Wave Propagation Analysis



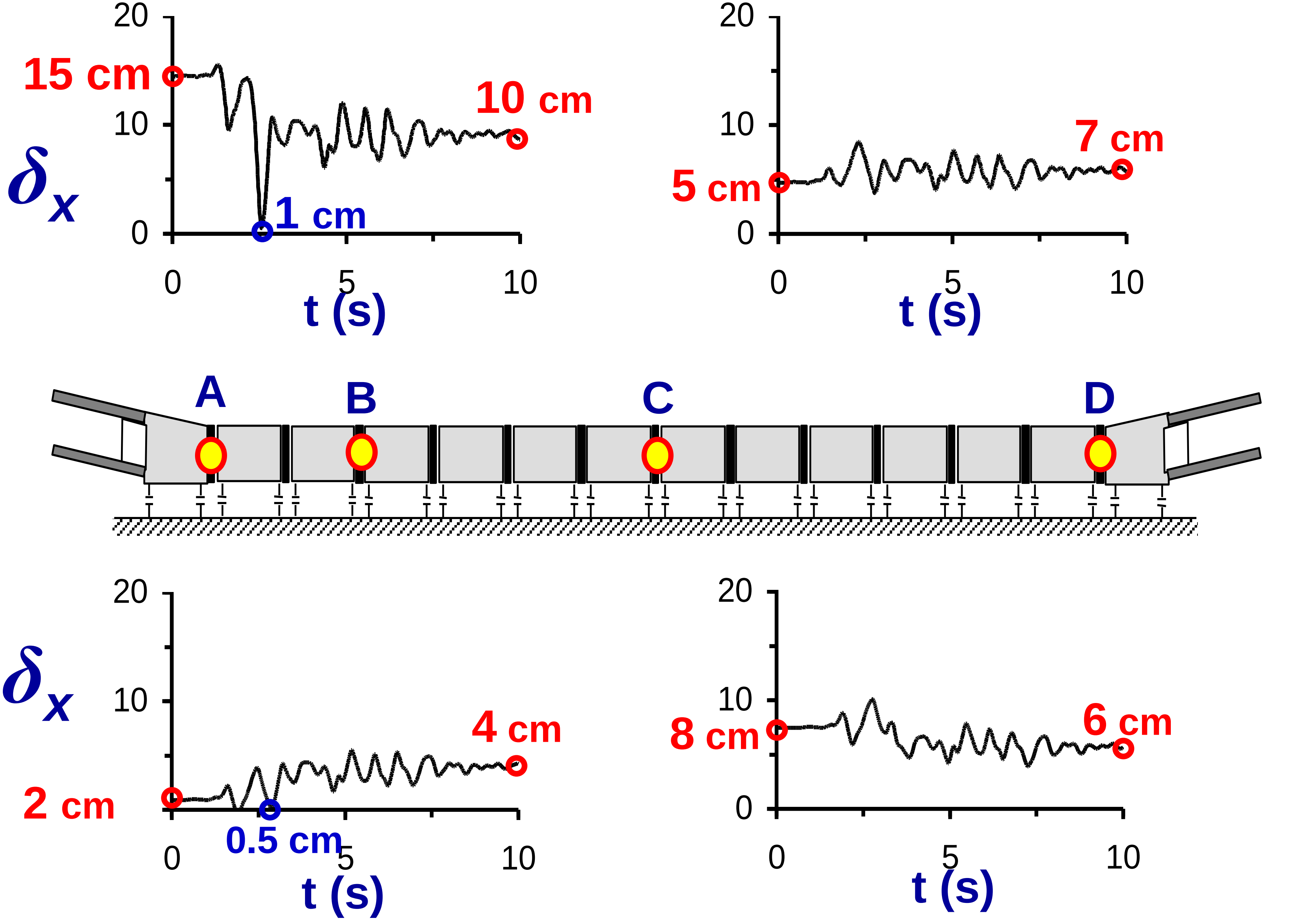
Application of Seismic Base Excitation

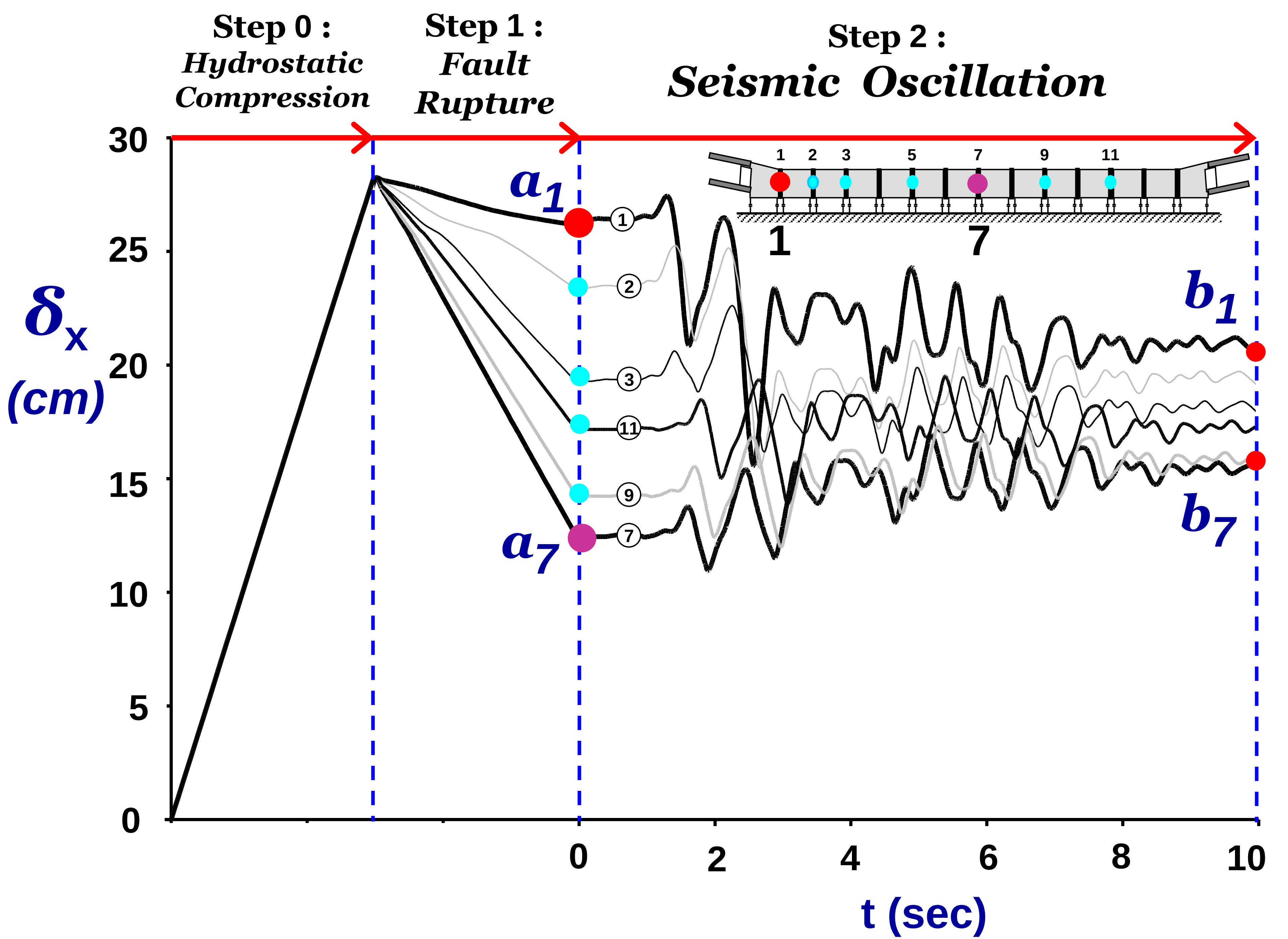


C_a : apparent wave velocity $\Rightarrow$ ***Time lag***

$$t_i = x_i / C_a$$

Joint Deformation




Step 0 :
Hydrostatic Compression
Step 1 :
Fault Rupture
Step 2 :
Seismic Oscillation
δ_x (cm)
30
25
20
15
10
5
0
0
2
4
6
8
10
t (sec)
a_1
a_7
b_1
b_7
1
2
3
11
9
7
1 2 3 5 7 9 11
1
7

CONCLUSIONS

1. Immersed Tunnels:

Capable of Withstanding Significant Fault + Dynamic Deformations

PREREQUISITE:

(a) Special Gina Profiles

(e.g., h = 50 cm)

(b) Small Length of Segments

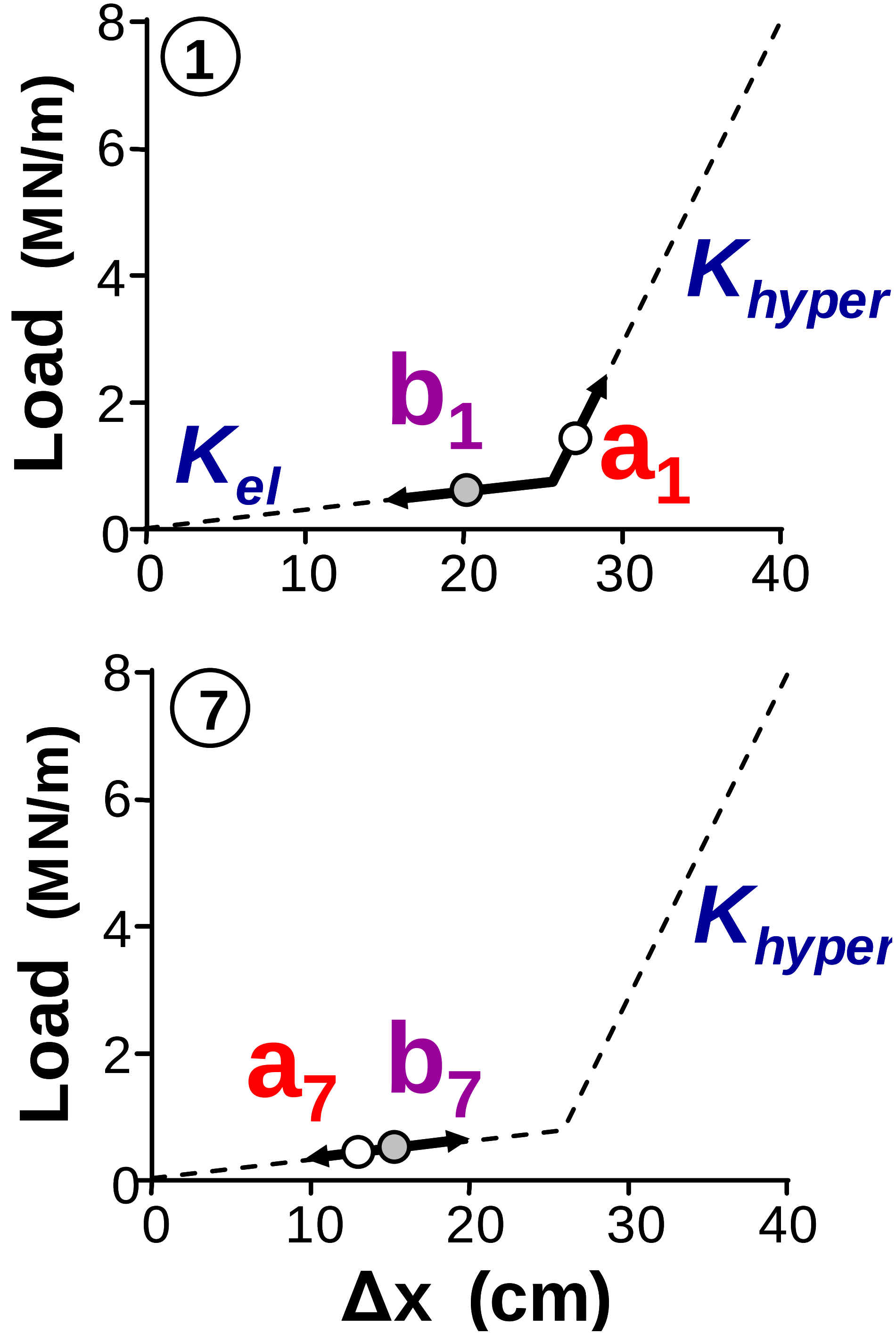
(e.g., L = 70 m)

CONCLUSIONS

2. The "injury" of Immersed Tunnels from Fault Offset at the Baserock can be "healed" after strong seismic shaking

Thank you

for your attention



1
Load (MN/m)
8
6
4
2
0
0
10
20
30
40
K hyper
b 1
a 1
K el
7
Load (MN/m)
8
6
4
2
0
0
10
20
30
40
K hyper
a 7
b 7
Δx (cm)