Evaluation of Performance of Diaphragm Walls

Richard N. Hwang, Ph.D
Senior Vice President
MAA Group

Classification of Excavations

Shallow : **up to 5m, or 1-level basement**

Mid-depth: **5m to 10m, or 2-3 levels**

Deep: **10m to 20m, or 4-5 levels**

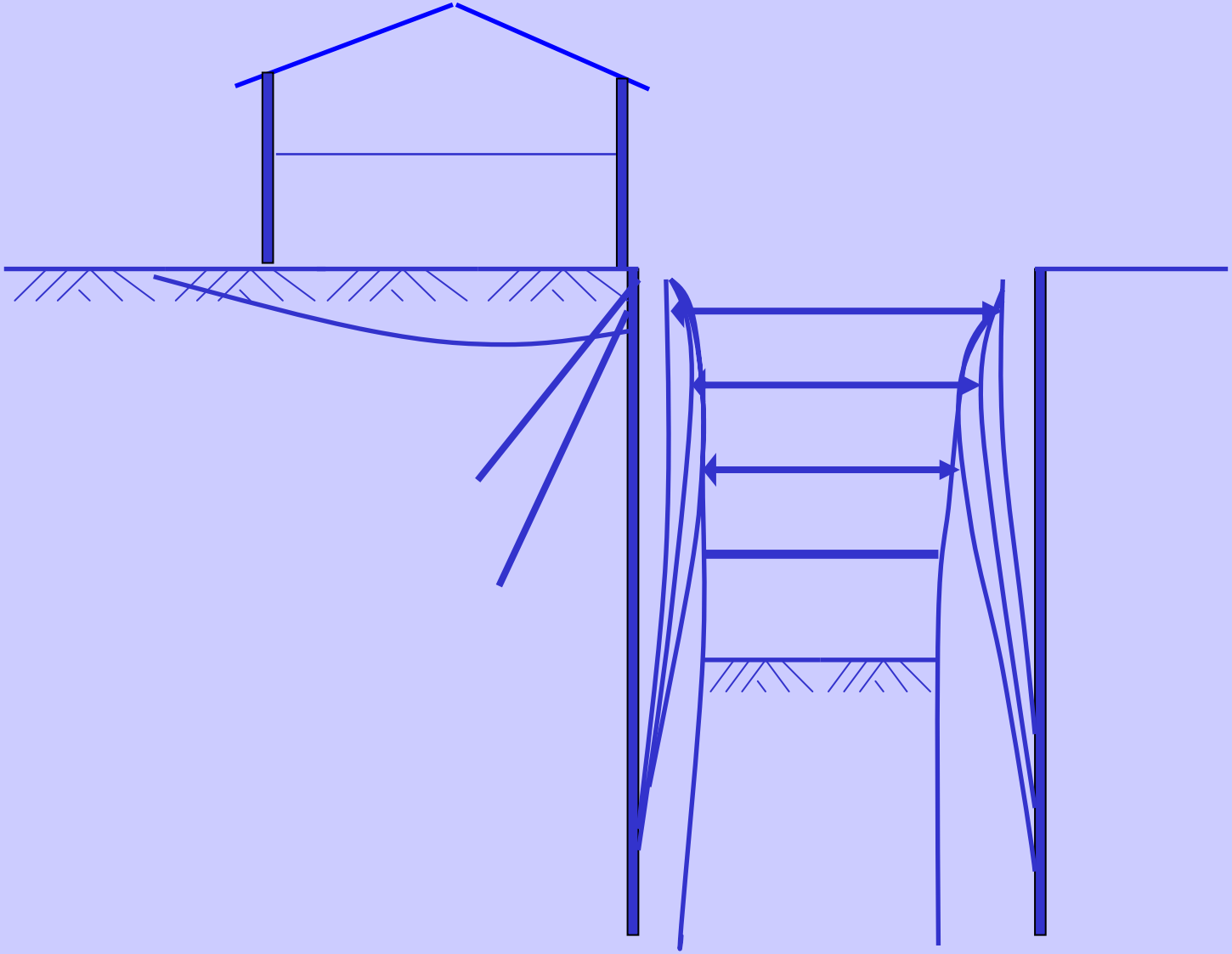
Very Deep: **20m to 30m, or 6-or-more levels**

Extremely Deep: **30m or greater in depth**

Retaining Walls

- Shallow: Sheet Piles
- Mid-depth: Contiguous Bored Piles
- Deep: Diaphragm Walls
- Very Deep: Diaphragm Walls + Ground Treatment
- Extremely Deep: Special Considerations


82 9 28



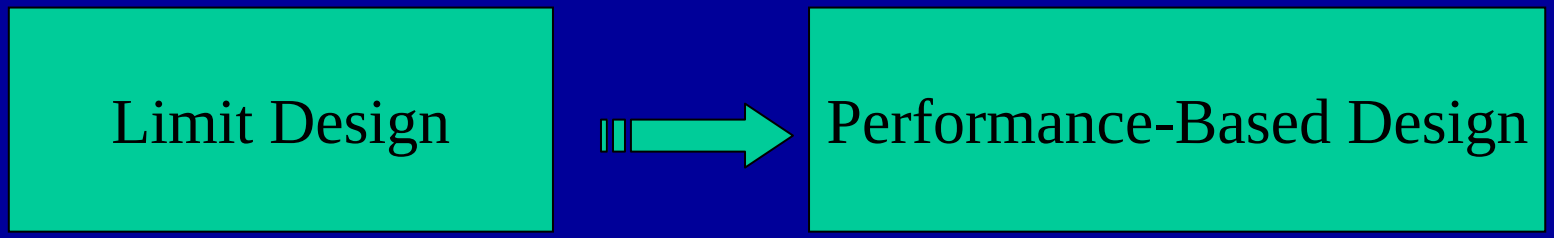
Limit Design

- Structurally Sound
- Toe Stable
- Apply Factors of Safety
- Hope wall deflections, and hence ground settlements, will be acceptable

- Reason: Don’t know how to compute wall deflections

Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Boundaries (vertical and horizontal)
- Workmanship/Promptness of Preloading

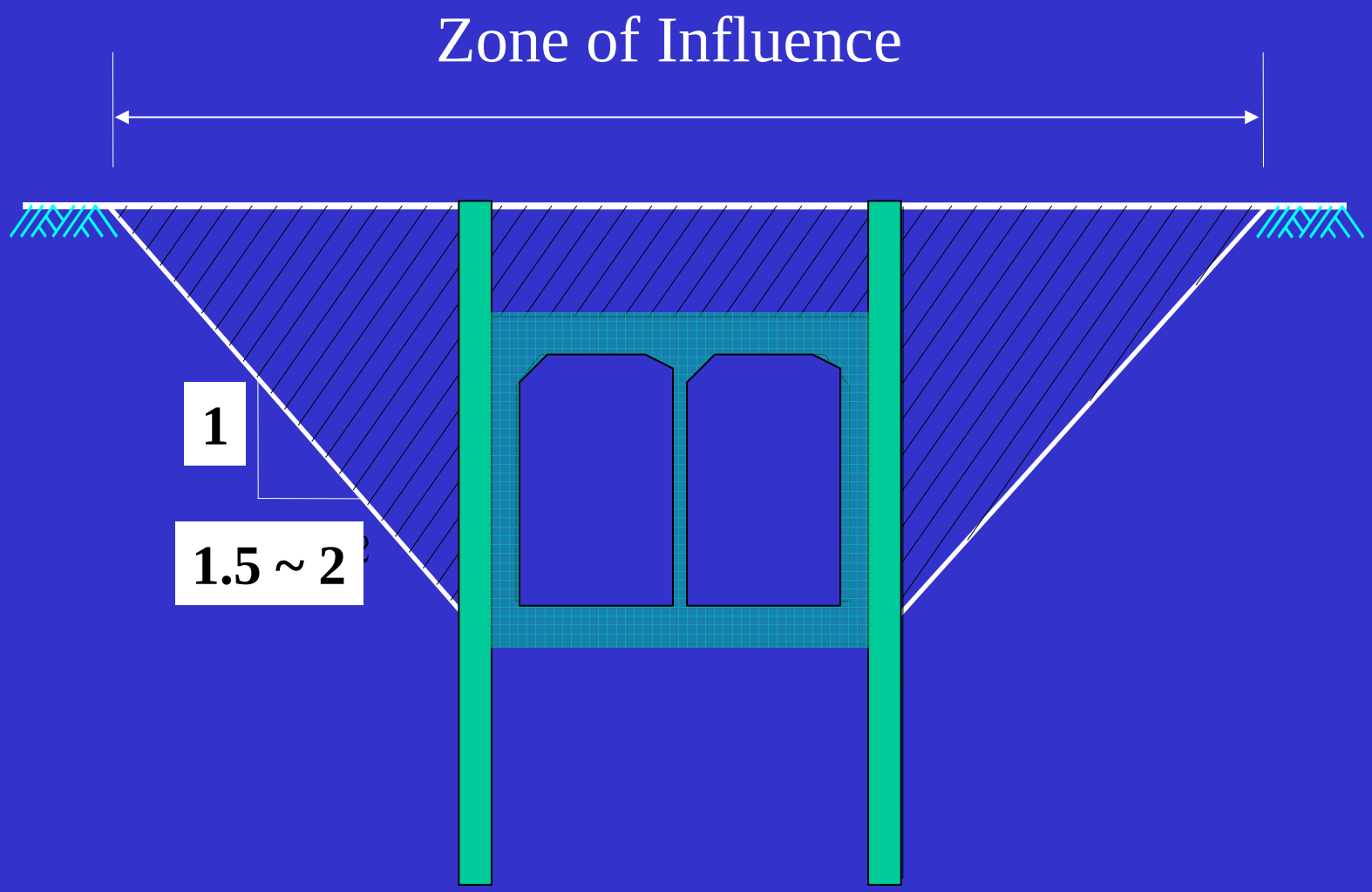


People are more conscious about their safety and their rights
Methods and tools are available for computing ground movements

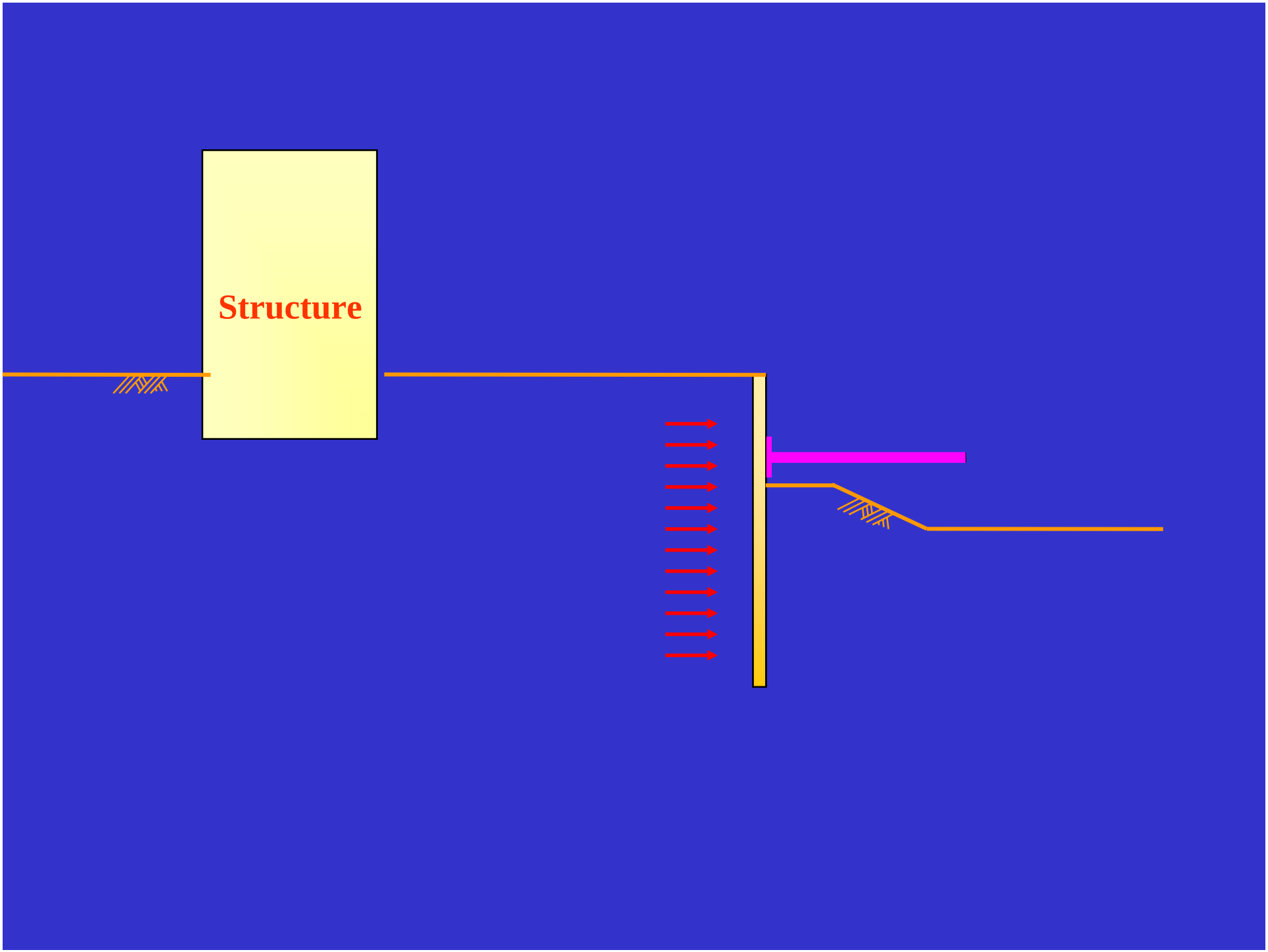
Performance-Based Design

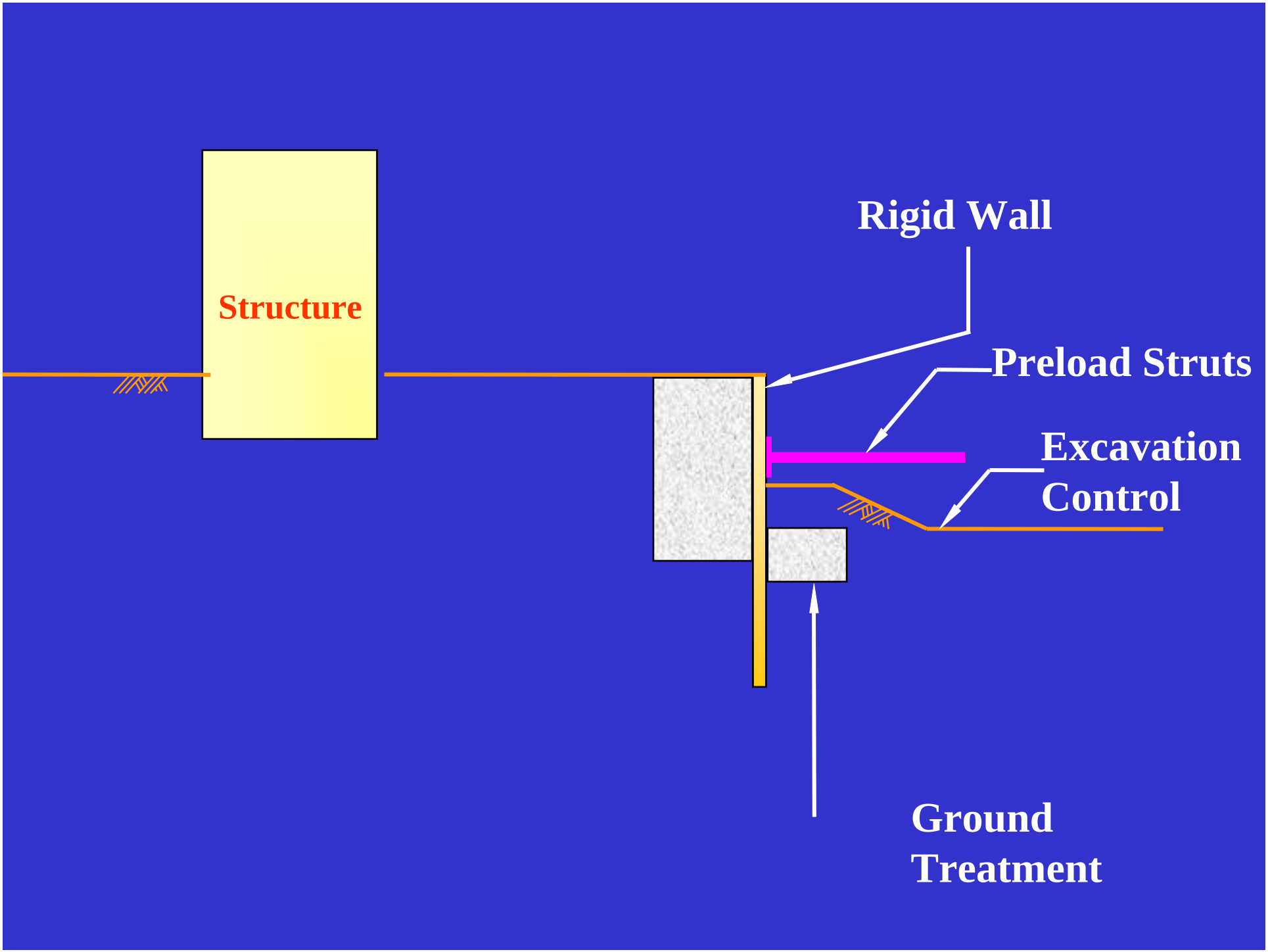
- Designer shall “compute” wall deflections, evaluate the influences of these deflections on adjacent structures, and ensure that adjacent structures will not be damaged.
- If an adjacent structures is likely to be damaged, designer shall make efforts to reduce wall deflections.

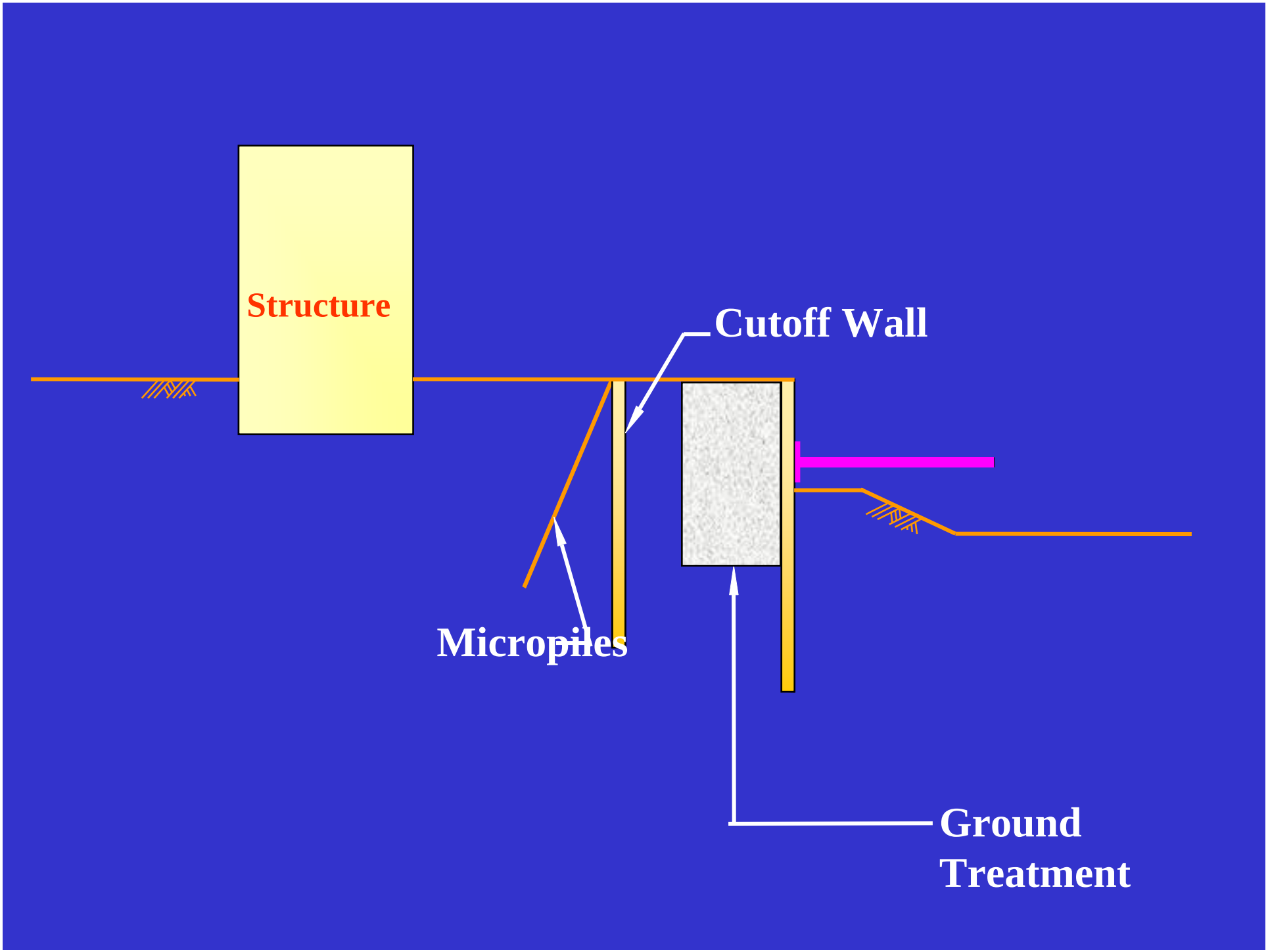
- Or, he shall take measures to reduce ground movements at the base of adjacent structure.
- Or, he shall protect the adjacent structure against damages by strengthening the structure.

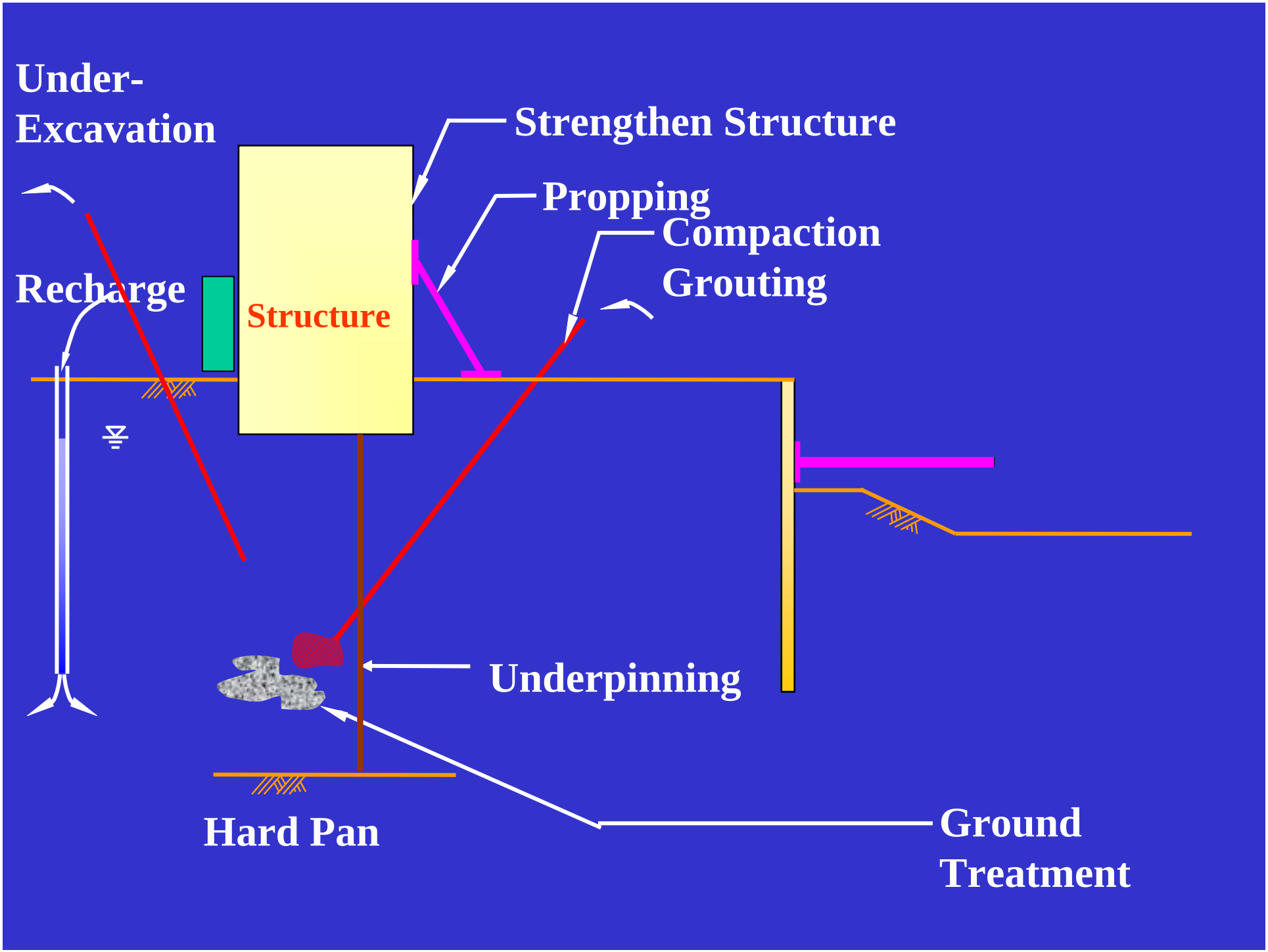


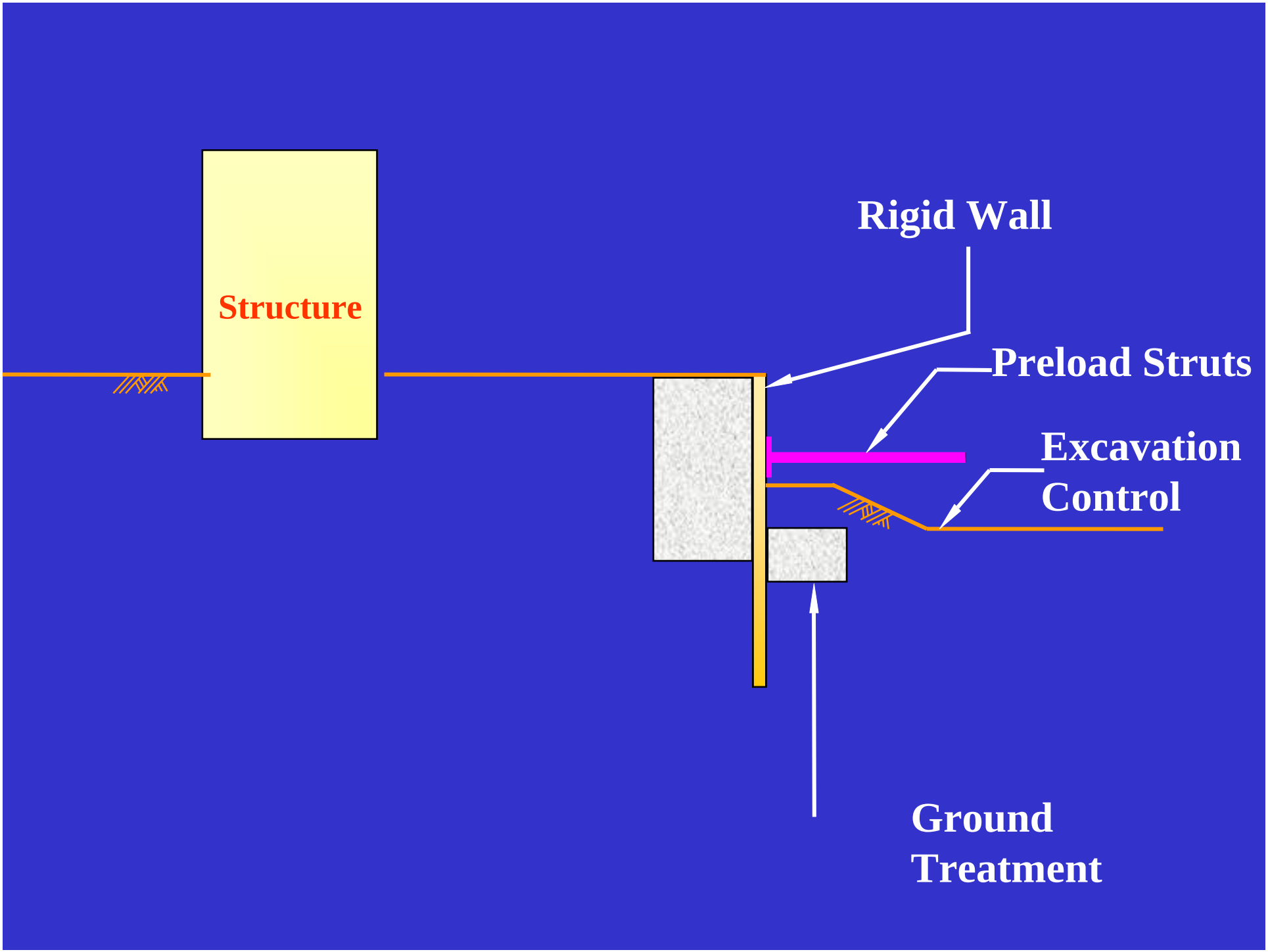
Cut & Cover Constructions


Structure


Structure
Rigid Wall
Preload Struts
Excavation
Control
Ground
Treatment


Structure
Cutoff Wall
Micropiles
Ground
Treatment


Under-
Excavation
Strengthen Structure
Propping
Compaction
Grouting
Recharge
Structure
Underpinning
Hard Pan
Ground
Treatment


Structure
Rigid Wall
Preload Struts
Excavation
Control
Ground
Treatment

Building Protection

- All protection measures and remedial measures are costly and ineffective.
- The best strategy is to limit ground movements at source.
- Since ground movements are mainly induced by wall deflections, it is desirable to limit wall deflections.

Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Boundaries (vertical and horizontal)
- Workmanship/Promptness of Preloading

Methods of Analysis

- Numerical
  - Beam on Springs?
  - Finite Difference/Finite Element?
  - 2D/3D?
  - Linear/Non-linear?
  - Drained/Undrained?
- Empirical


Nicoll Highway, Singapore (2004/4/20)

Failure of Nicoll Highway
20 April, 2004

- Committee of Inquiry
- 173 witnesses
- 20 experts
- Final Report – May, 2005

The experts from NLC note that despite more than six months of intensive work by the six teams of experts who have been reviewing the collapse at M3 (in which failure occurred), the experts still can not reach any agreement on the correct input parameters to be adopted in a back analysis. Very significant difference still remain, particularly respect to the parameters to be adopted for JGP.

It is also noted that because of the stiffness characteristics of the ground, diaphragm wall and JGP are all highly non linear, it is virtually impossible to obtain agreement between the monitored strut loads and wall displacements throughout all the stages of excavation sequence using a single set of linear elastic stiffness value, as adopted in Plaxis analyses.

Wong Kai Sin

If analyses are done correctly, numerical methods can give reliable results.

Empirical Approach

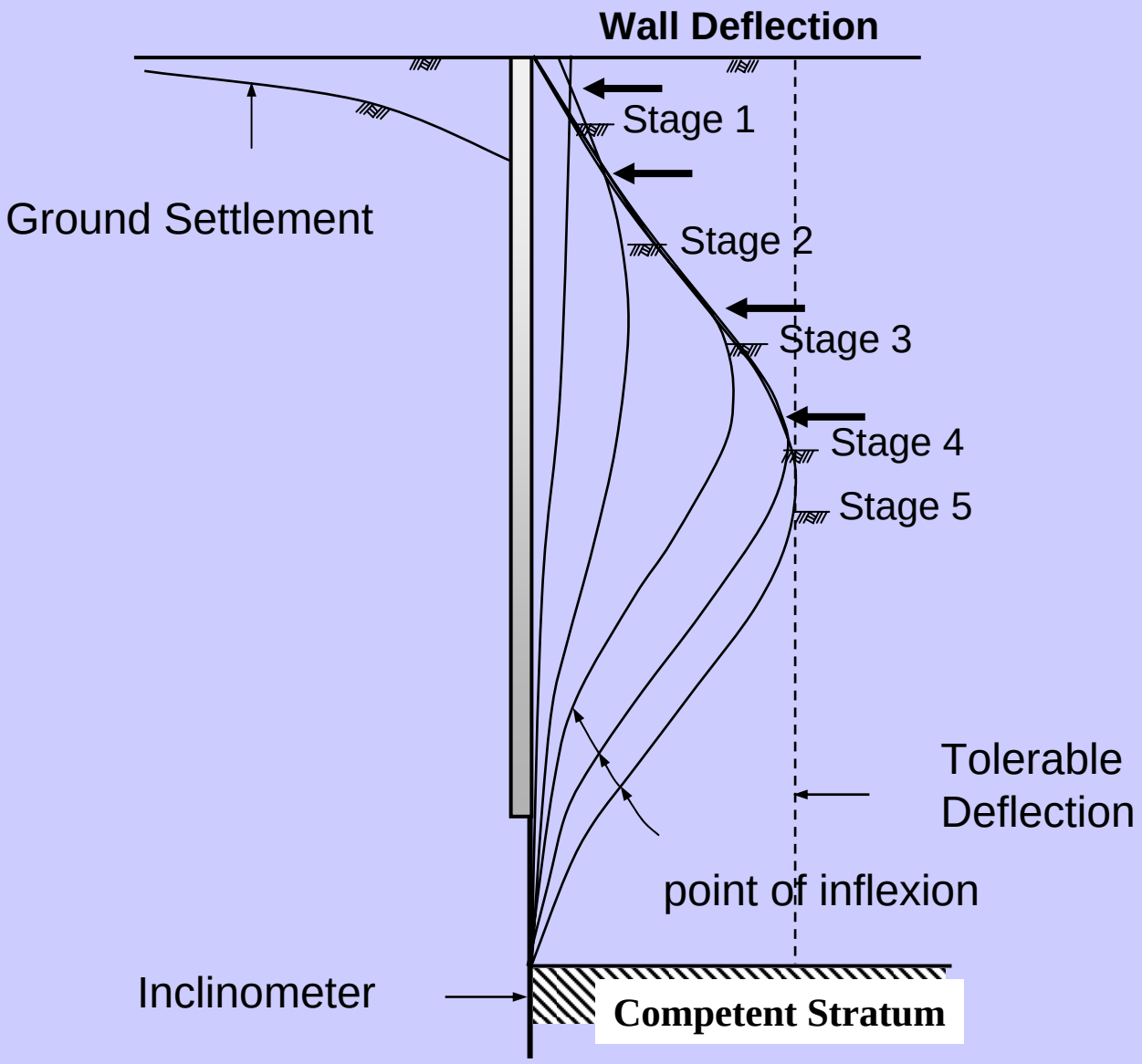
- Shall have a sufficient number of cases to make statistic analyses meaningful.
- Data must be reliable.
- Good engineering judgment is vital.

Factors to be Considered

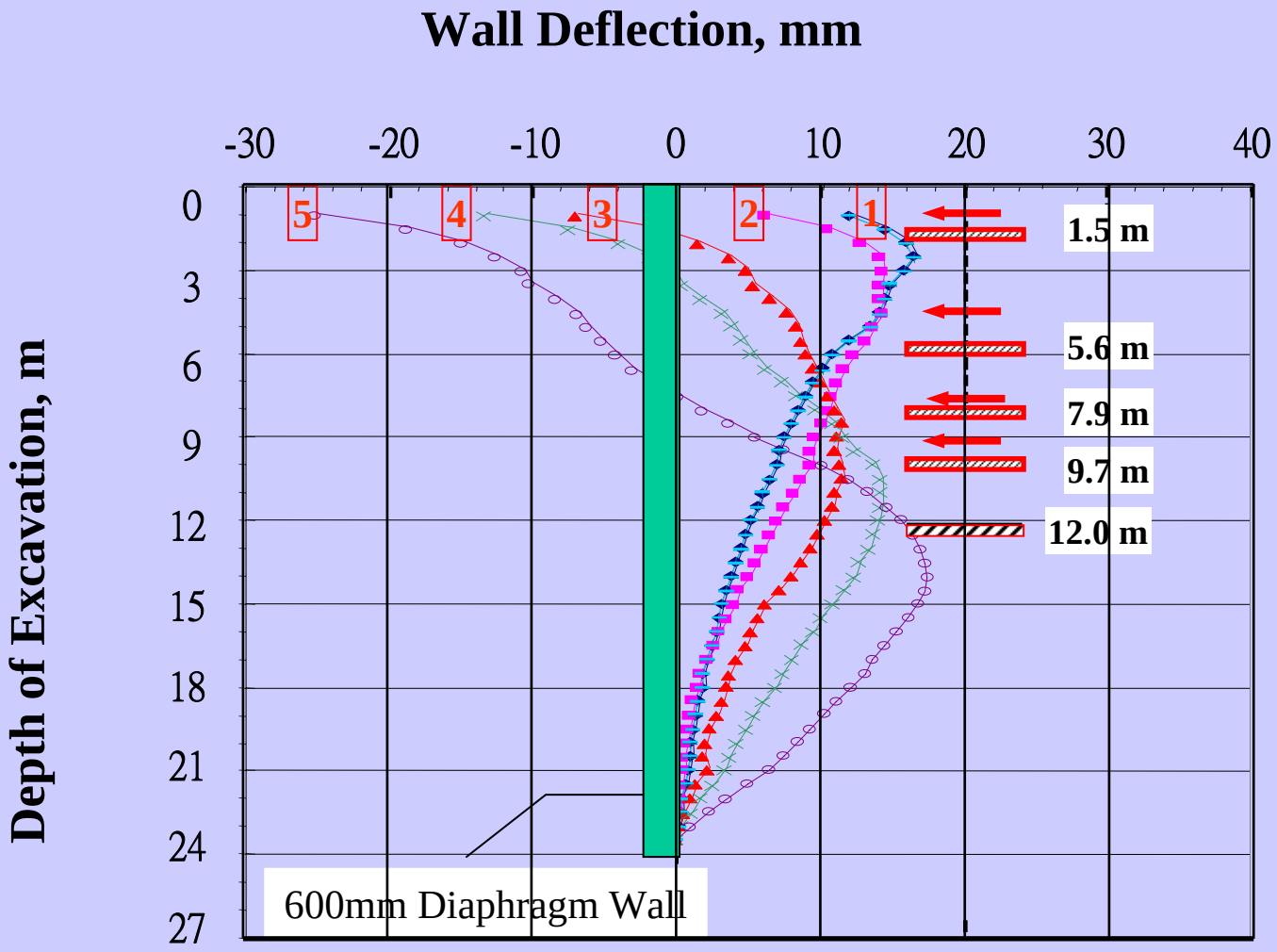
- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions
- Method of Construction
- Surcharge Load/Structure/Basement/Pileboundaries
- Workmanship/Promptness of Preloading

Empirical Approach

- Shall have a sufficient number of cases to make statistic analyses meaningful.
- Data must be reliable.
- Good engineering judgment is vital.



Ideal Wall Deflection Profiles



(a) Before Adjustment for Toe Movements

Shortening of preloaded struts

Grade 50 Steel

f_y = 50 ksi

$f_a = 0.3f_y$ = 15 ksi

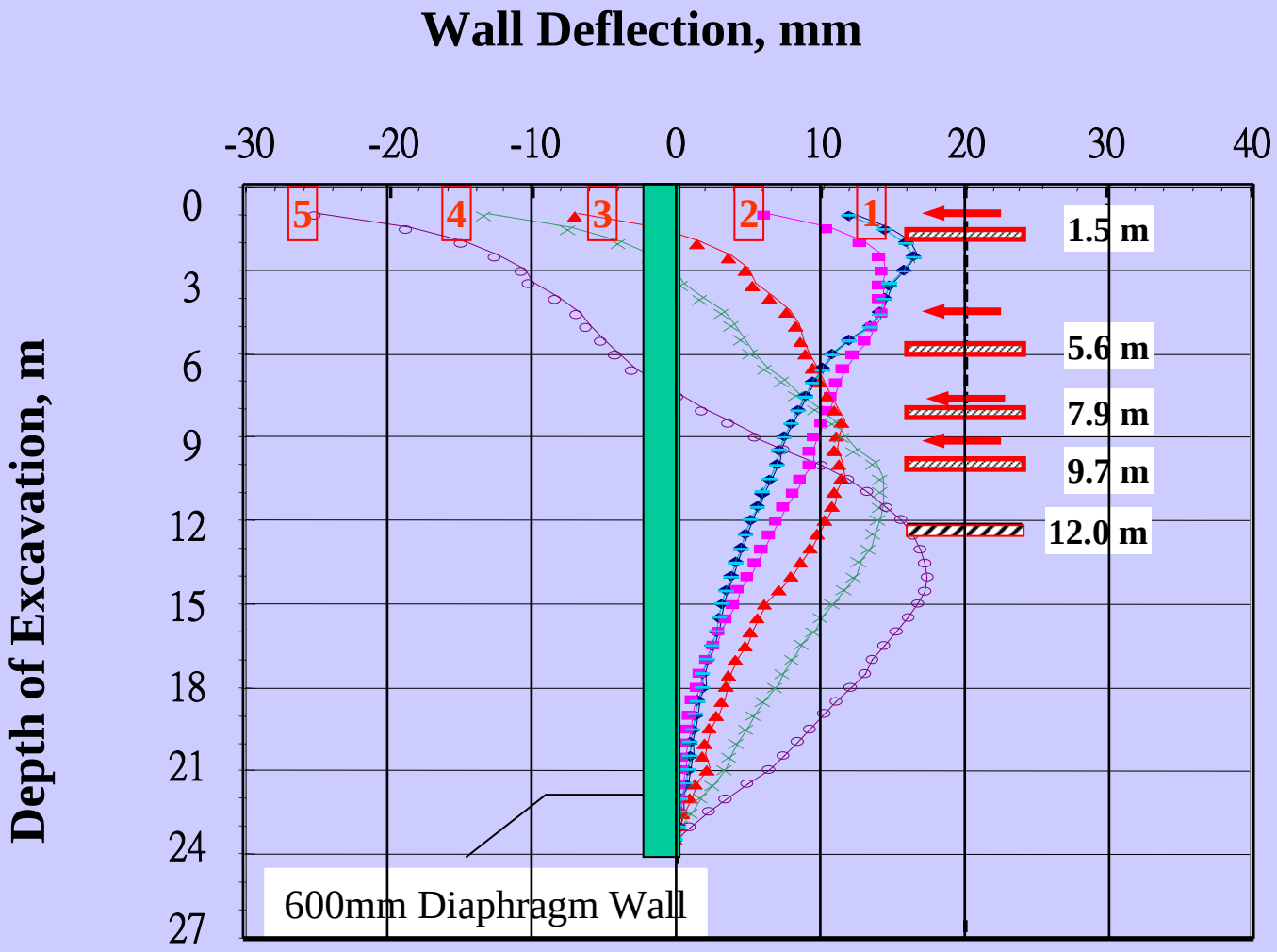
E = 30,000 ksi

L= 20m (span of strut)

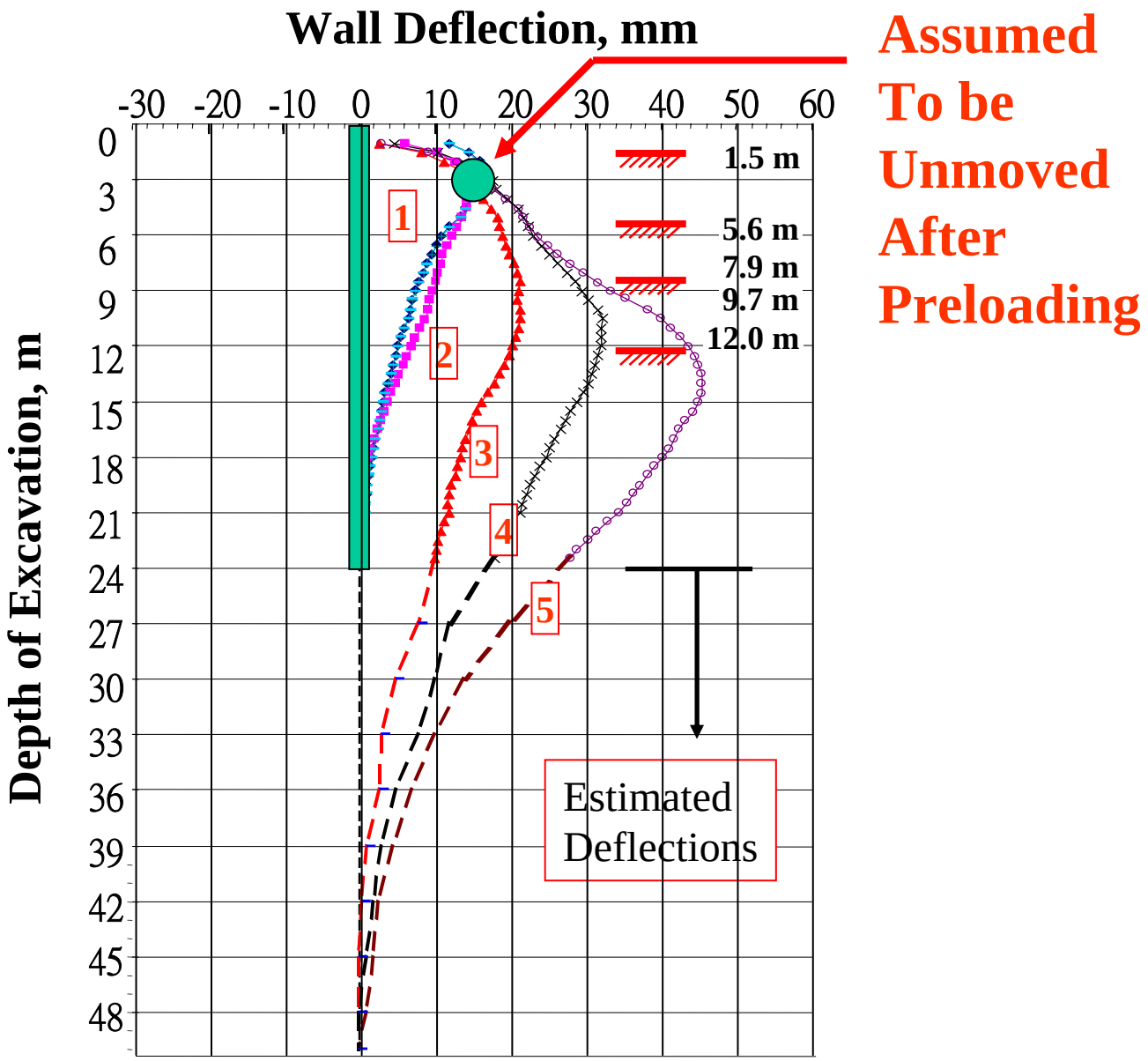
Δ = 15/30,000 x 20 x 1000 = 10mm

Δ /2 = 5mm (reduction due to preload)

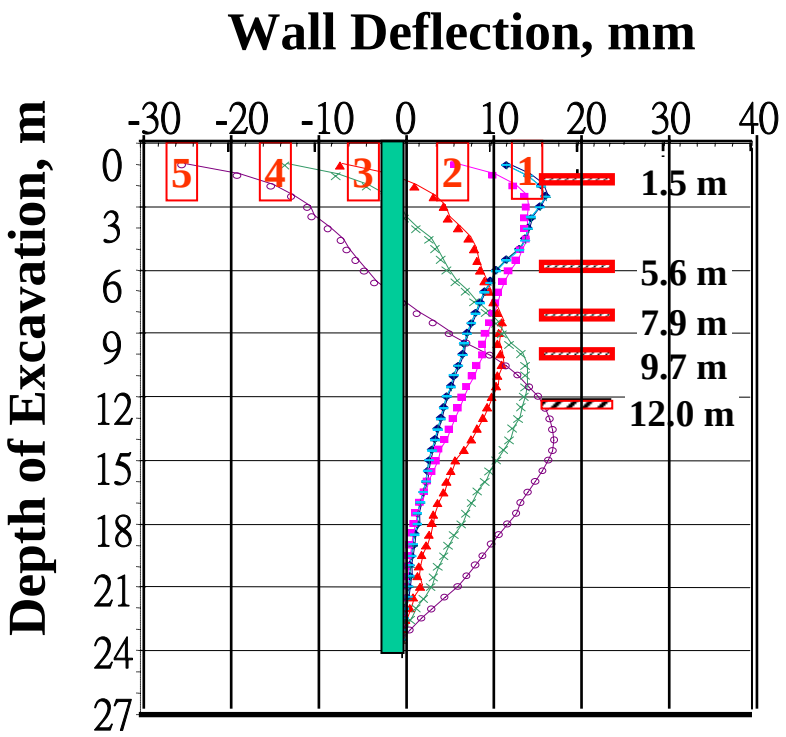
Movement at each end < 2.5mm



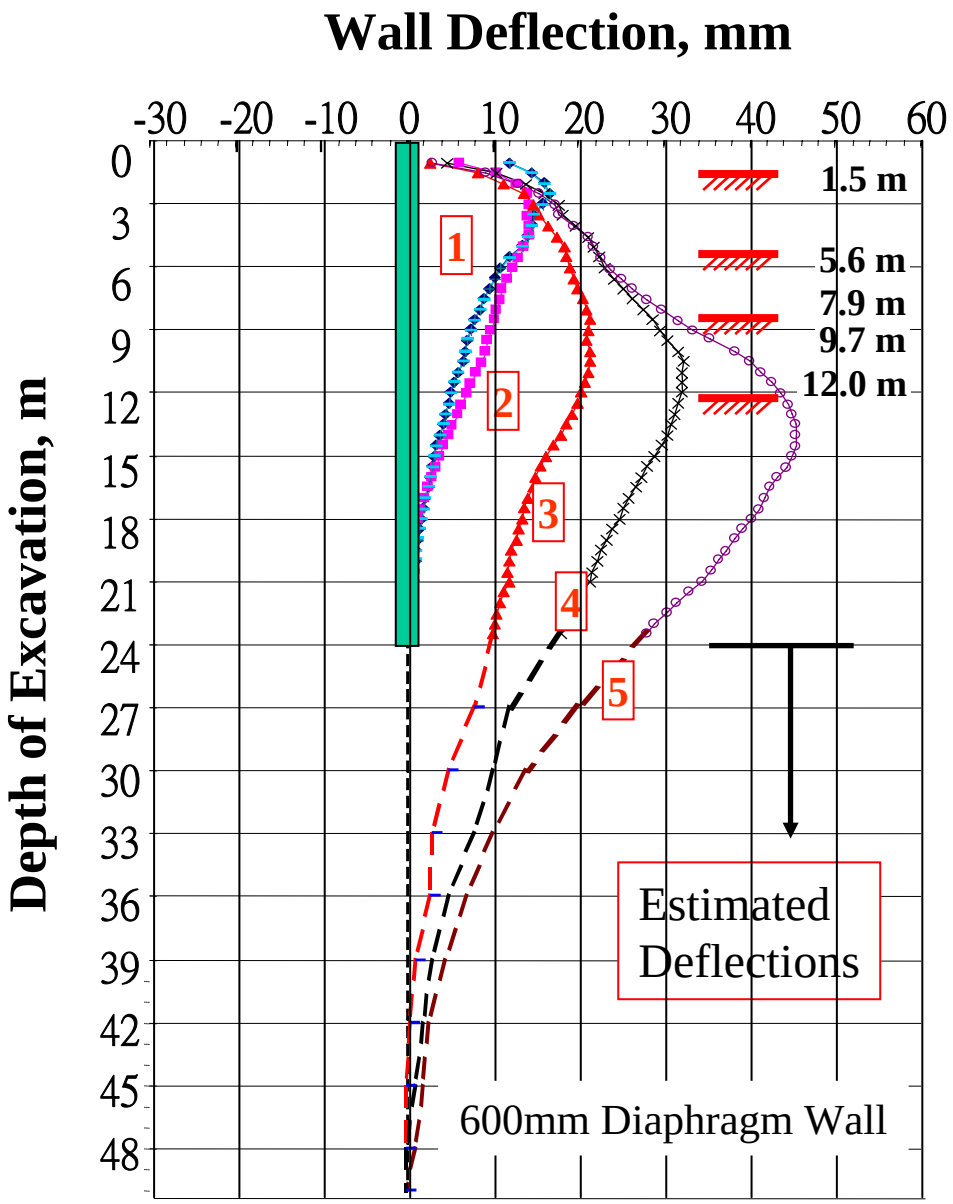
(a) Before Adjustment for Toe Movements



(b) After Adjustment for Toe Movements



(a) Before Adjustment for Toe Movements



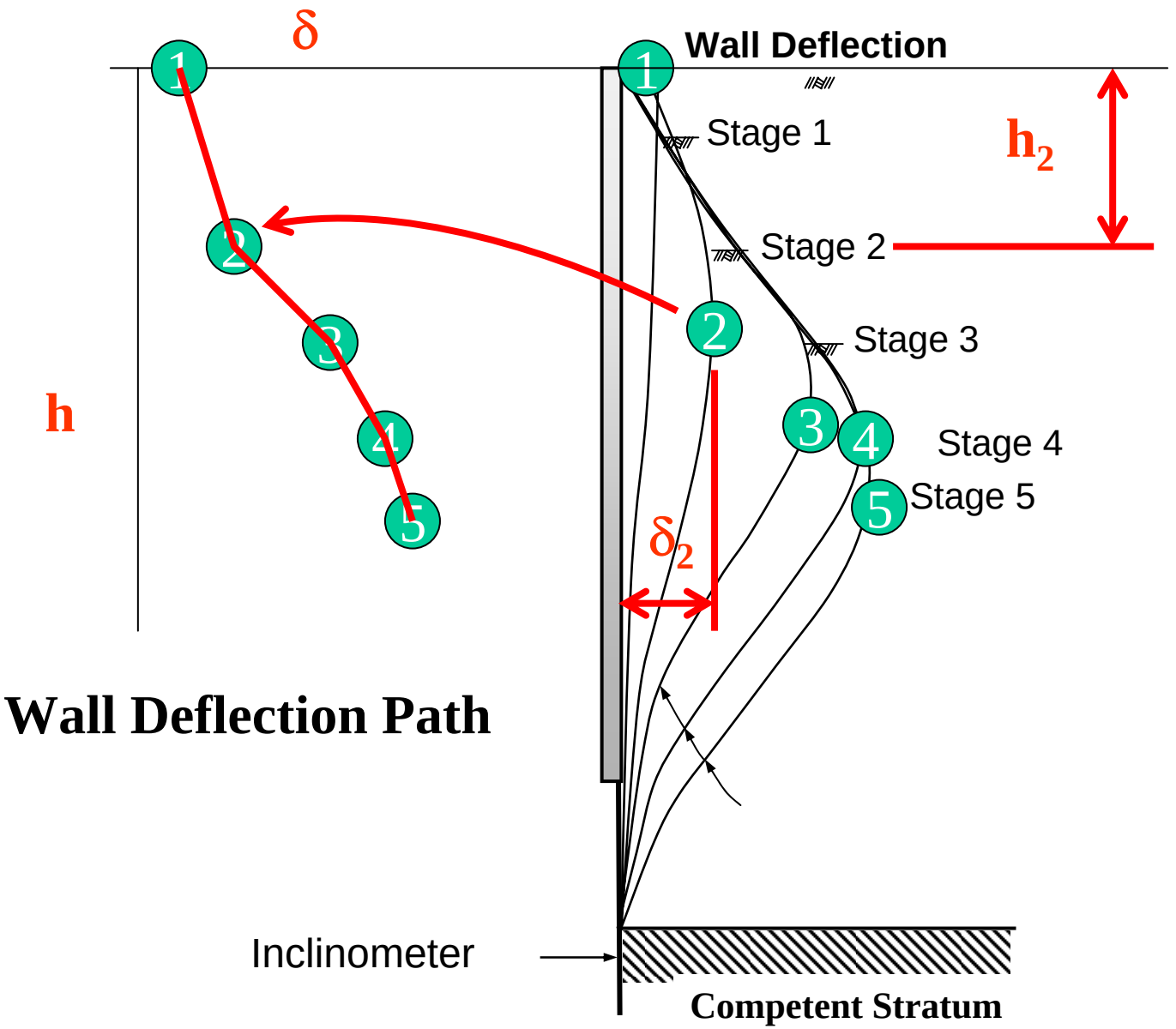
(b) After Adjustment for Toe Movements

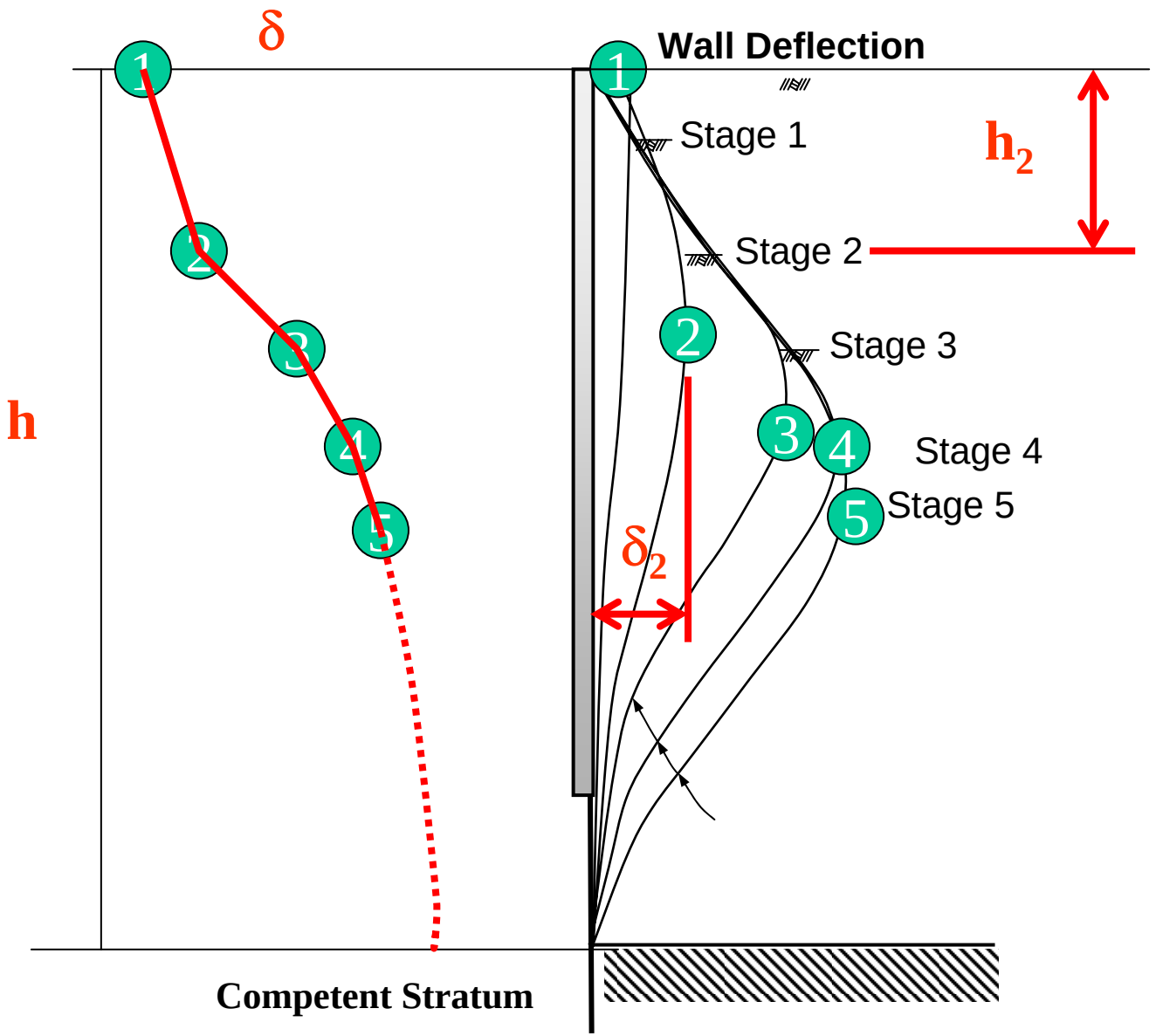
Empirical Approach

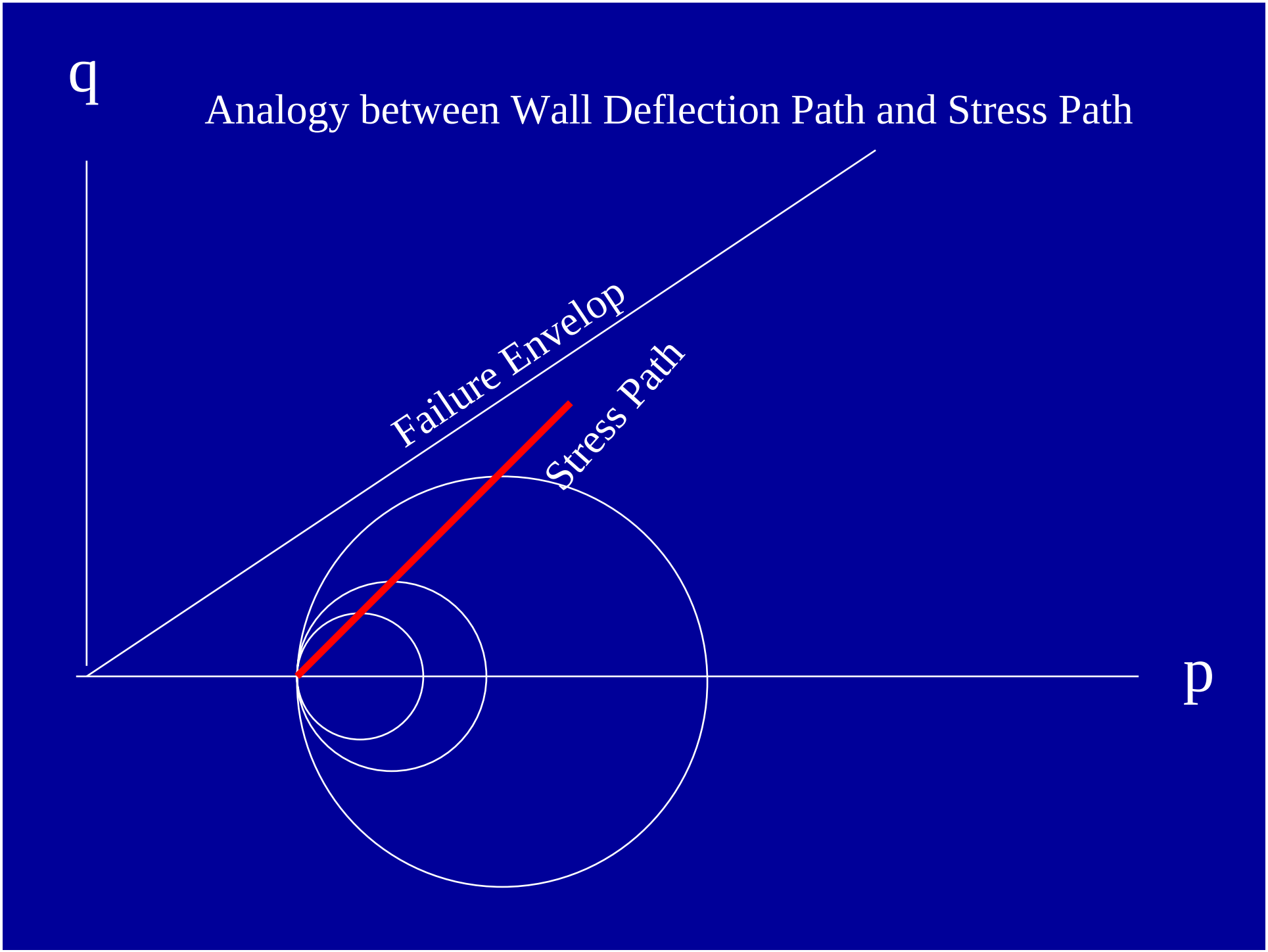
- Shall have a sufficient number of cases to make statistic analyses meaningful.
- Data must be reliable.
- Good engineering judgment is vital.

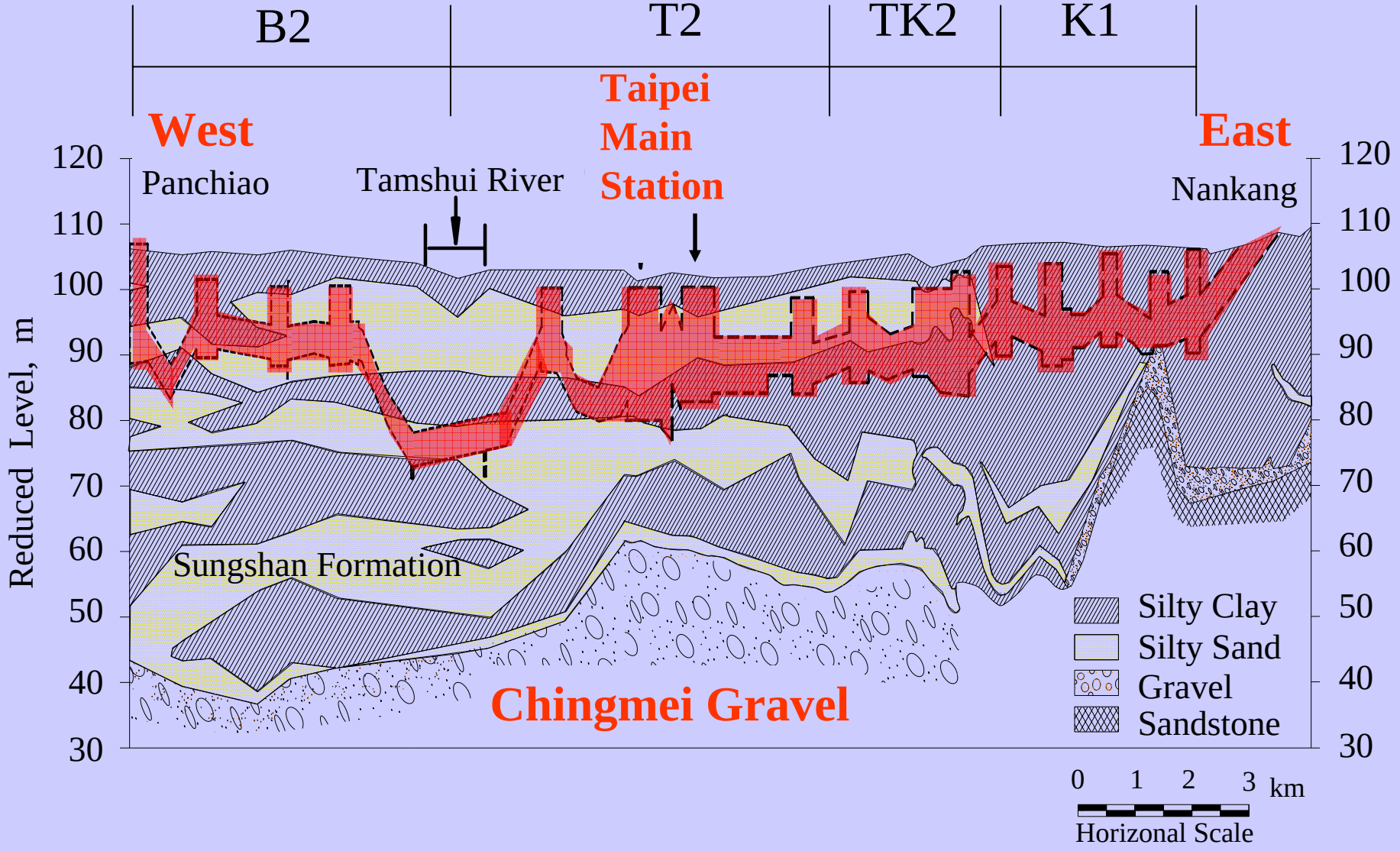
Performance of Walls

- Wall Deflection Path
- Reference Envelops

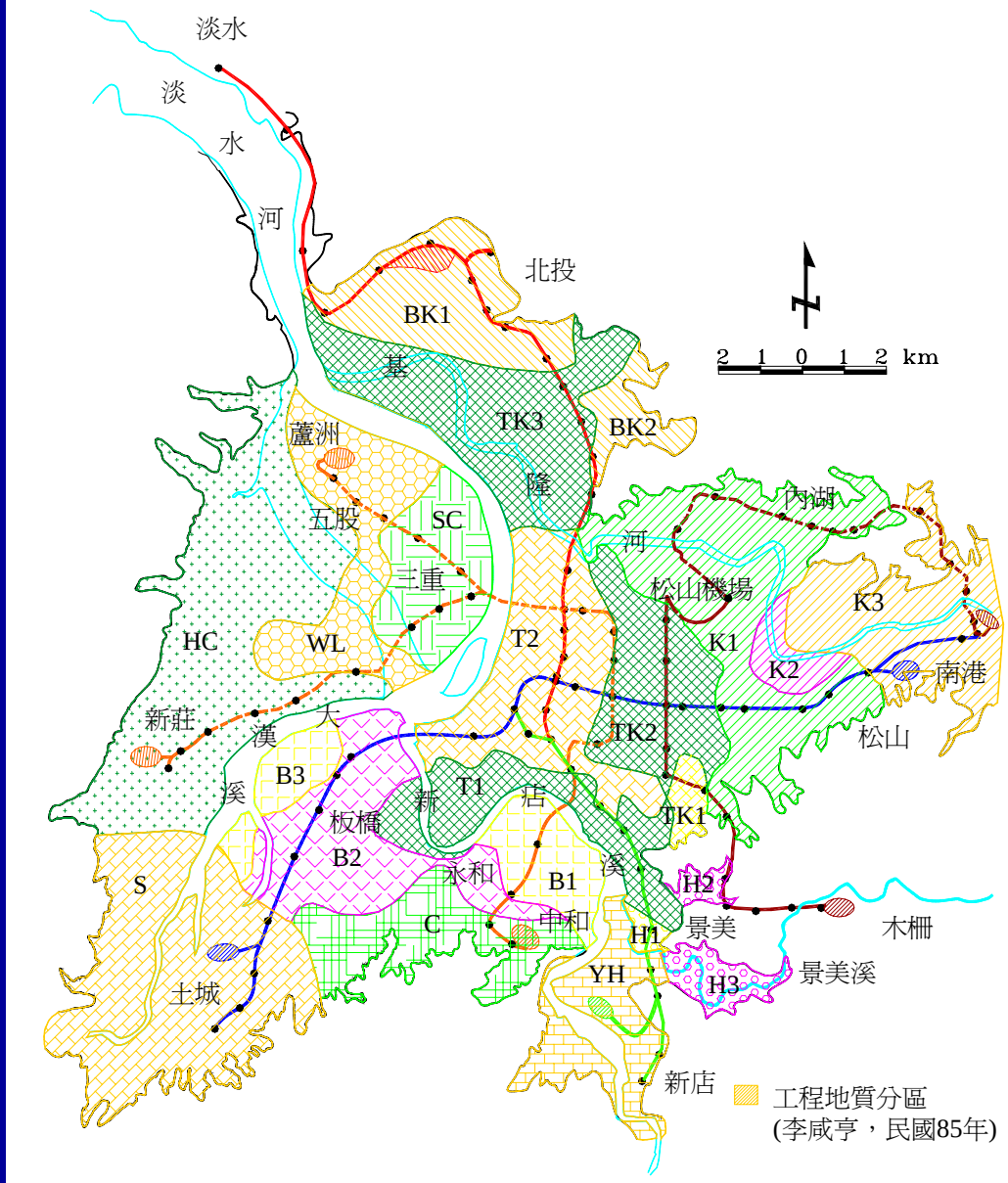

δ
h
1
2
3
4
5
Wall Deflection Path
Wall Deflection
Stage 1
Stage 2
Stage 3
Stage 4
Stage 5
h2
δ2
Inclinometer
Competent Stratum


δ
Wall Deflection
h
Stage 1
Stage 2
Stage 3
Stage 4
Stage 5
h2
δ2
Competent Stratum


q
Analogy between Wall Deflection Path and Stress Path
Failure Envelop
Stress Path
p

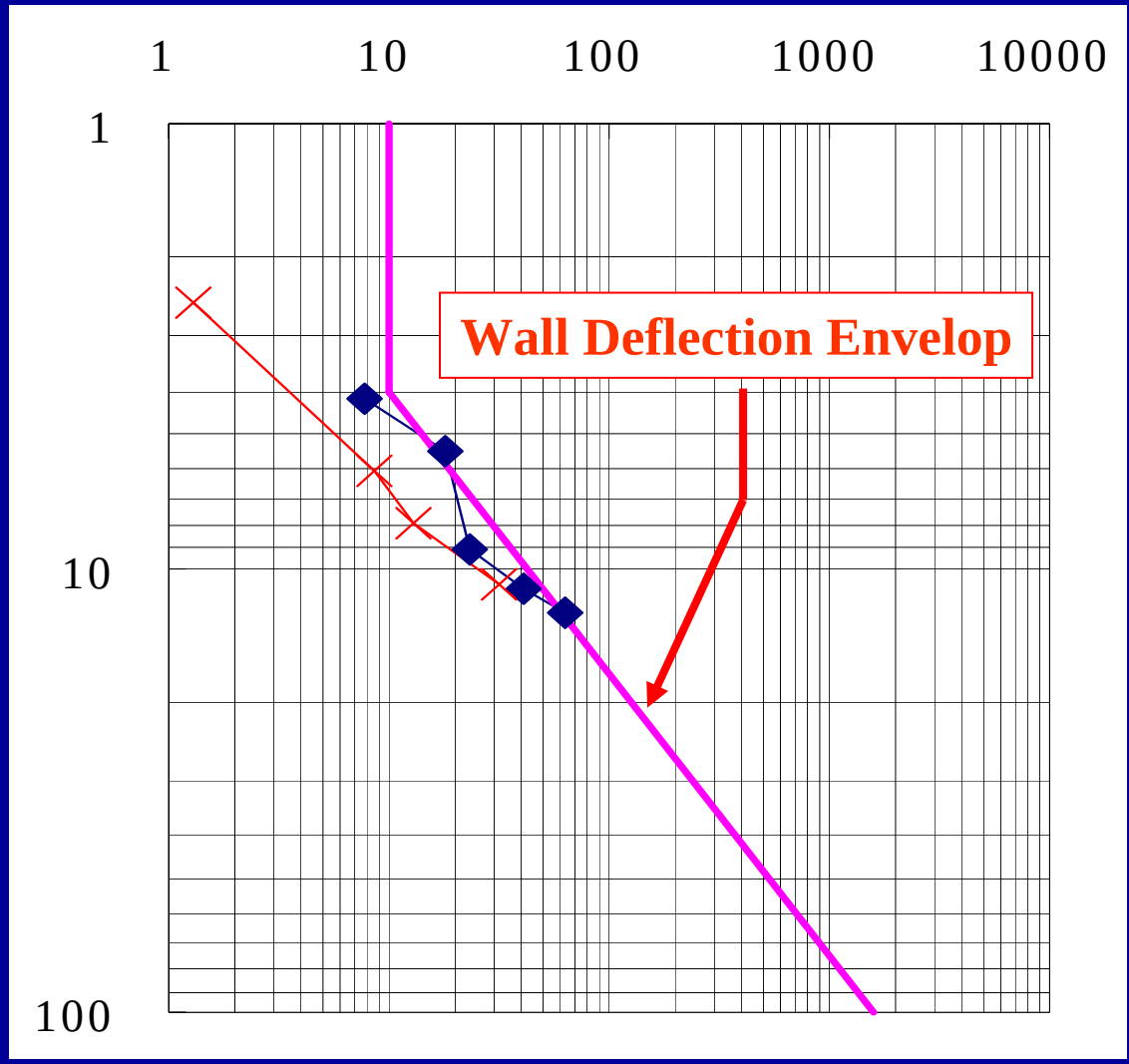


E-W Geological Profile of the Taipei Basin



Geological Zonation of the Taipei Basin

Maximum Wall Deflection, mm



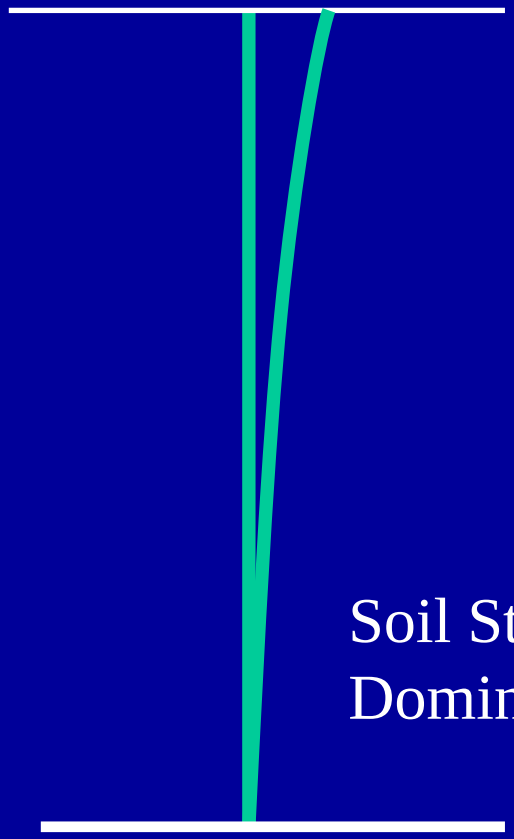
600mm Walls in T2 Zone of Taipei Basin

Reference Envelop

- Reasonable upper bound to guide preliminary design
- Applicable to a certain combination of factors affecting wall deflections.

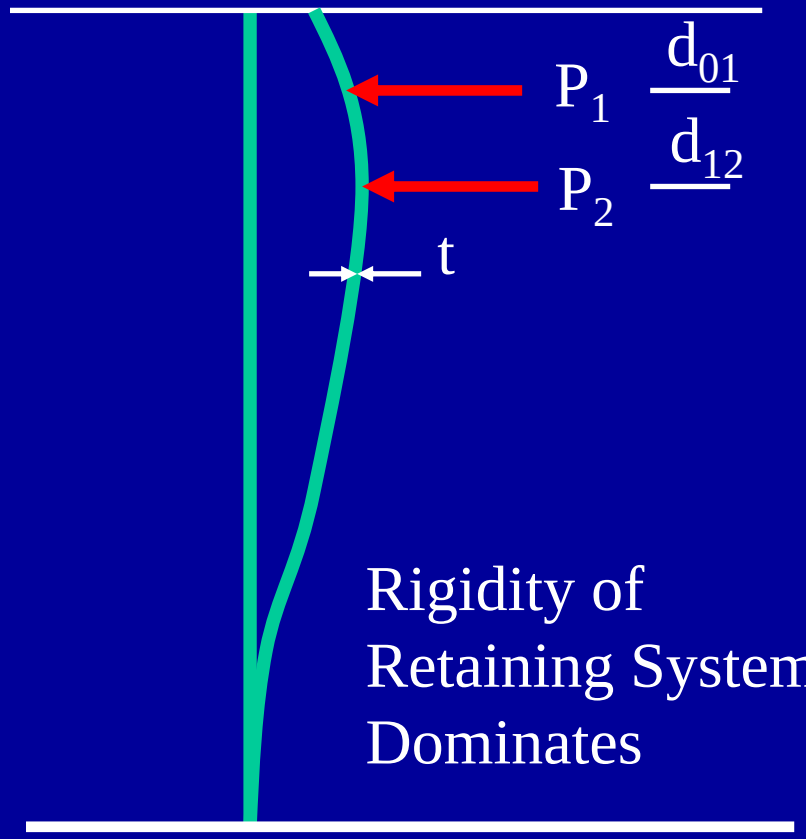
Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Boundaries
- Workmanship/Promptness of Preloading



Soil Stiffness
Dominates

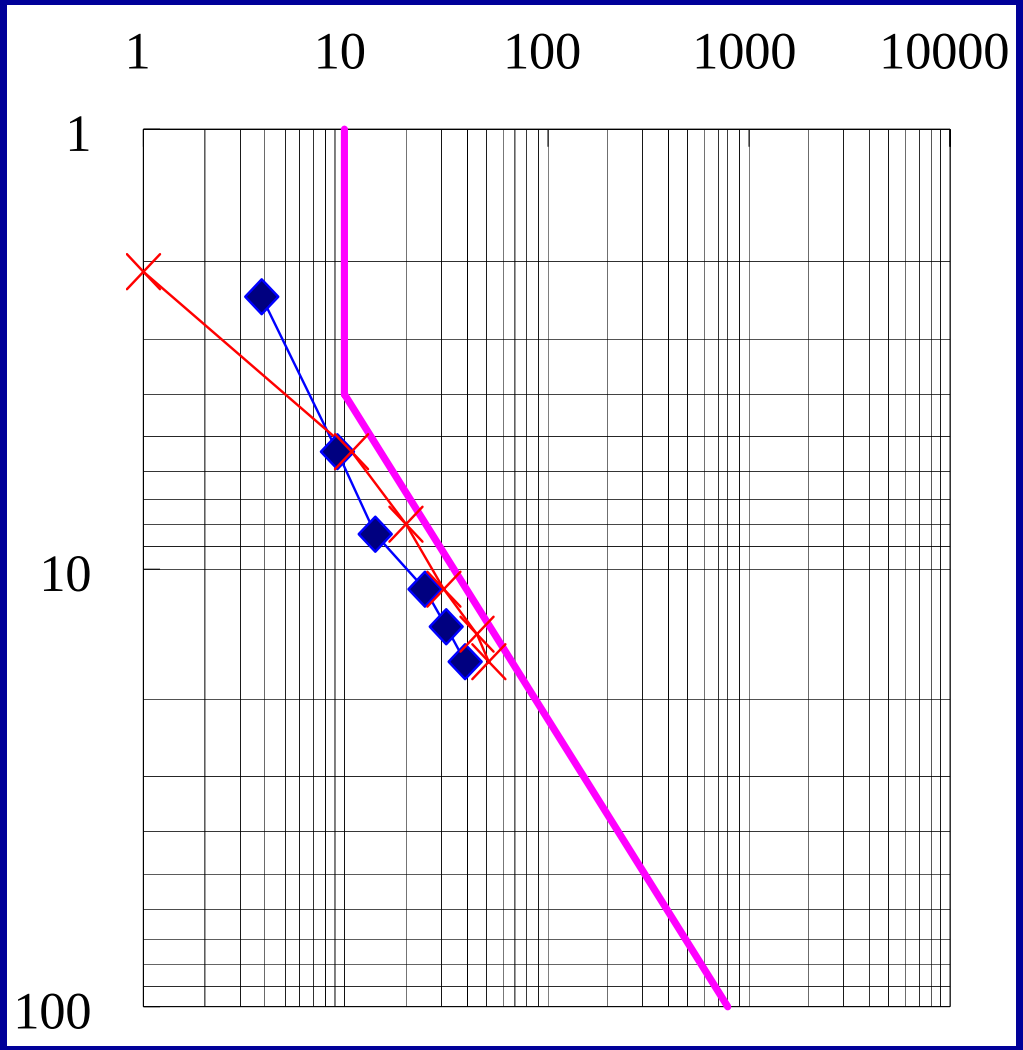
Cantilever



Rigidity of
Retaining System
Dominates

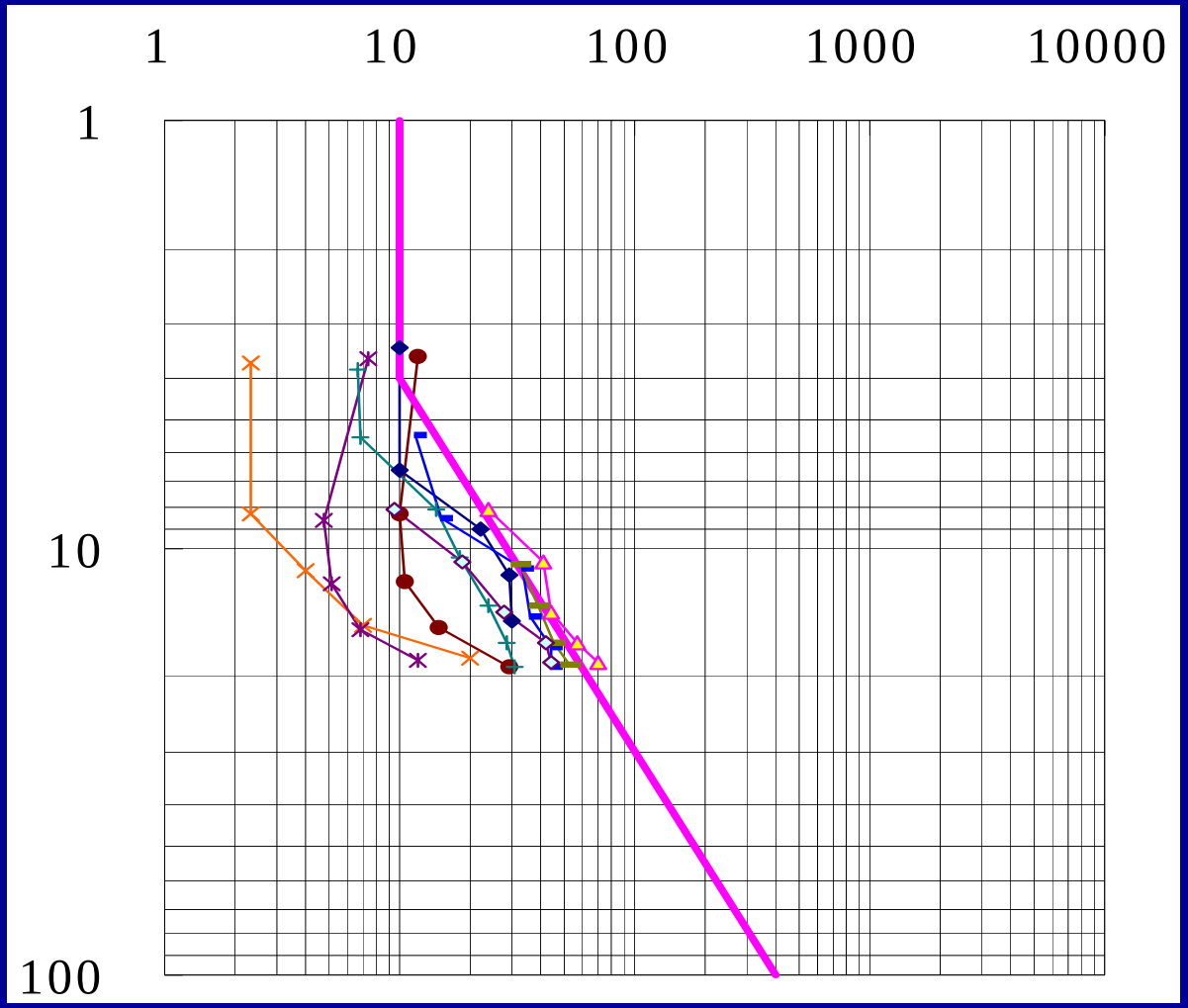
Supported

Maximum Wall Deflection, mm



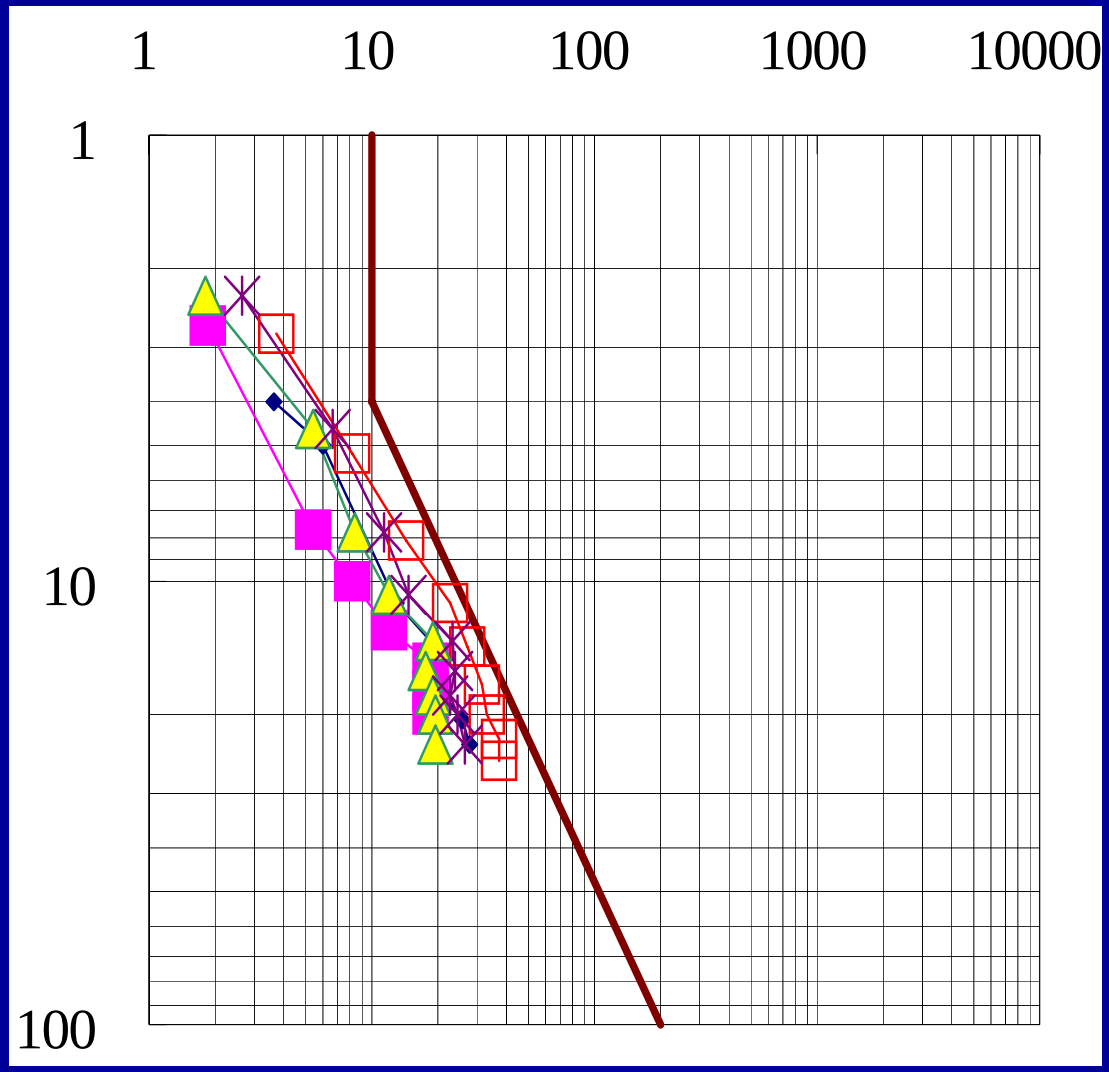
800mm Walls in T2 Zone of Taipei Basin

Maximum Wall Deflection, mm

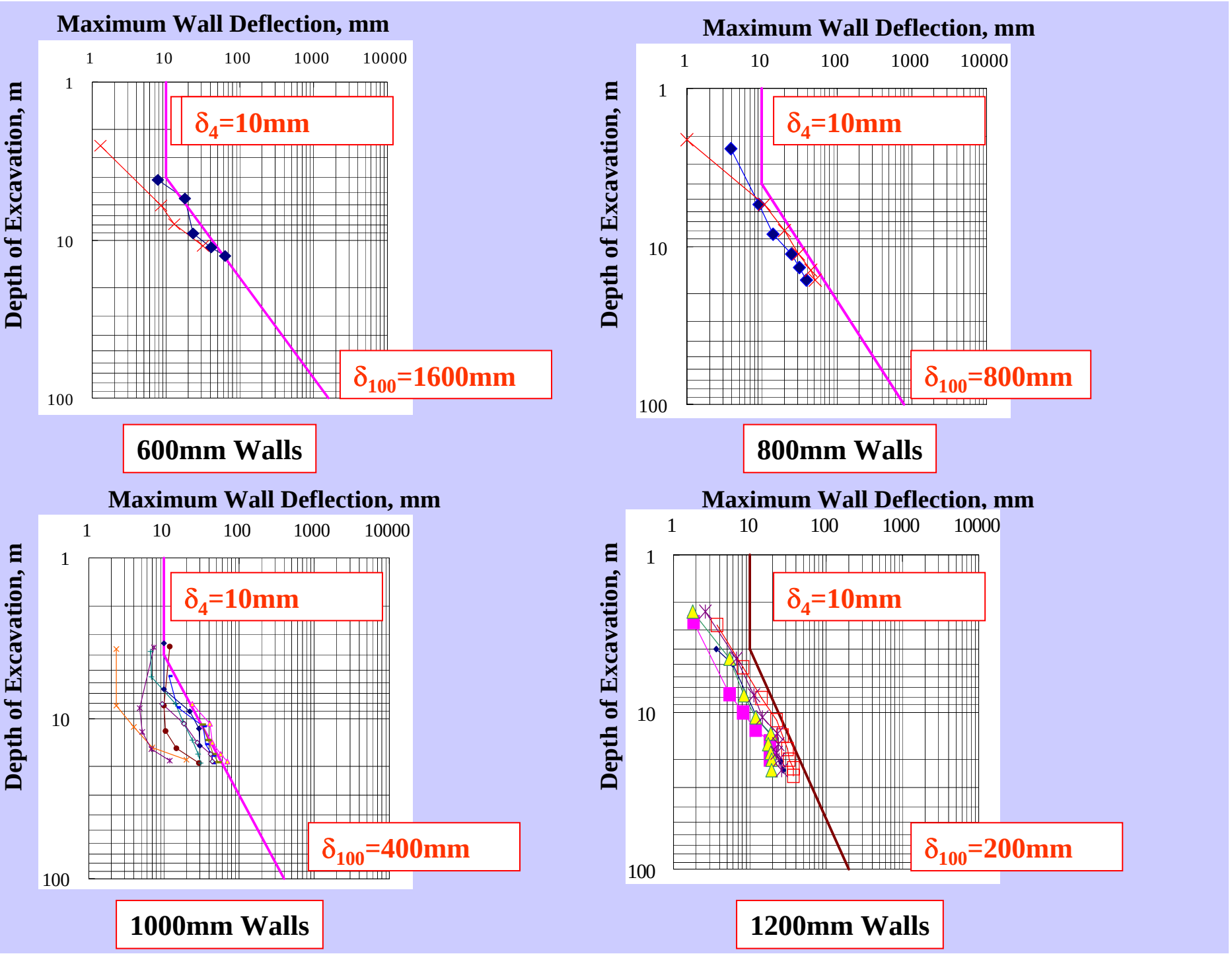


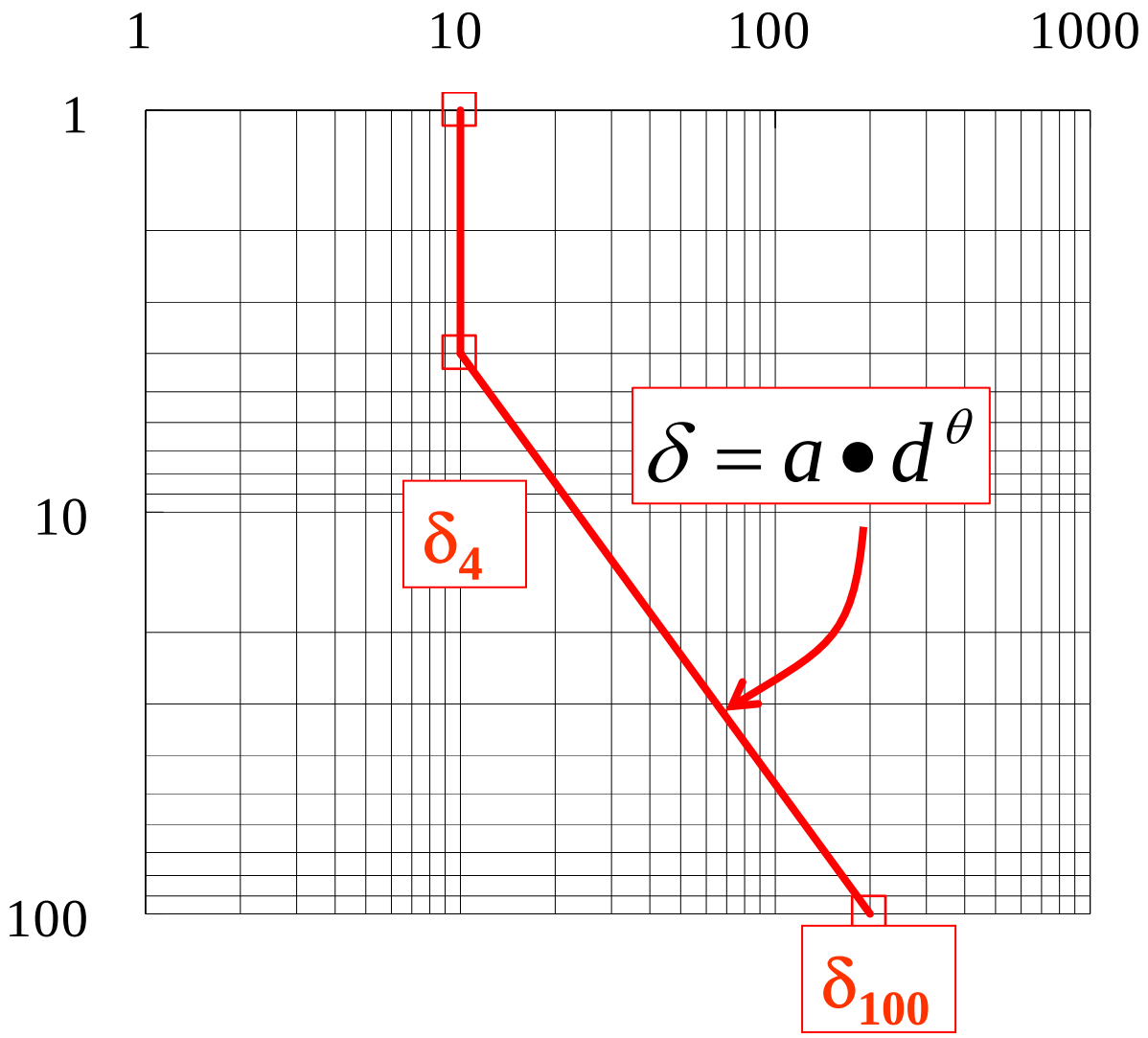
1000mm Walls in T2 Zone of Taipei Basin

Maximum Wall Deflection, mm



1200mm Walls in T2 Zone of Taipei Basin


Maximum Wall Deflection, mm
1
10
100
1000
10000
Depth of Excavation, m
1
10
100
δ4=10mm
δ100=1600mm
600mm Walls
Maximum Wall Deflection, mm
δ4=10mm
δ100=800mm
800mm Walls
Maximum Wall Deflection, mm
δ4=10mm
δ100=400mm
1000mm Walls
Maximum Wall Deflection, mm
δ4=10mm
δ100=200mm
1200mm Walls

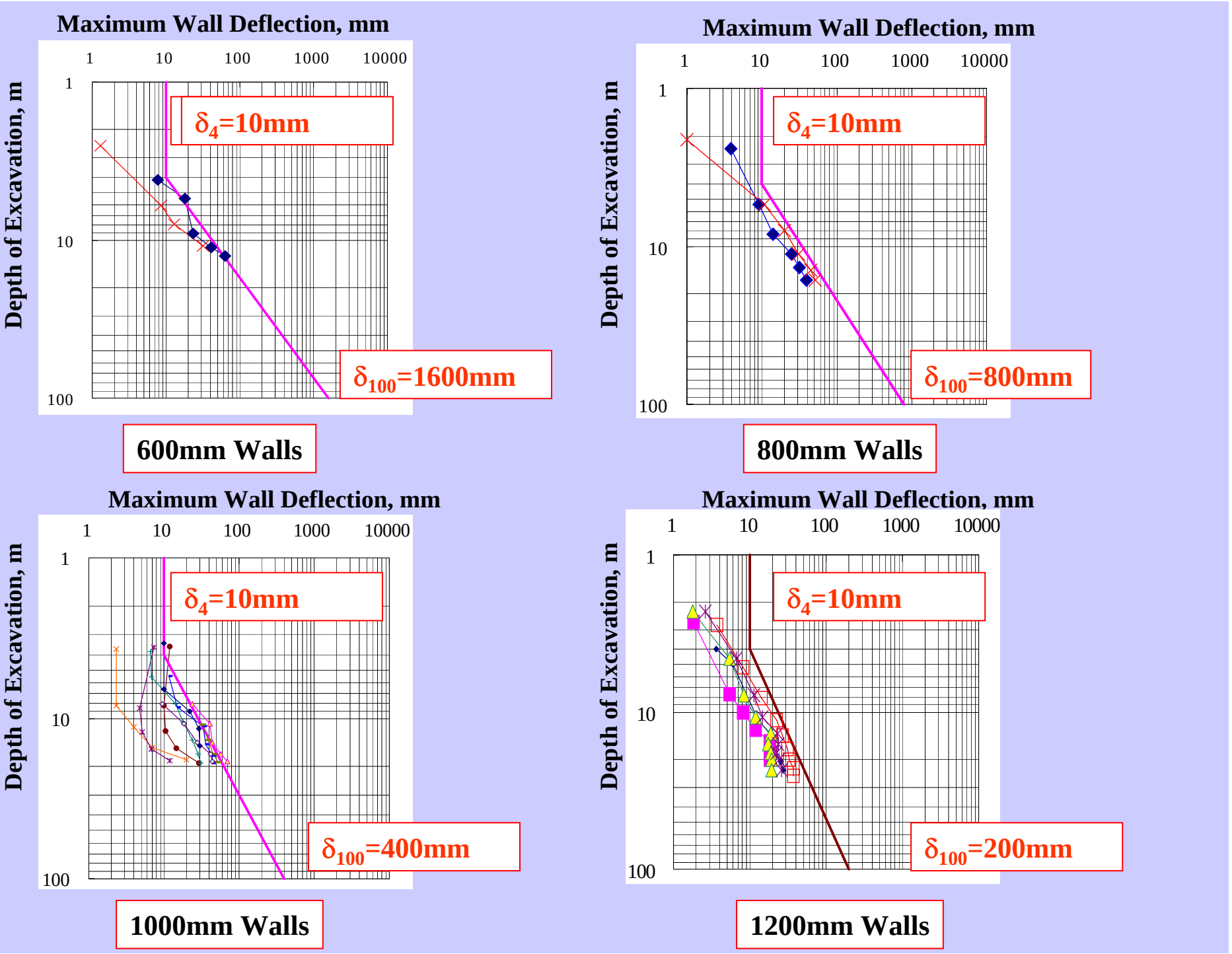

1
10
100
1000
1
10
100
$\delta = a \bullet d^{\theta}$
δ_4
δ_{100}

General Expression

$$\delta = ad^{\theta}$$

$$\log \delta = \log a + \theta \log d$$

$$\theta = 0.715 \bullet \log\left(\frac{\delta_{100}}{\delta_4}\right)$$


Maximum Wall Deflection, mm
1
10
100
1000
10000
Depth of Excavation, m
1
10
100
δ4=10mm
δ100=1600mm
600mm Walls
Maximum Wall Deflection, mm
δ4=10mm
δ100=800mm
800mm Walls
Maximum Wall Deflection, mm
δ4=10mm
δ100=400mm
1000mm Walls
Maximum Wall Deflection, mm
δ4=10mm
δ100=200mm
1200mm Walls

Values of θ governed by wall stiffness

- 600mm walls : 1.576
- 800mm walls : 1.363
- 1000mm walls : 1.147
- 1200mm walls : 0.932

For T2 Zone, Buttom-Up, no Ground Treatment, & Similar Strutting and Preloading Scheme

Deflection Paths

- δ_4 =10mm
- δ_{100}
  - 600mm walls : 1600mm
  - 800mm walls : 800mm
  - 1000mm walls : 400mm
  - 1200mm walls : 200mm

$$\delta_{100} = \left(\frac{\delta_{100}}{\delta_4} \right) \bullet \delta_4$$

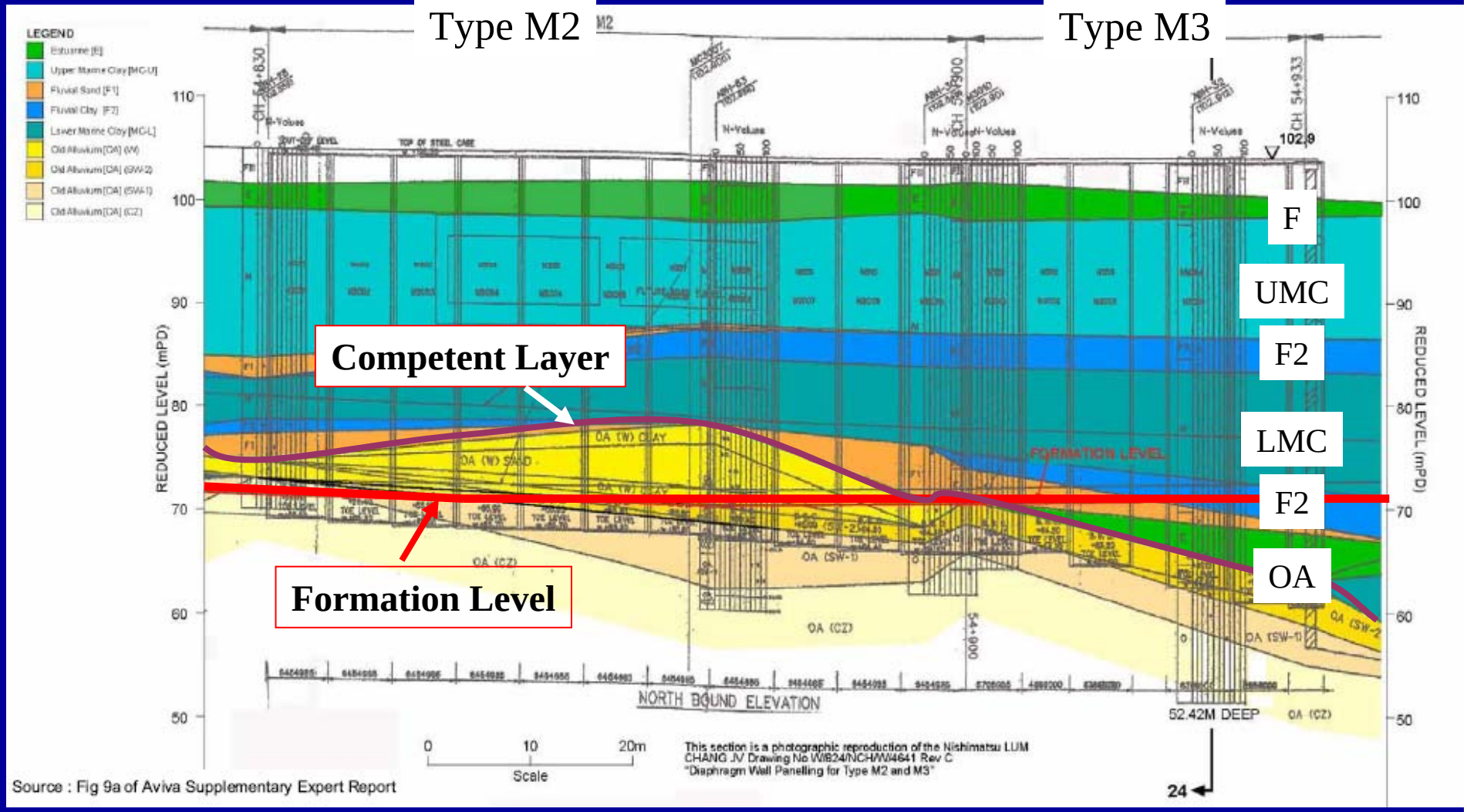
Bottom-Up Constructions in T2 Zone

- δ_4 =10mm
- δ_{100}
  - 600mm walls : 160 δ_4
  - 800mm walls : 80 δ_4
  - 1000mm walls : 40 δ_4
  - 1200mm walls : 20 δ_4

Factors to be Considered

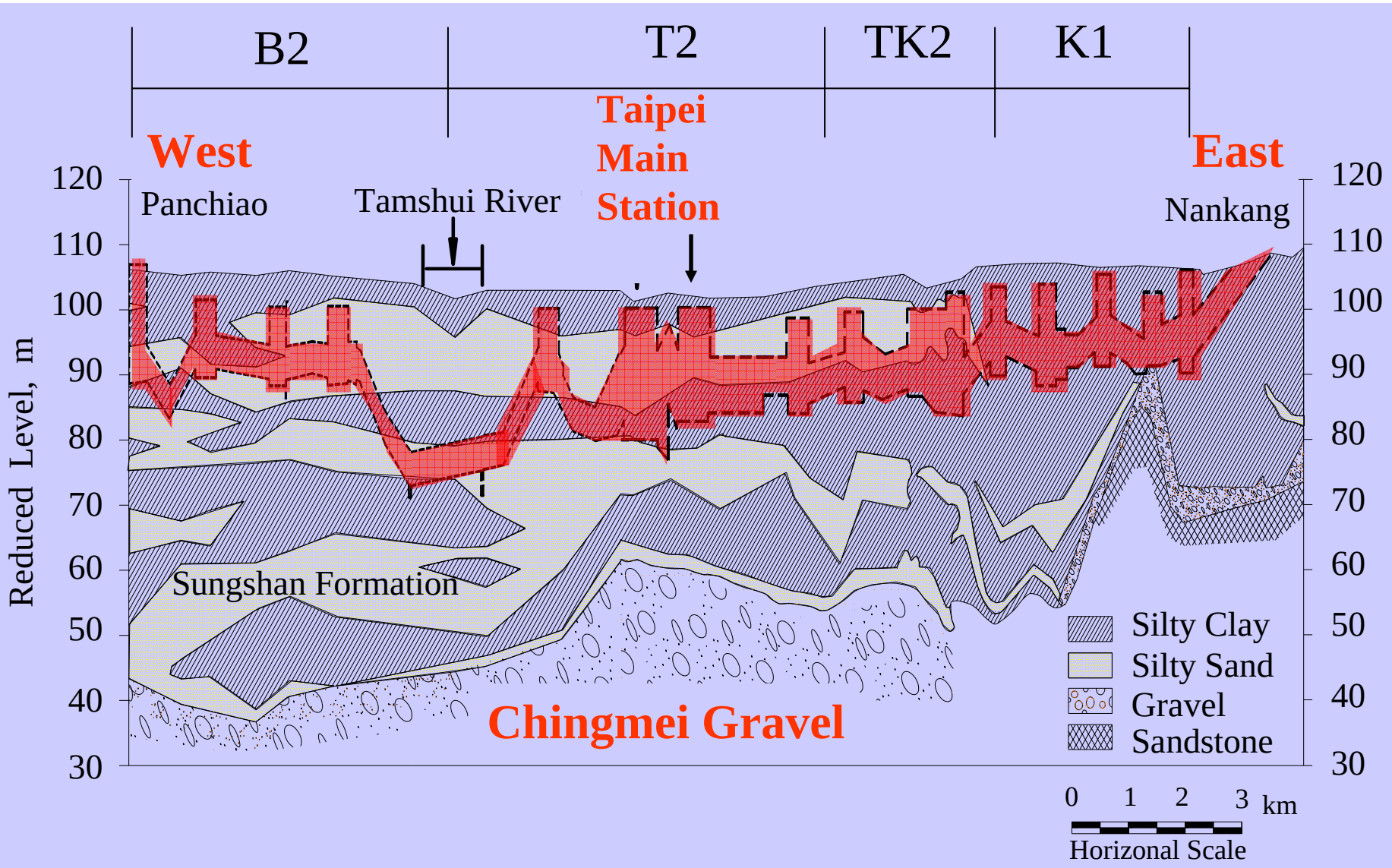
- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Workmanship/Promptness of Preloading


Nicoll Highway, Singapore (2004/4/20)

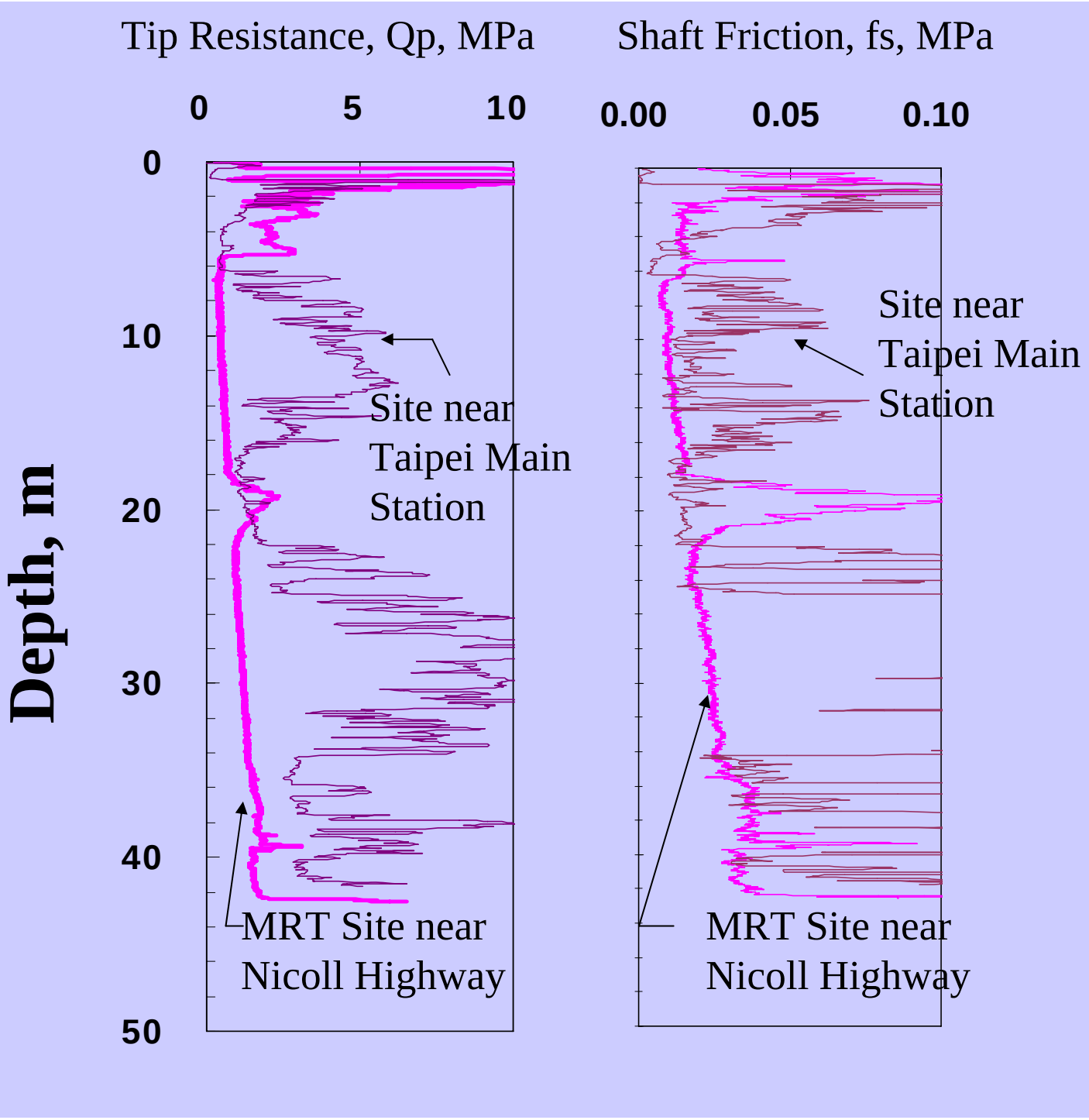


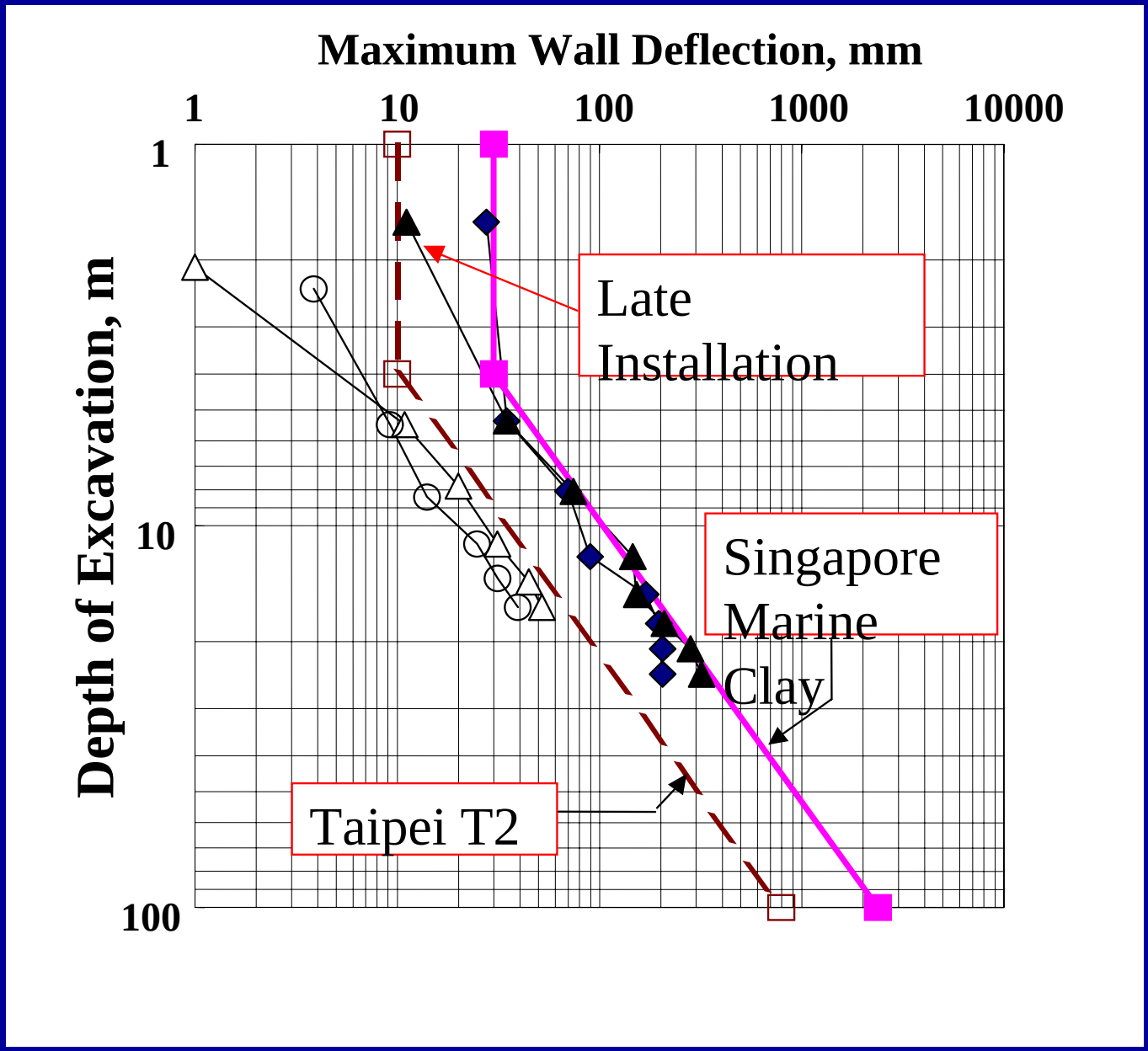
資料來源： COI, 2005

Soil Profile Near Nicoll Highway



E-W Geological Profile of the Taipei Basin


Tip Resistance, Qp, MPa
Shaft Friction, fs, MPa
0
5
10
0.00
0.05
0.10
Depth, m
0
10
20
30
40
50
Site near Taipei Main Station
MRT Site near Nicoll Highway
Site near Taipei Main Station
MRT Site near Nicoll Highway



Compare T2 Zone and Singapore Marine Clay (800mm Wall)

Effects of Ground Conditions

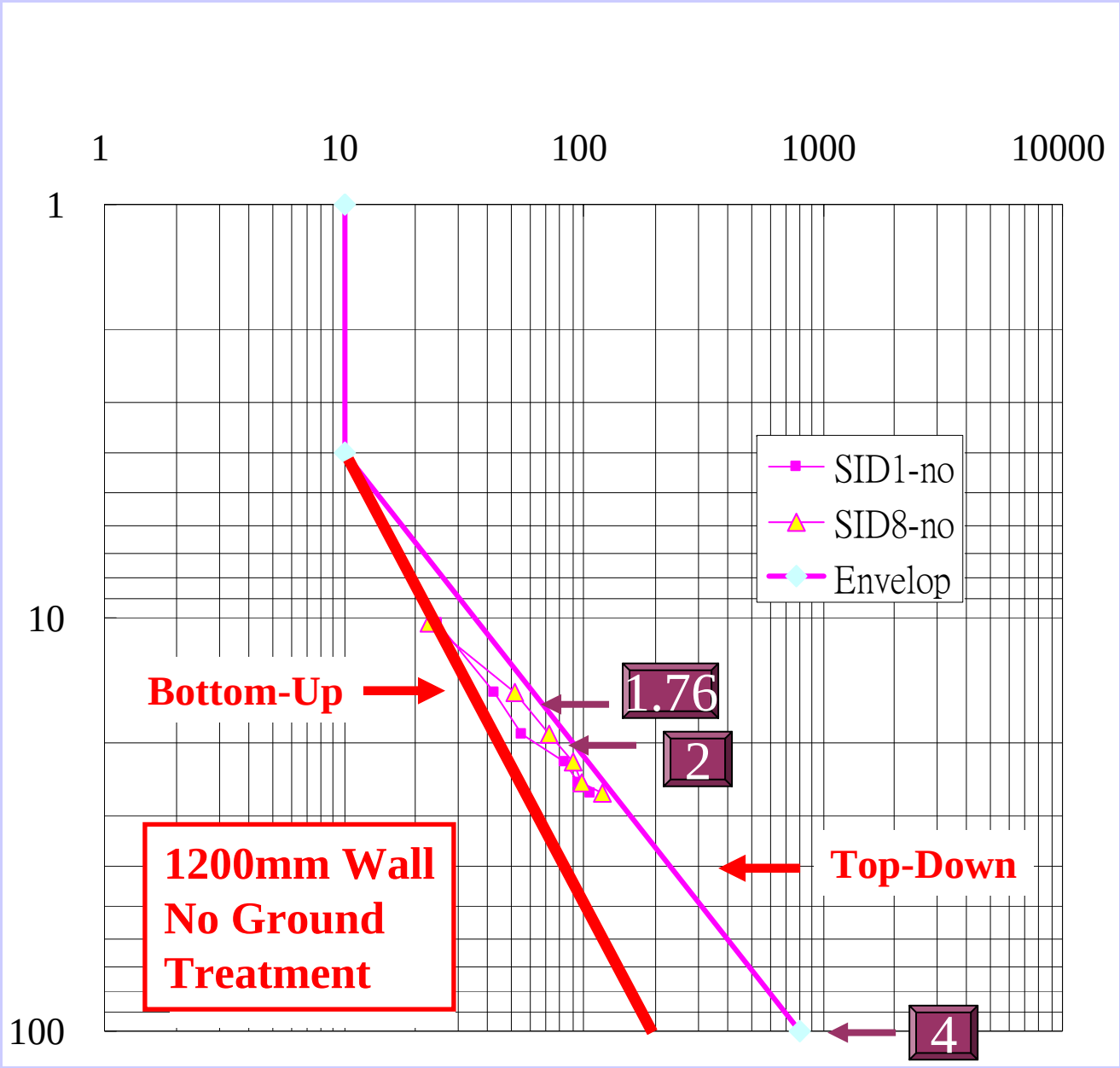
$$\delta_{100} = \left(\frac{\delta_{100}}{\delta_4} \right) \bullet \delta_4$$

Bottom-Up Constructions in Singapore Marine Coastal Deposits

- δ_4 =10mm **x 3**
- δ_{100}
  - 600mm walls : 160 δ_4
  - 800mm walls : 80 δ_4
  - 1000mm walls : 40 δ_4
  - 1200mm walls : 20 δ_4

Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Boundaries
- Workmanship/Promptness of Preloading

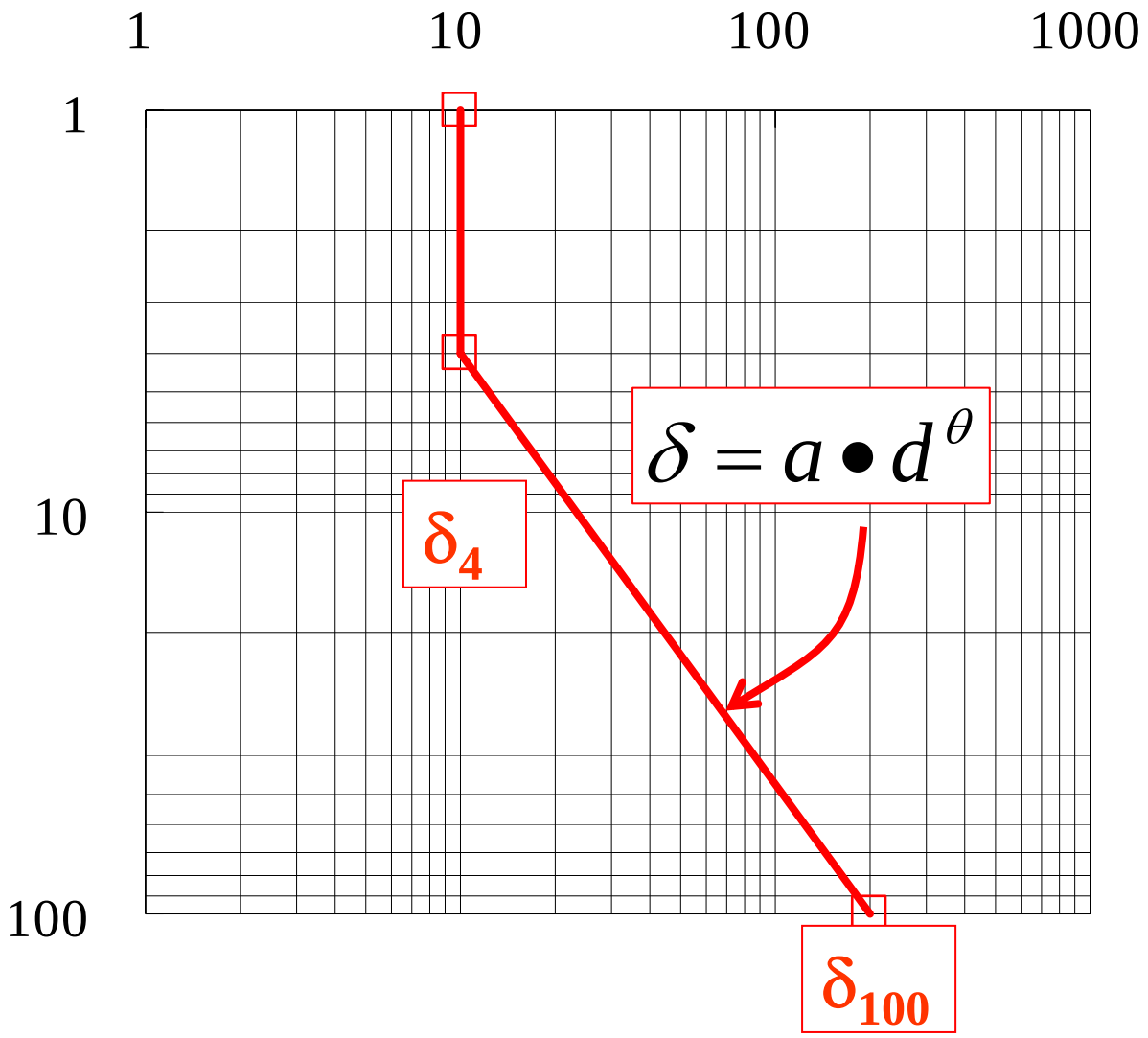

1
10
100
1000
10000
1
10
100
SID1-no
SID8-no
Envelop
Bottom-Up
1.76
2
Top-Down
4
1200mm Wall
No Ground
Treatment

$$\delta_{100} = \left(\frac{\delta_{100}}{\delta_4} \right) \bullet \delta_4$$

Top-Down Constructions in T2 Zone

- δ_4 =10mm
- δ_{100}
  - 600mm walls : 160 δ_4
  - 800mm walls : 80 δ_4
  - 1000mm walls : 40 δ_4
  - 1200mm walls : 20 δ_4

} x **4**


1
10
100
1000
1
10
100
$\delta = a \bullet d^{\theta}$
δ_4
δ_{100}

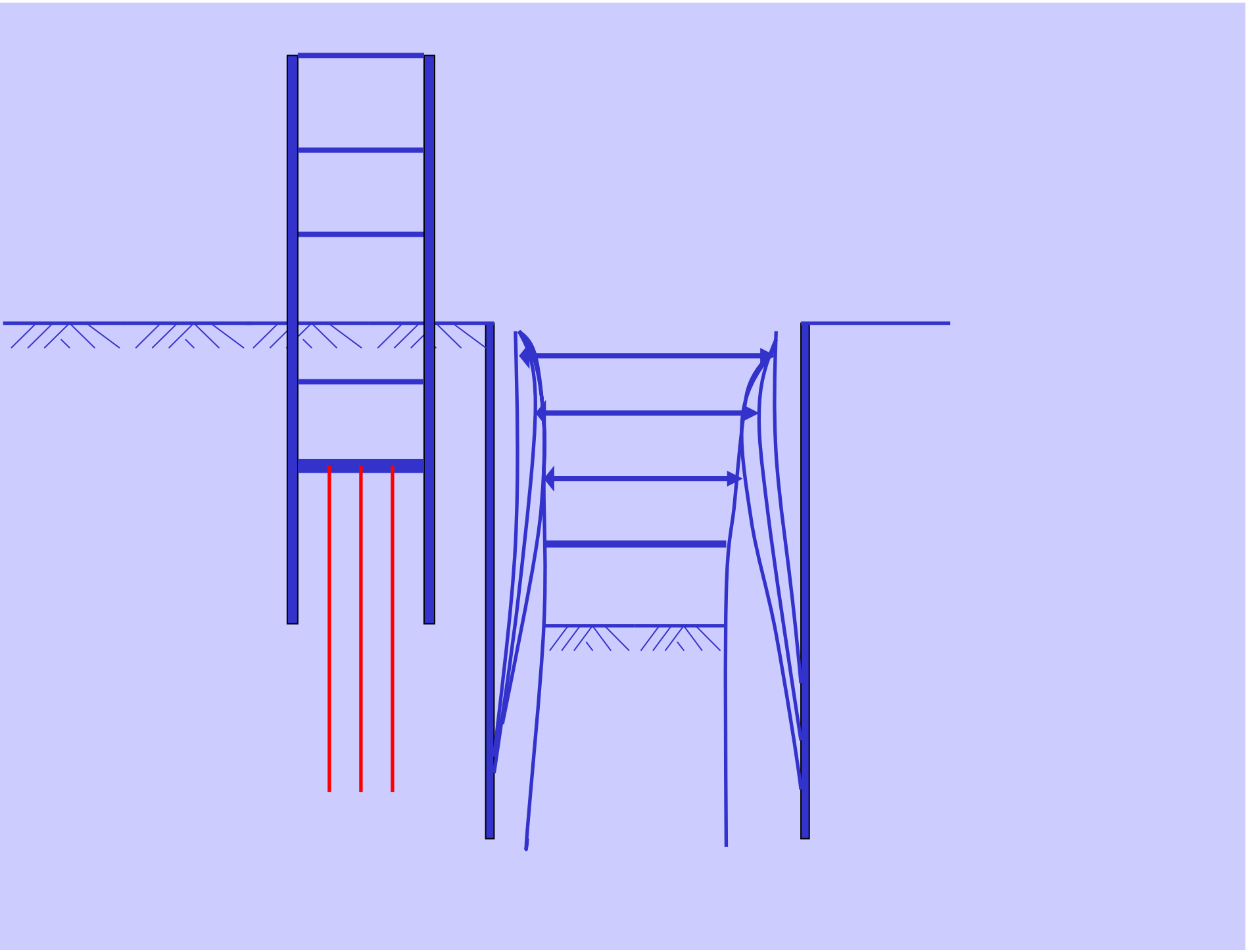
$$\delta_{100} = \left(\frac{\delta_{100}}{\delta_4} \right) \bullet \delta_4$$

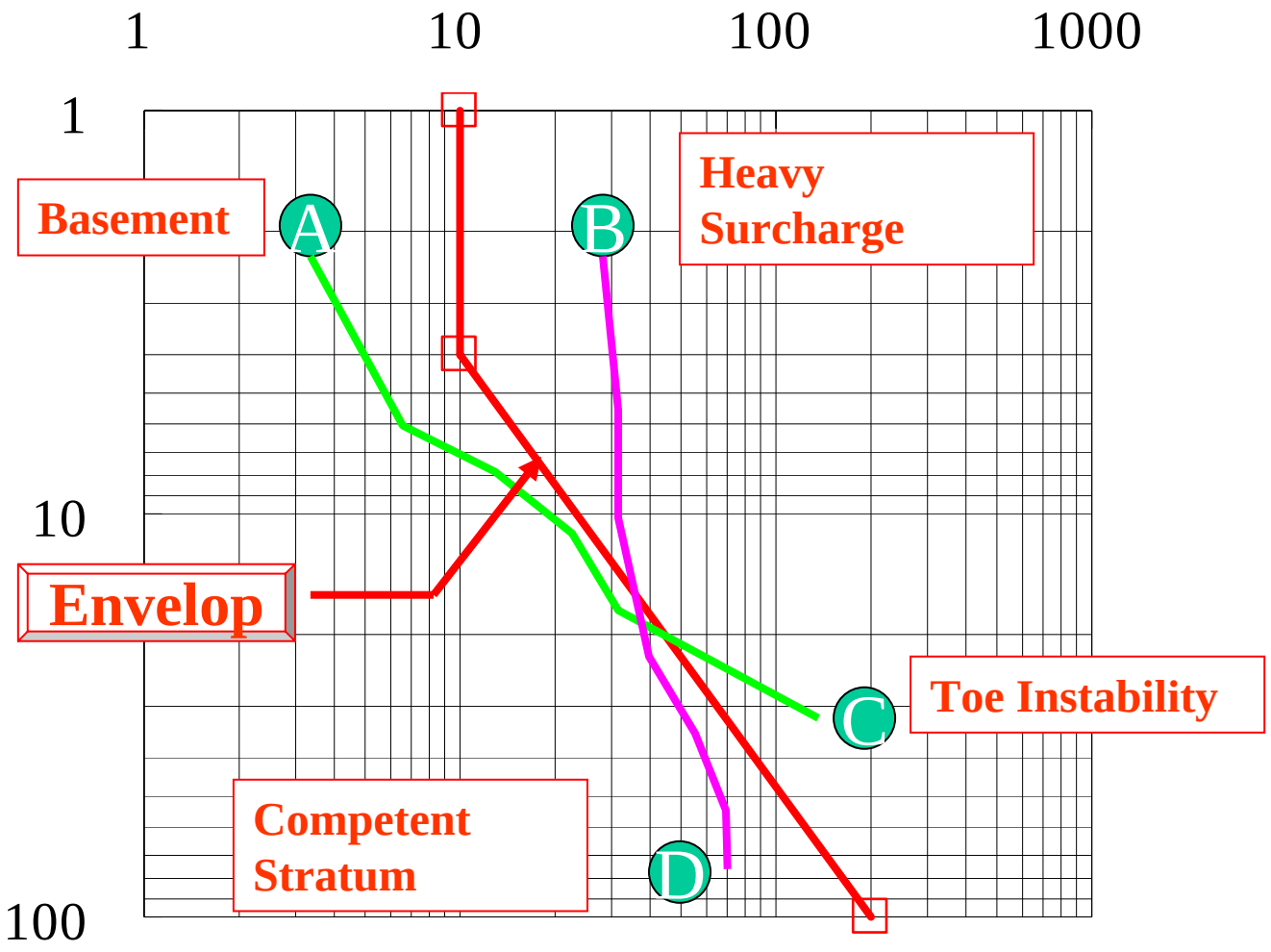
$$\delta_{100} = C_{mc} \bullet C_t \bullet \delta_4$$

Method of Construction	Rigidity of Retaining System	Stiffness of Soils
Bottom-Up: 1 Top-Down: 4	1200mm: 20 1000mm: 40 800mm: 80 600mm: 160	T2: 1(=10mm) SMC: 3

Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions/Treatment
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Workmanship/Promptness of Preloading



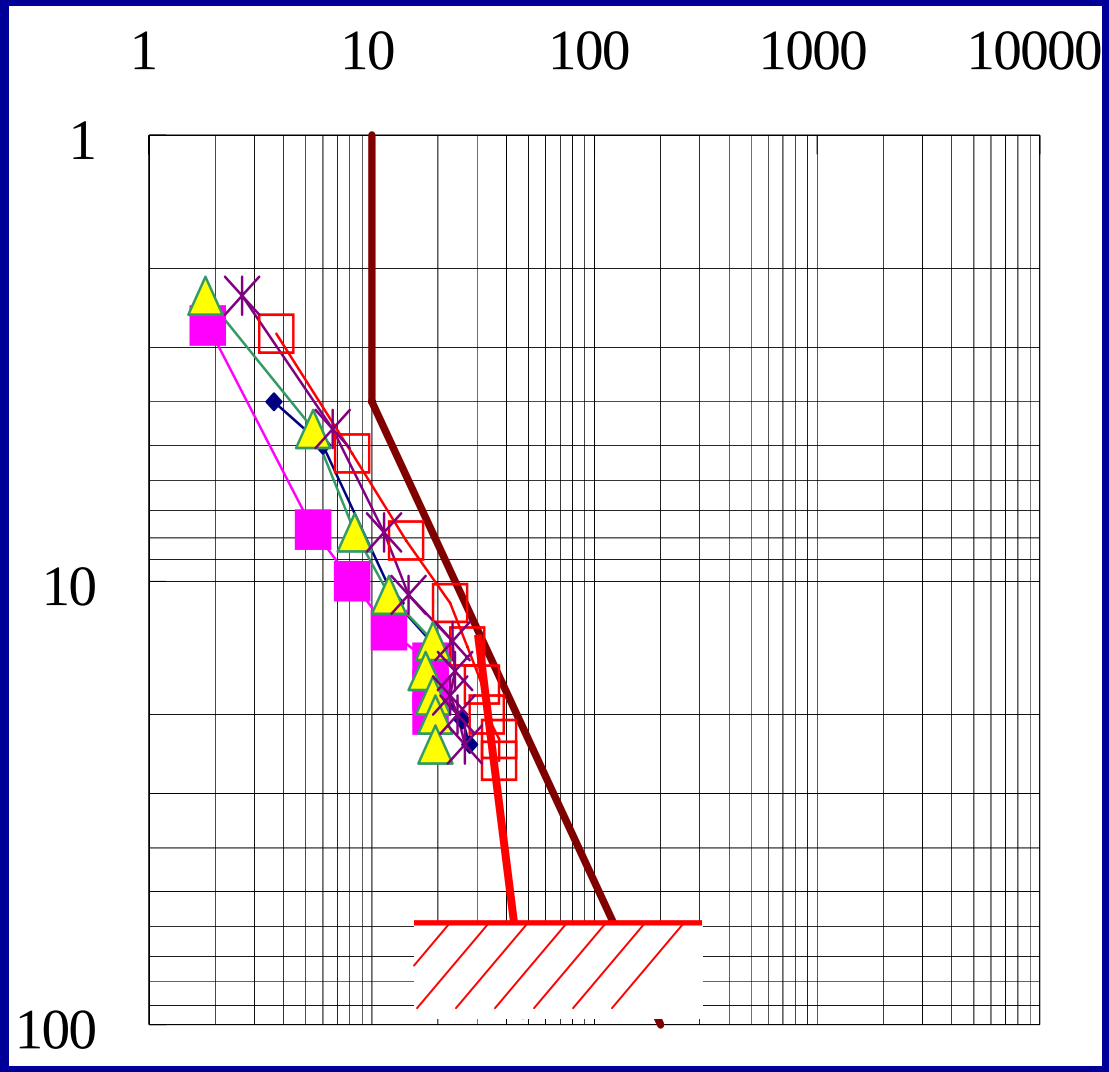


Interpretation of Wall Deflection Path

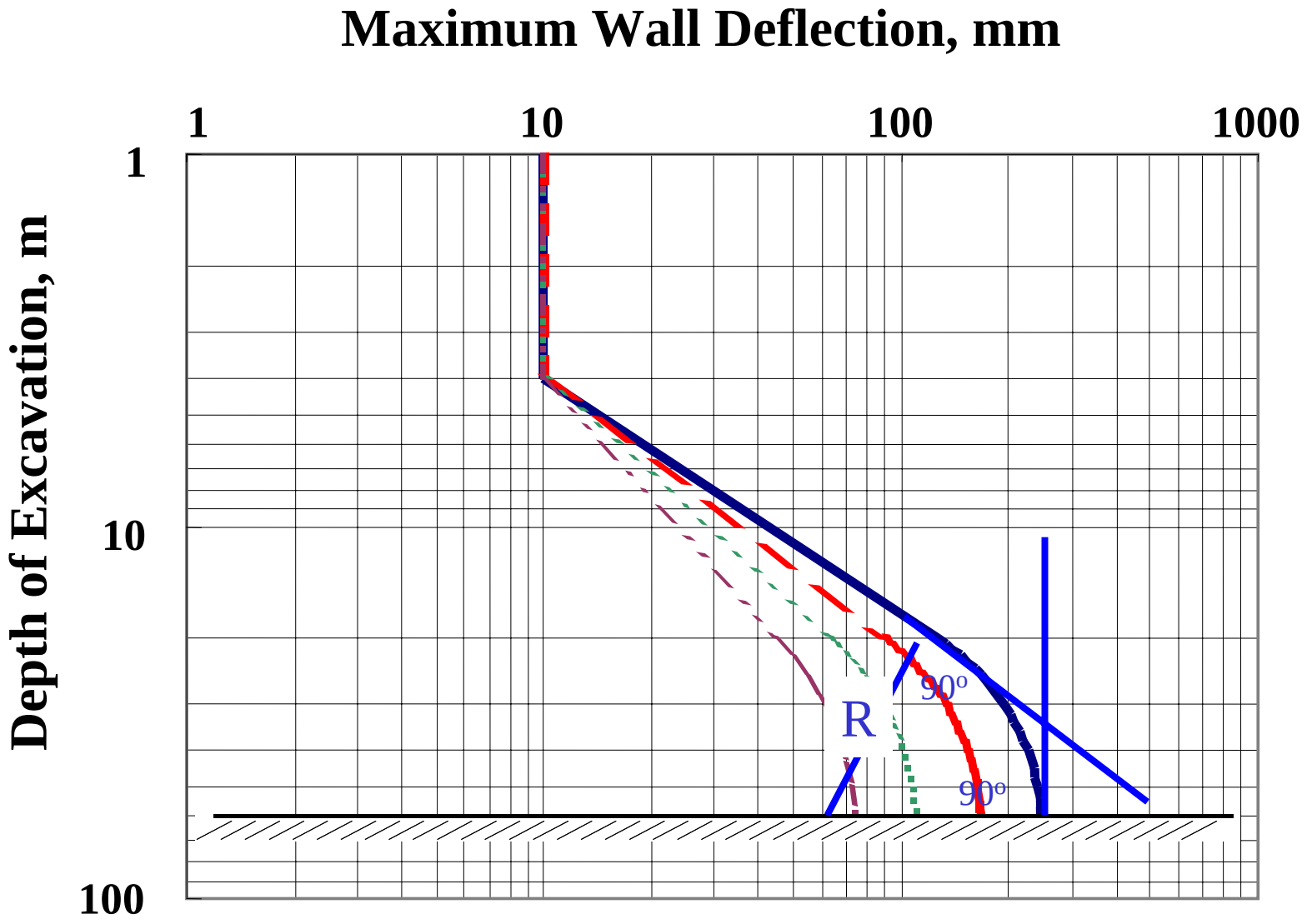
Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions/Treatment
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Boundaries
- Workmanship/Promptness of Preloading

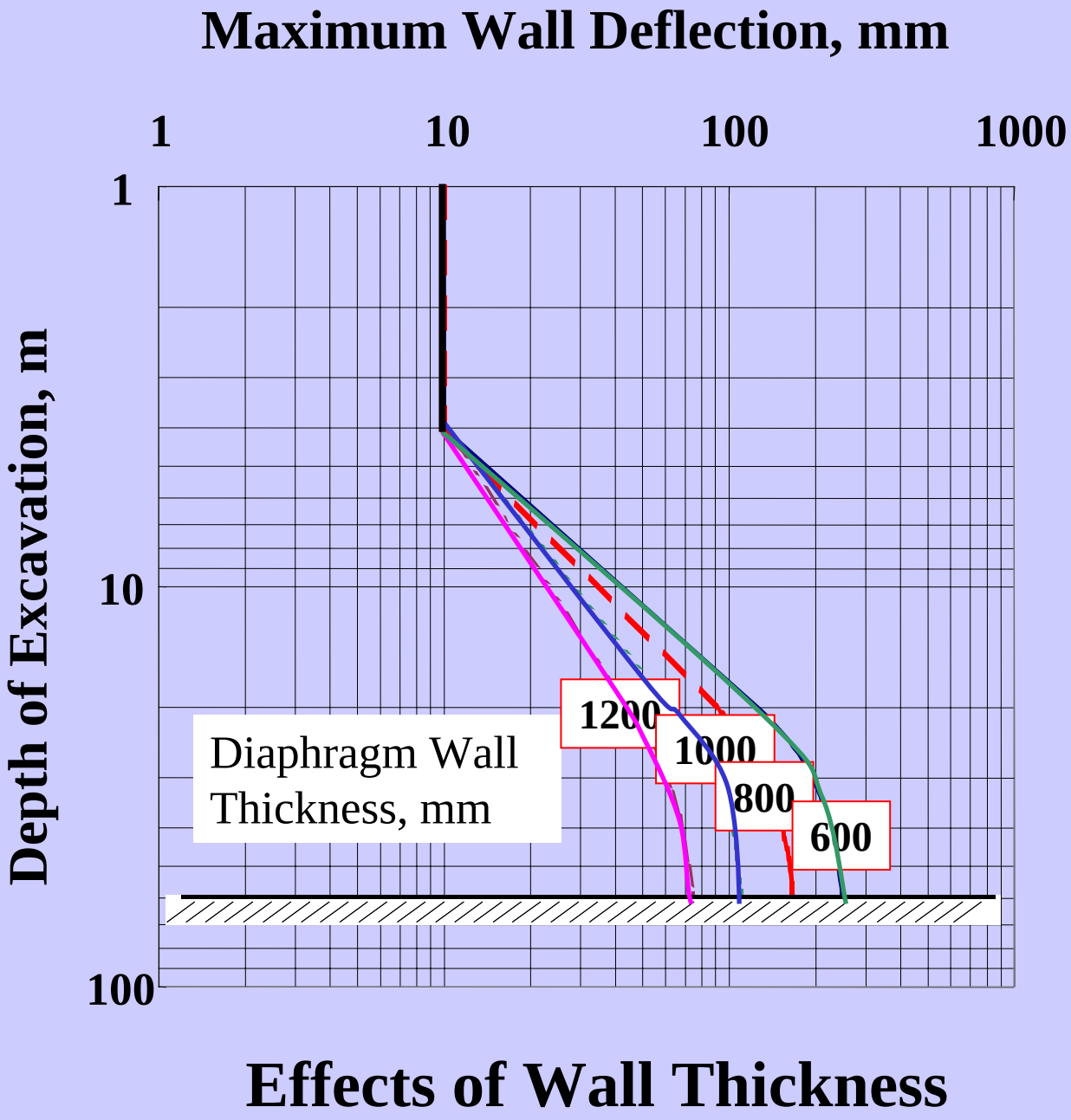
Maximum Wall Deflection, mm



1200mm Walls in T2 Zone of Taipei Basin



Assuming Competent Stratum at a Depth of 60m



Effects of Wall Thickness

Factors to be Considered

- Depth of Excavation
- Stiffness of Retaining Structure (Wall, Strut, Spacing, Preload)
- Ground Conditions/Treatment
- Method of Construction
- Surcharge Load/Structure/Basement/Pile
- Boundaries
- Workmanship/Promptness of Preloading

Workmanship

- The effects of over-excavation, delay in strutting and preloading, etc. are implicitly incorporated by enveloping deflection paths.
- Extraordinary deflection paths shall be excluded.
- Therefore, reference envelops correspond to normal workmanship.

Conclusions

- The concept of “Reference Envelop” can be adopted to evaluate the performance of diaphragm walls.
- It can also be used to evaluate the effects of various factors affecting the performance of walls.

Conclusions

- Factors affecting wall deflections, from a practical point of view, can be decoupled.
- Wall deflections for shallow excavations are dominated by ground conditions and surcharge load.
- Slopes of deflection paths are dominated by rigidity of retaining structures (wall thickness, spacing between struts, preload, etc.)

Future Studies

- Buttress/Wall thickness
- Grout Slab /Thickness of Soft Deposits
- Ground Treatment/ Soil properties

Thank You for Your Attention