NEW ZEALAND GEOTECHNICAL SOCIETY inc.

An NZGS 1 day short course

NEW ZEALAND GEOTECHNICAL SOCIETY inc.

Ground movement control

Deep excavations

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Outline

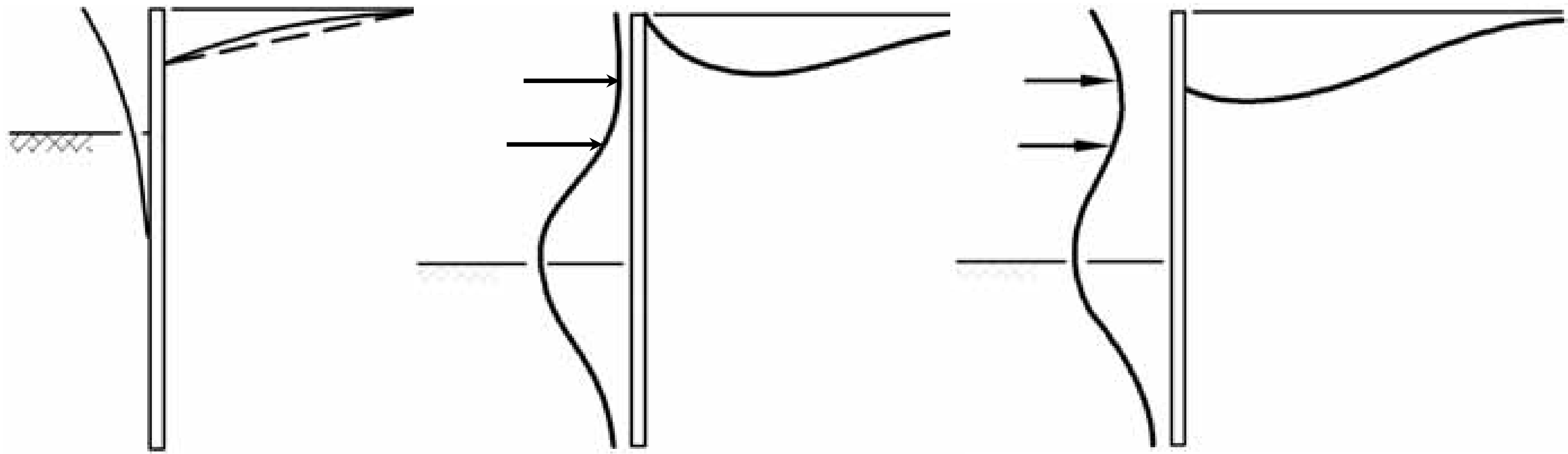
- Introduction. Generation of ground movements by deep excavations
- Empirical methods for estimating ground movements
- Methods for calculating ground movements
- Procedures for control and reduction of movements
- A case history
- Excavations with large movements: announcing failure?
- Conclusions

Excavation-induced ground movements

- The performance of an excavation with retaining walls inevitably causes movements in the wall and surrounding ground
  - We will mainly focus on “normal” movements (i.e. on those corresponding to an adequate construction not on those arising from accidents)
  - We will focus on movements associated basically to the excavation process
- Tolerance concerning the acceptable deformation level (in urban environment) has reduced significantly in recent years
  - It means enhanced requirements for estimation and control of movements

Deformation mechanisms

- Two basic deformation modes



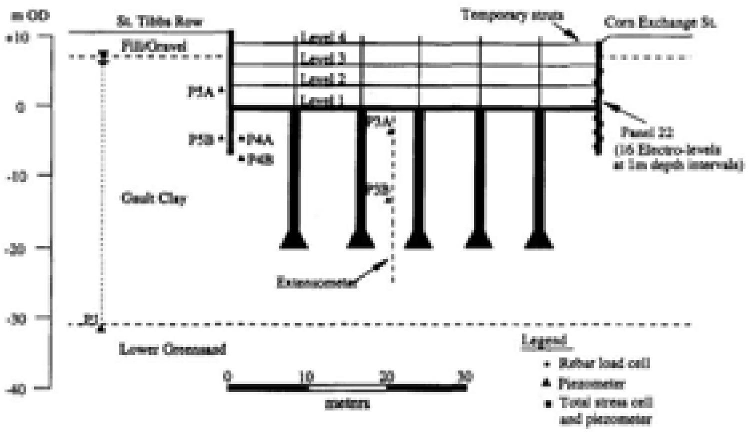
Cantilever wall

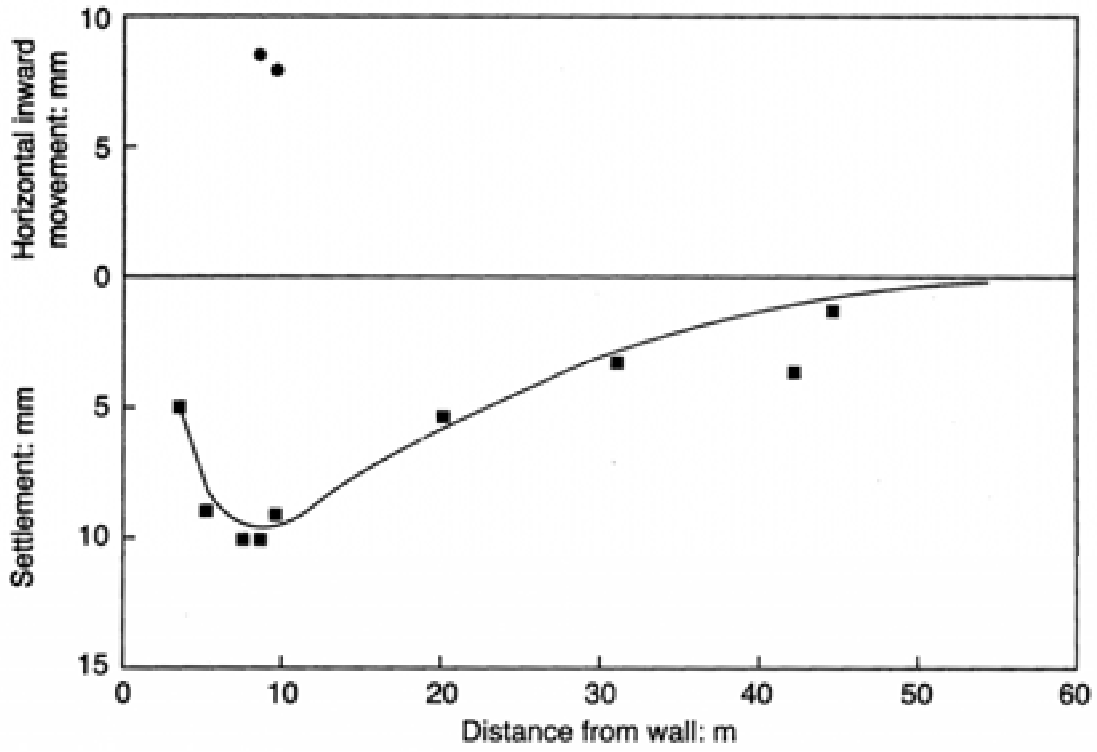
Propped wall

Total displacements

Deformation mechanisms

- Surface horizontal displacements often ignored
  - they are more difficult to measure (less experience)

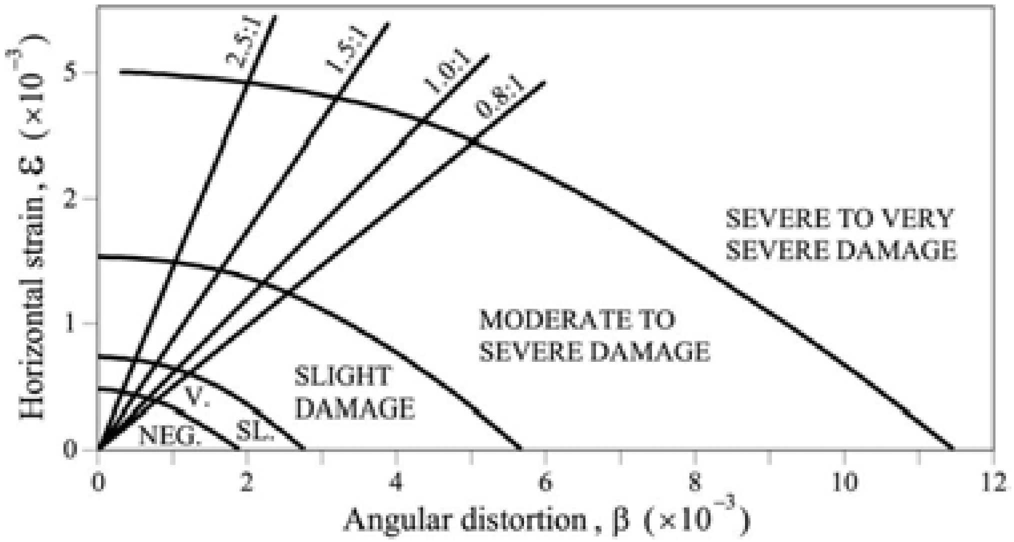


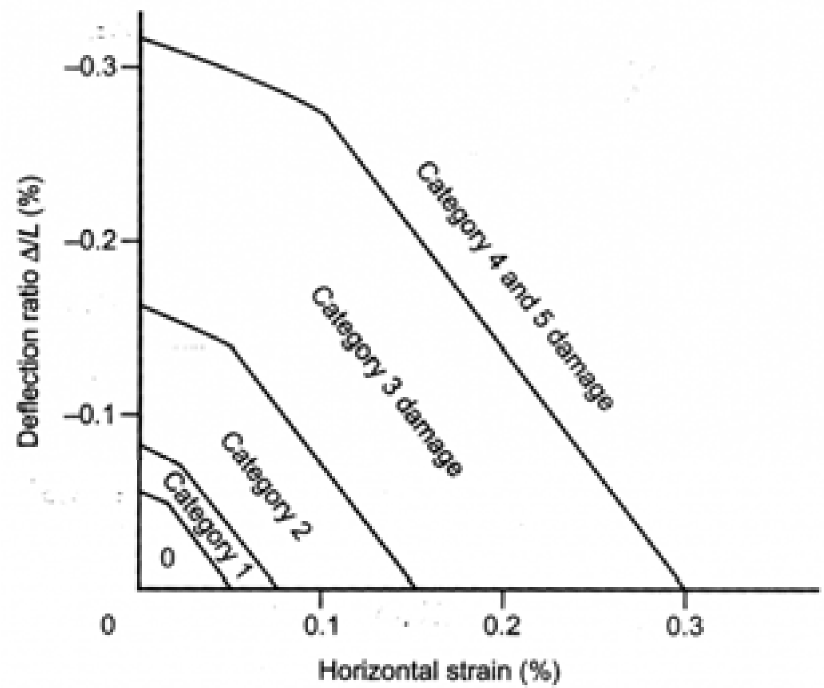


Lion Yard excavation (Ng, 1998)

Deformation mechanisms

- Tension horizontal deformation contributes significantly to damage of buildings and structures



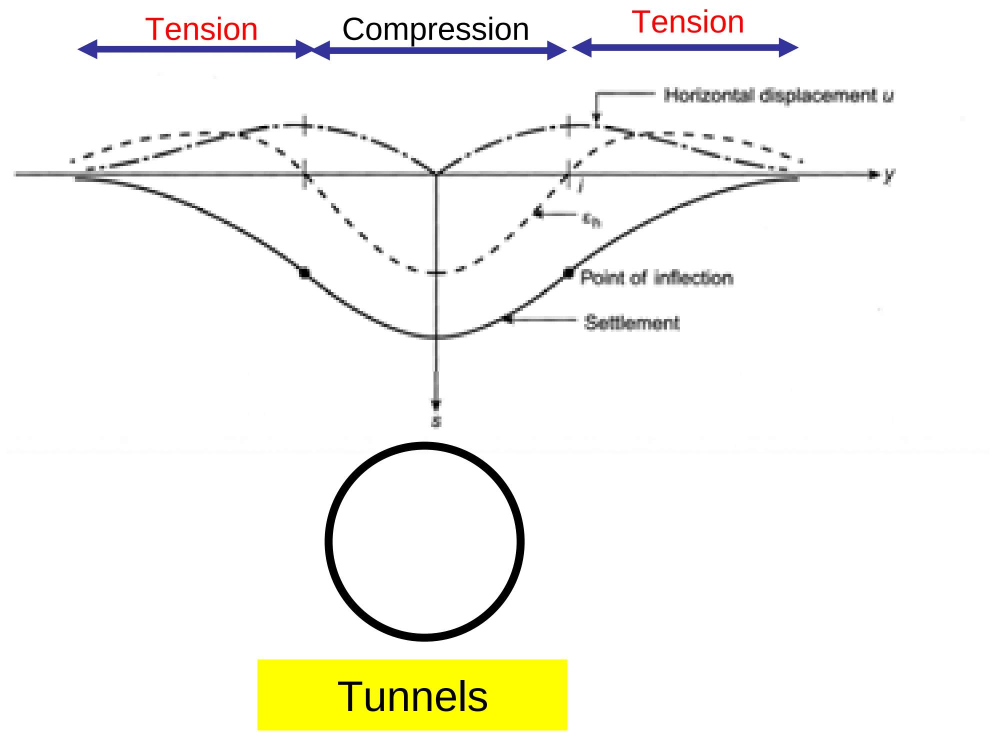


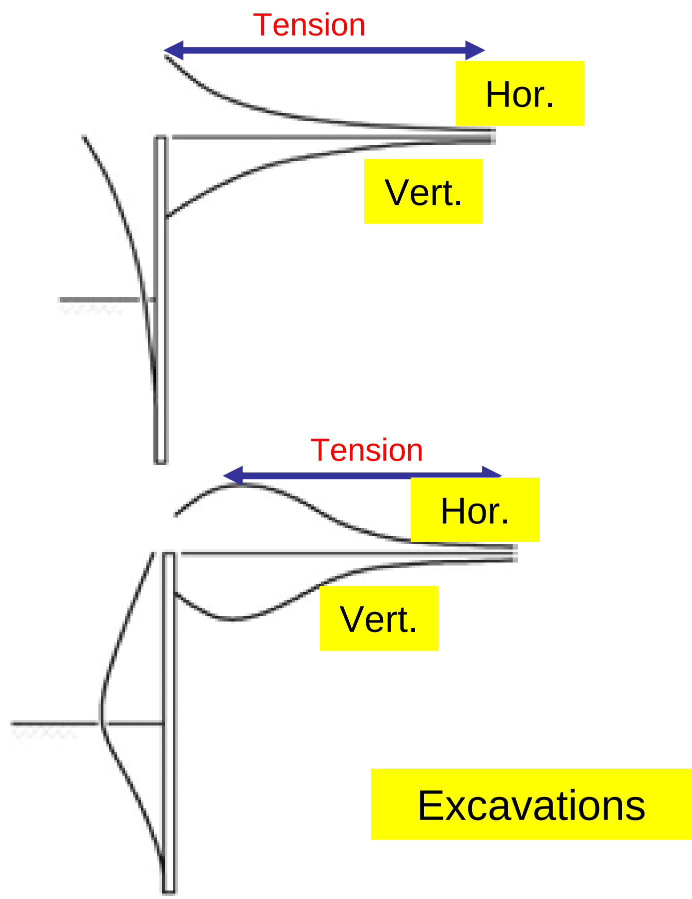
Boscardin & Cording (1989)

Burland (1998)

Deformation mechanisms

- Tension horizontal strains contribute significantly to the damage of buildings and structures
  - the majority of horizontal strains associated to deep excavations are tension strains (more unfavourable than in the tunnelling case)
  - the response of a building may depend significantly on its horizontal stiffness





Deformation mechanisms

- Factors that influence ground movements caused by excavations
  - stress changes in the ground (due to excavation and construction)
  - excavation size (depth and width)
  - ground properties
  - initial horizontal stresses in the ground
  - hydraulic conditions and their variation
  - wall and prop stiffness
  - preloading of propos and anchors
  - external loads
  - construction procedure
  - construction quality
  - others...

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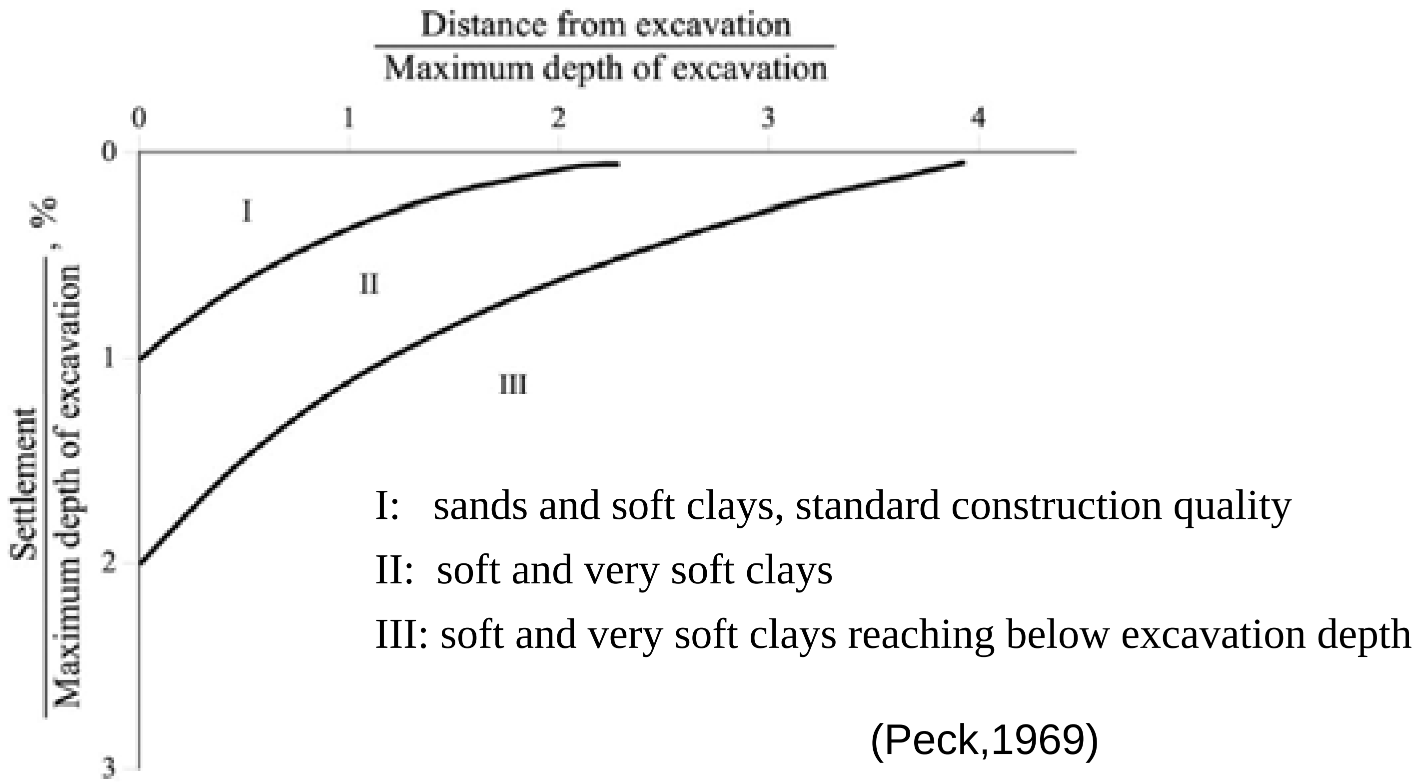
Settlements

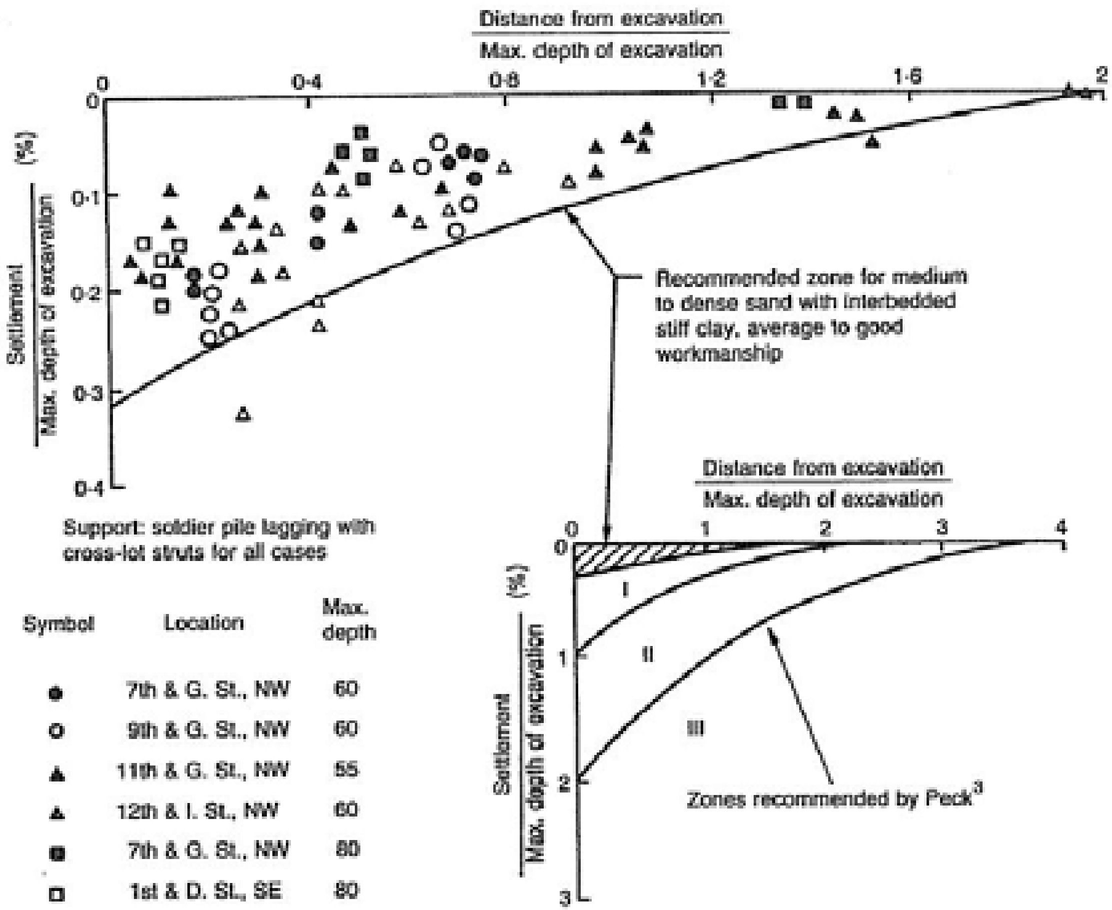


(Peck,1969)

- Curves obtained from excavations with sheet pile walls or soldier piles. Reduced embedment

Empirical methods for evaluating movements

- Support: soldier pile lagging with struts

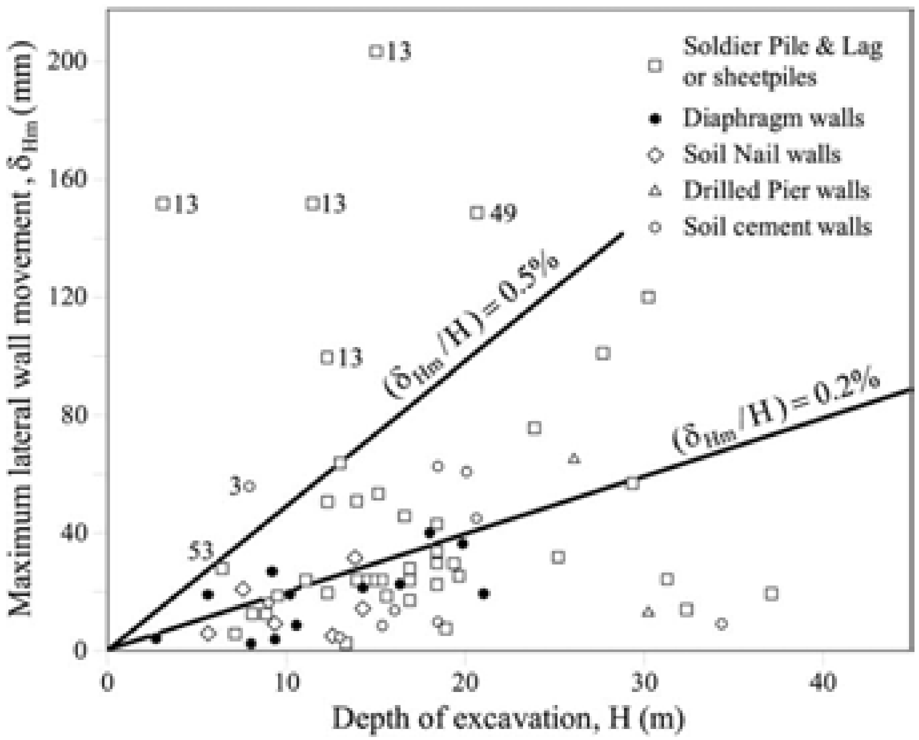


Medium to dense sand with interbedded stiff clay

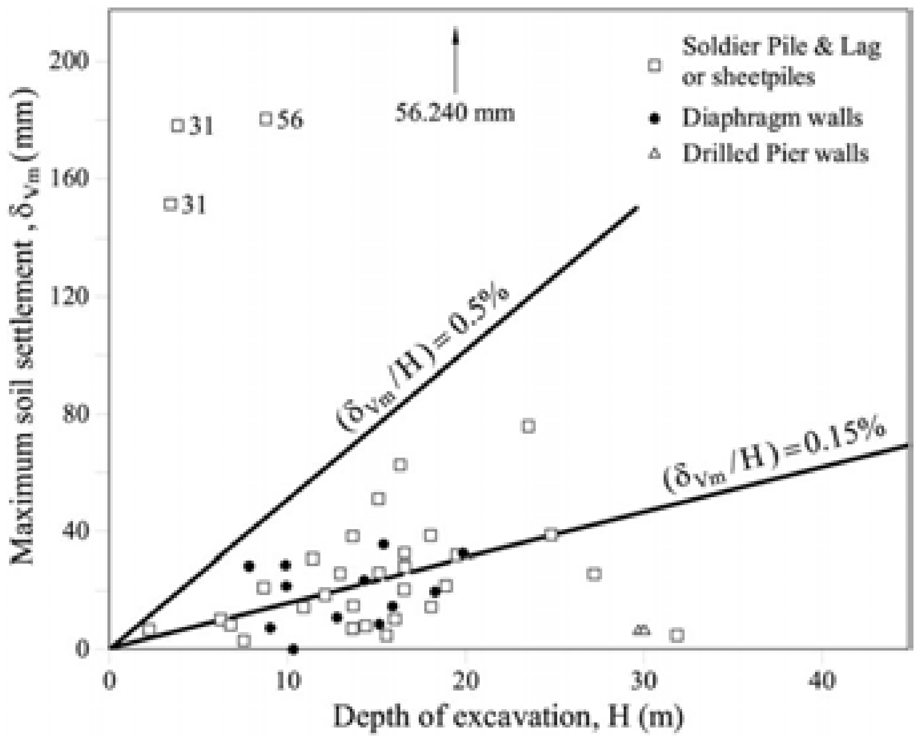
Excavations en Washington D.C. (O´Rourke, 1976)

Empirical methods for evaluating movements

- Stiff clays, residual soils and sands (Clough & O' Rourke, 1990)



Maximum lateral movement

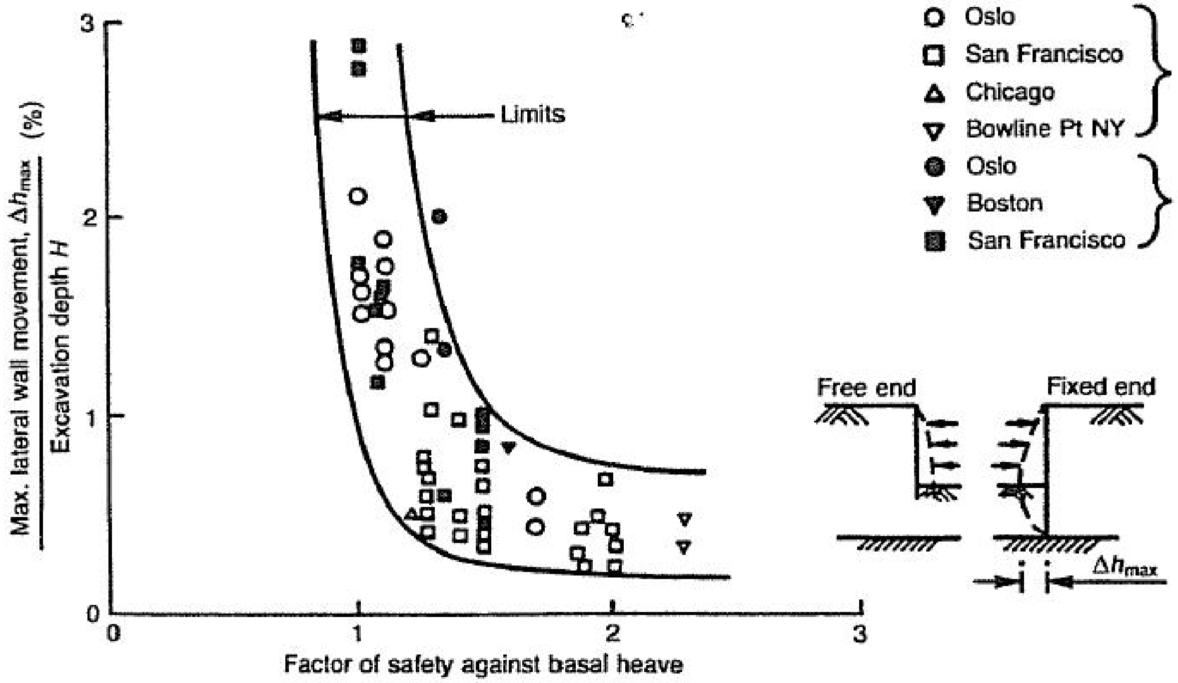


Maximum settlement

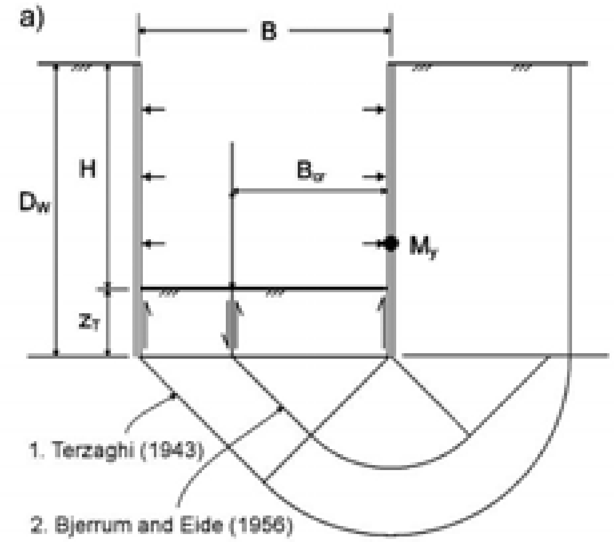
- The mean of maximum lateral movements measured around 0.2%
- The mean of maximum settlements measured around 0.15 %
- Large scatter, more in horizontal movements
- No significant differences between different wall types

Empirical methods for evaluating movements

- Soft clays (Mana & Clough, 1981)



Maximum horizontal movement

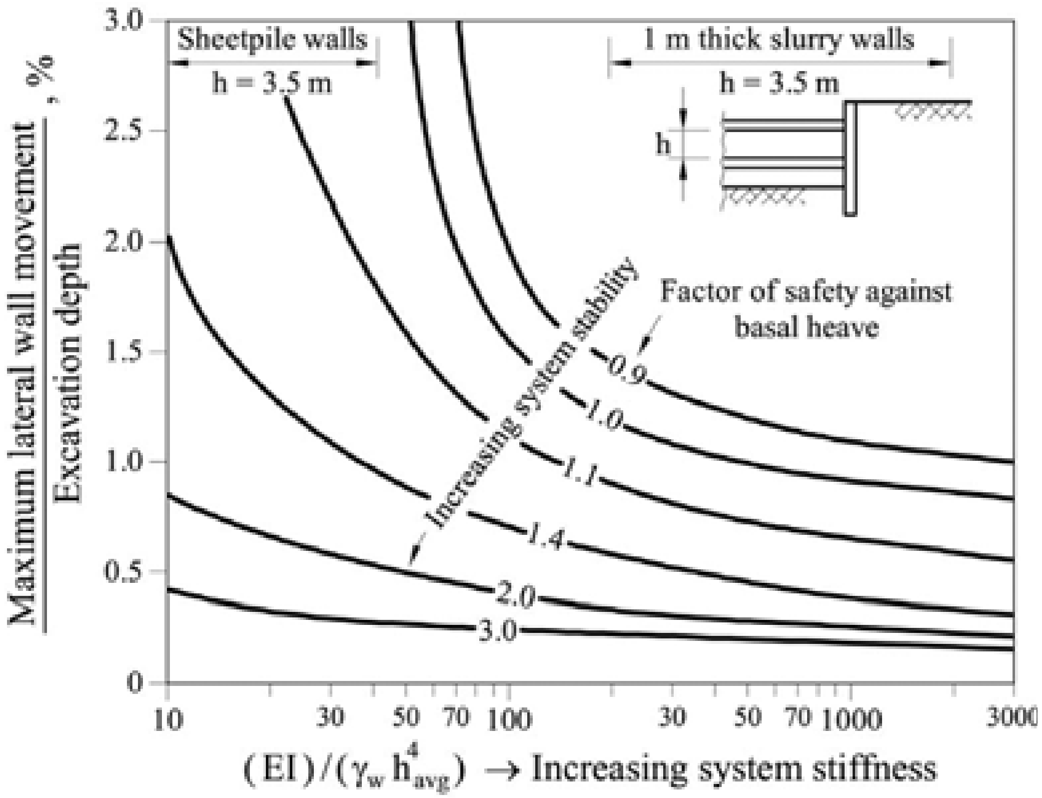


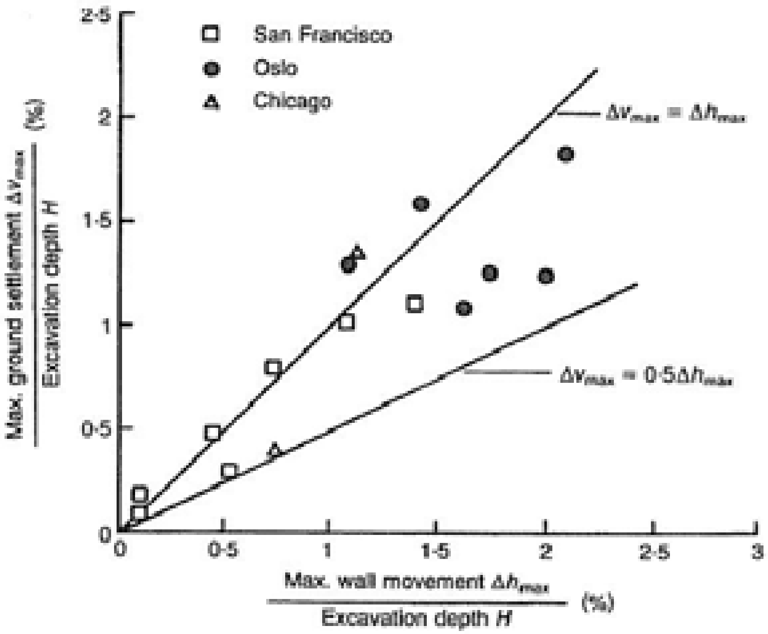
Bottom instability

- Movements associated to bottom instability are dominant when the factor of safety is low

Empirical methods for evaluating movements

- Soft clays (Clough & O' Rourke, 1990)





Maximum lateral movements

Settlements

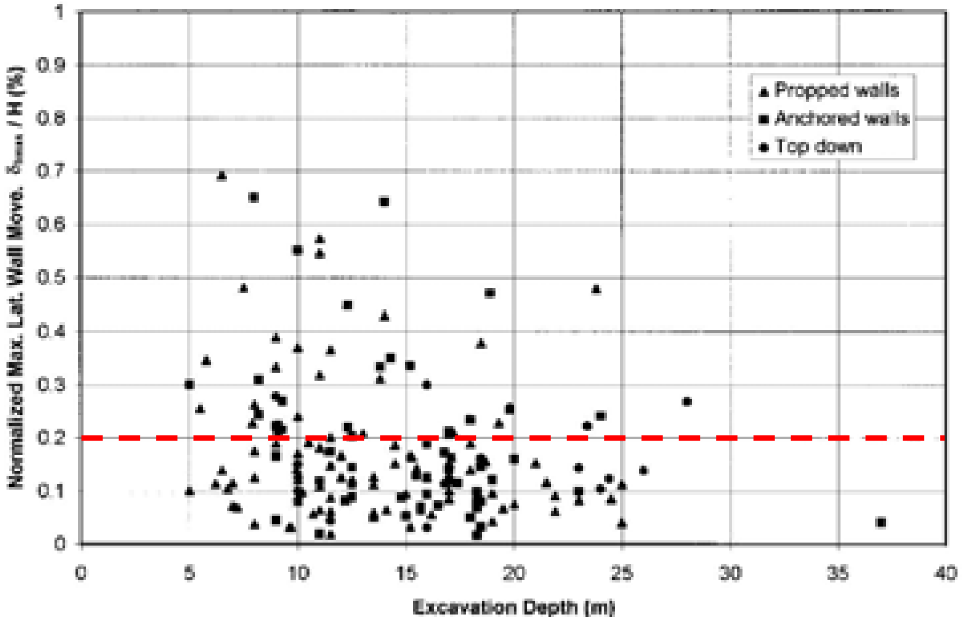
- System stiffness: $(EI)/(\gamma_w h^4)$
- Addenbrooke et al. (2000) defined system stiffness as $(EI)/(\gamma_w h^5)$

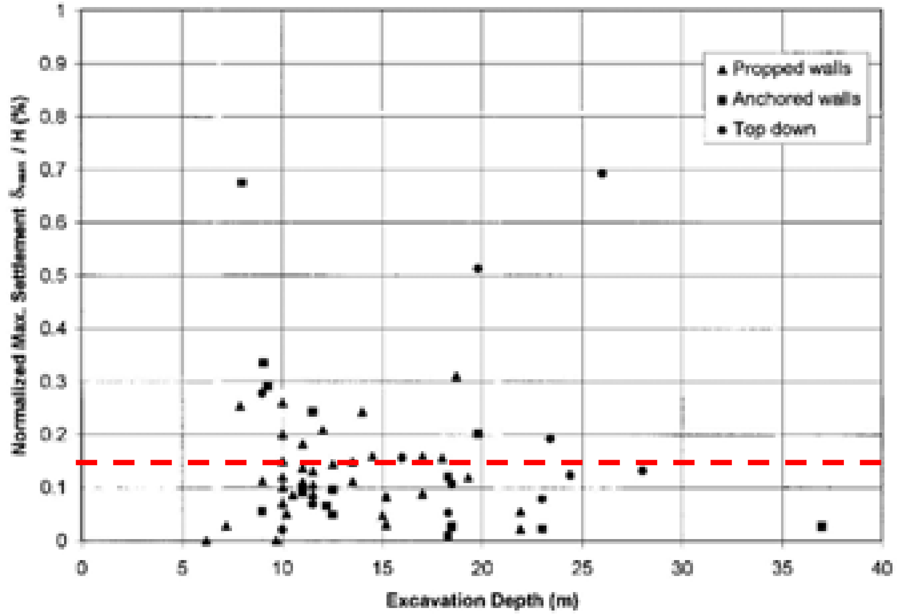
Empirical methods for evaluating movements

- Other databases
  - Karlsrud (1986): Oslo soft clay
  - Ou et al. (1993): Taipei soft clay
  - Wong et al. (1997): Singapore
  - Carder (1995): UK
  - Fernie and Suckling (1996): UK
  - Long (2001): 296 cases! (COST Action C-7)

Empirical methods for evaluating movements

- Long (2001) database. Excavations in medium and stiff soils





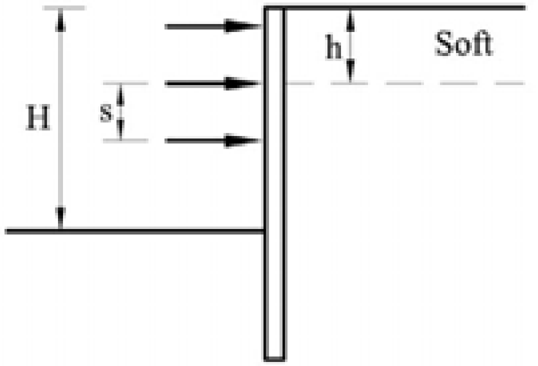
Maximum lateral movement

Maximum settlement

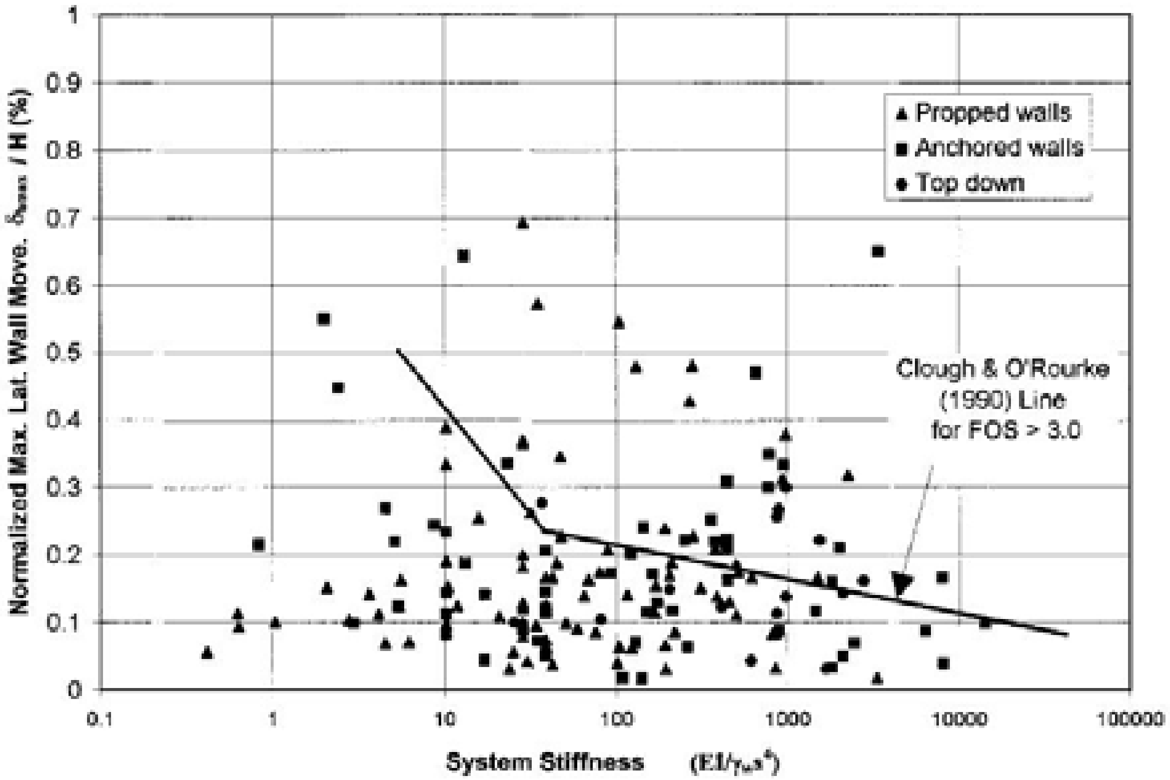
- Large scatter
- Generally values smaller than those collected by Clough & O'Rourke (1990)
- Little influence of the type of bracing (props, anchors, top-down)

Empirical methods for evaluating movements

- Long (2001) database. Excavations in stiff and medium soils



h < 0.6H



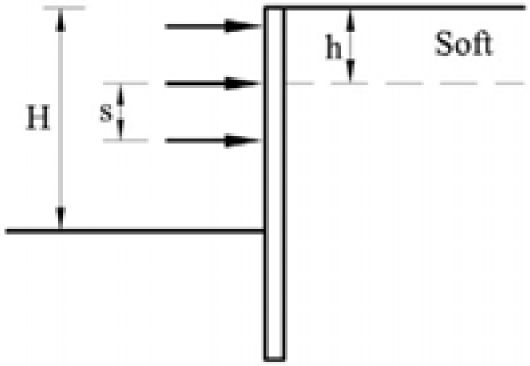
System stiffness: ($EI/\gamma s^4$) (Clough & O'Rourke, 1990)

Maximum lateral movement

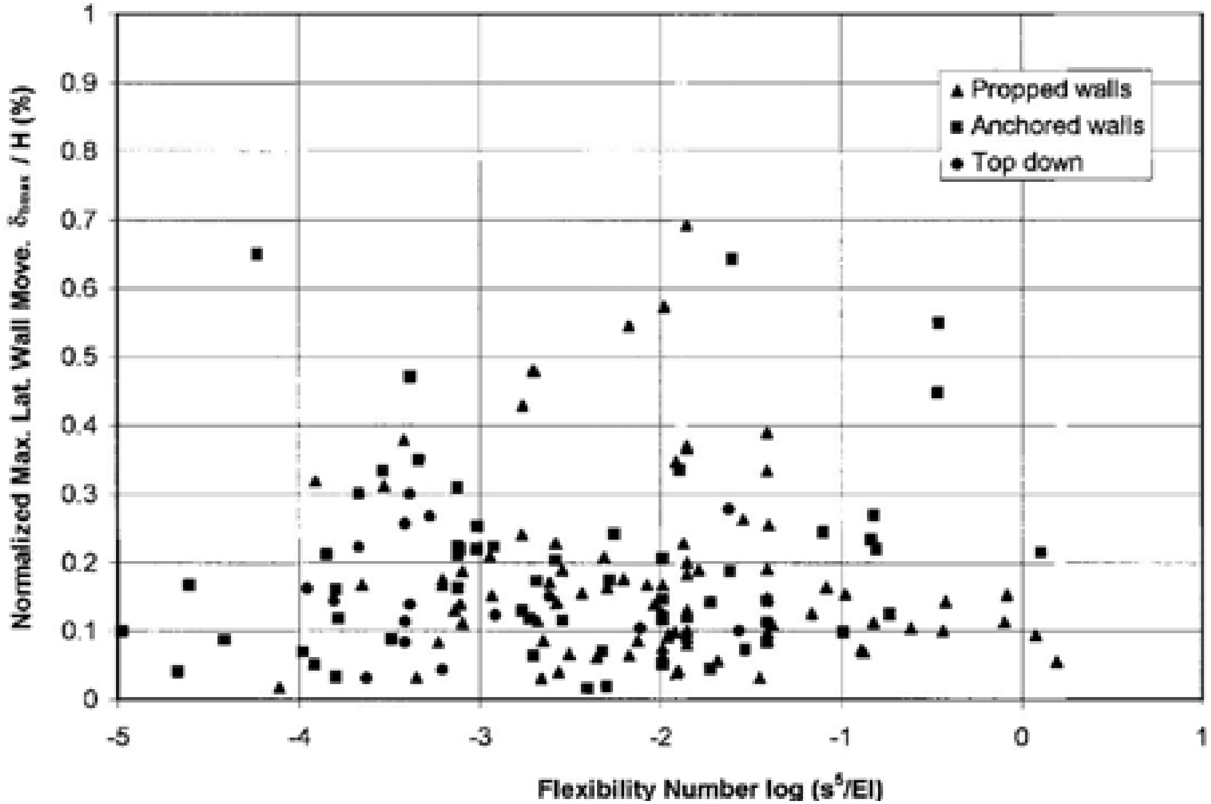
- System stiffness does not appear to be a critical parameter in these cases

Empirical methods for evaluating movements

- Long (2001) database. Excavations in stiff and medium soils



h < 0.6H



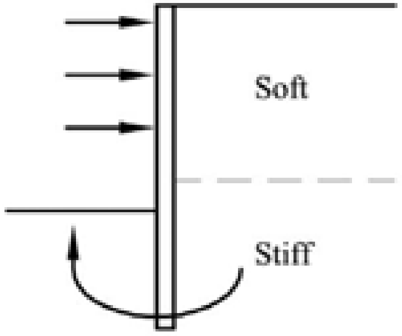
Flexibility number: $(s^5)/(EI)$ (Addenbrooke et al., 2000)

Maximum lateral movement

- System flexibility does not appear to be a critical parameter in these cases

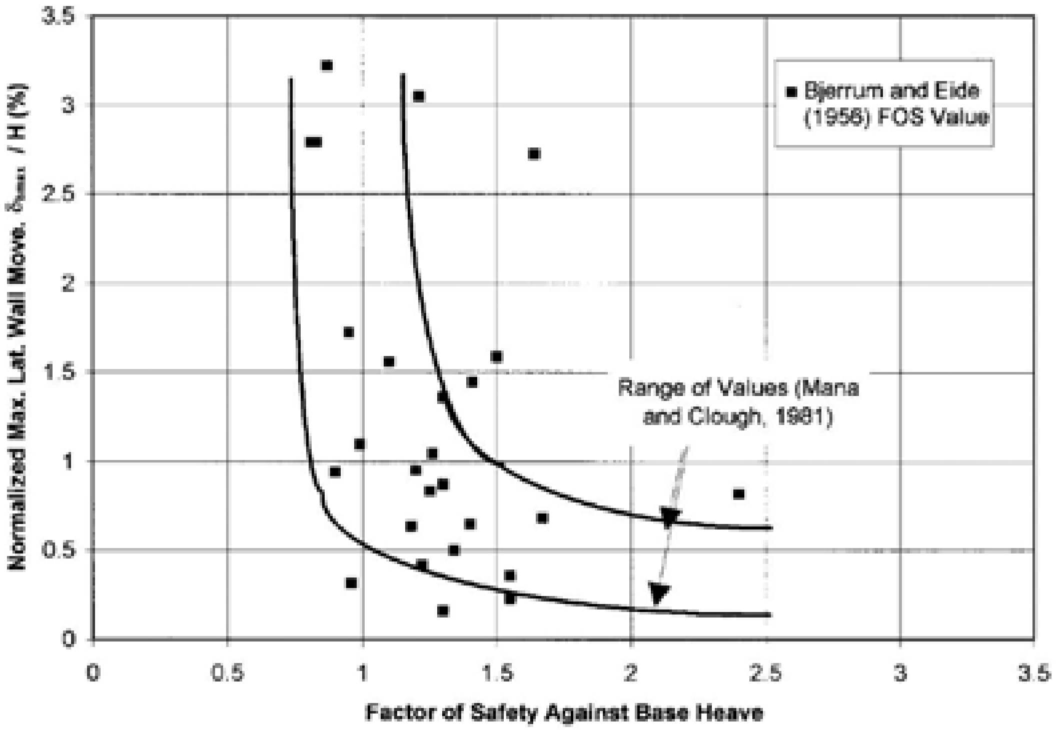
Empirical methods for evaluating movements

- Long (2001) database. Excavations in soft soils



h > 0.6H

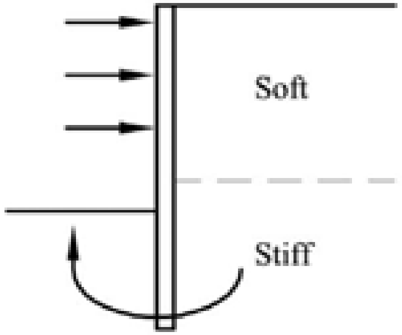
Low FS



Maximum lateral movement

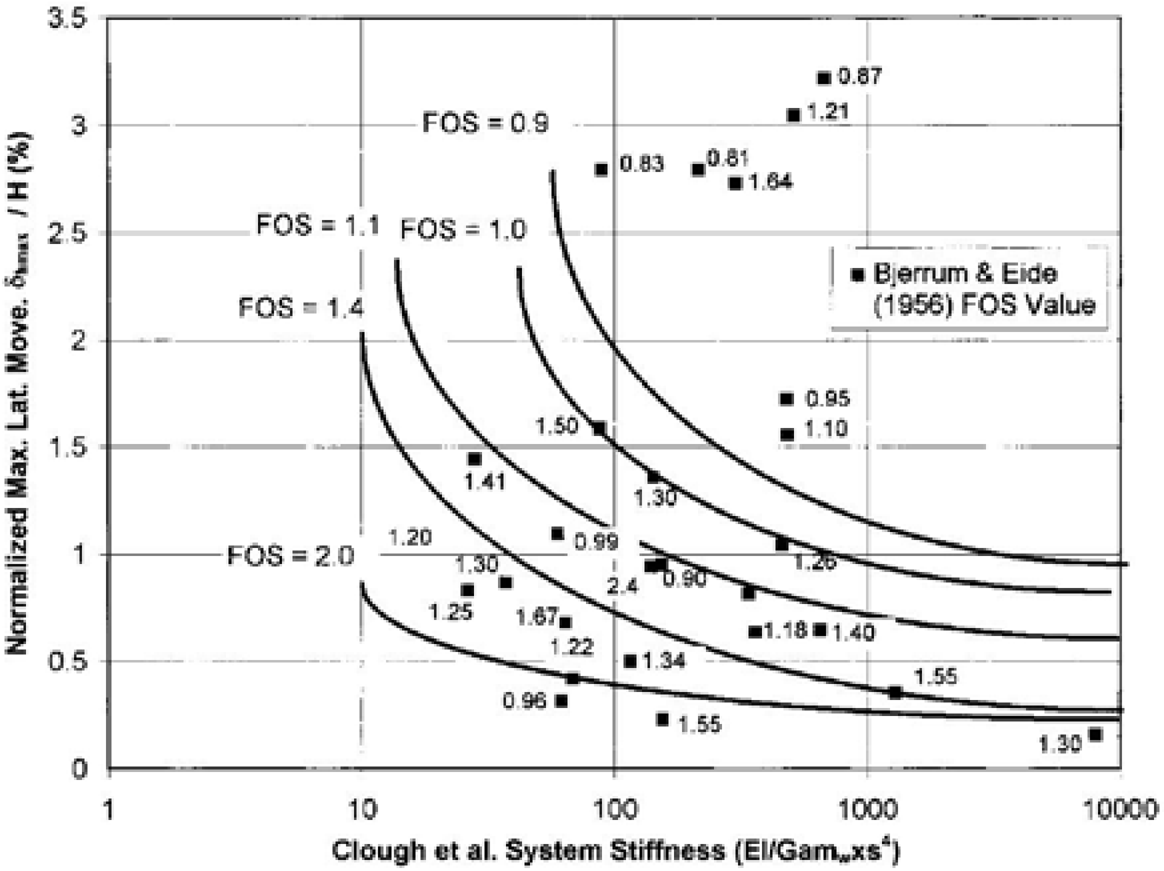
Empirical methods for evaluating movements

- Long (2001) database. Excavations in soft soils



h > 0.6H

Low FS



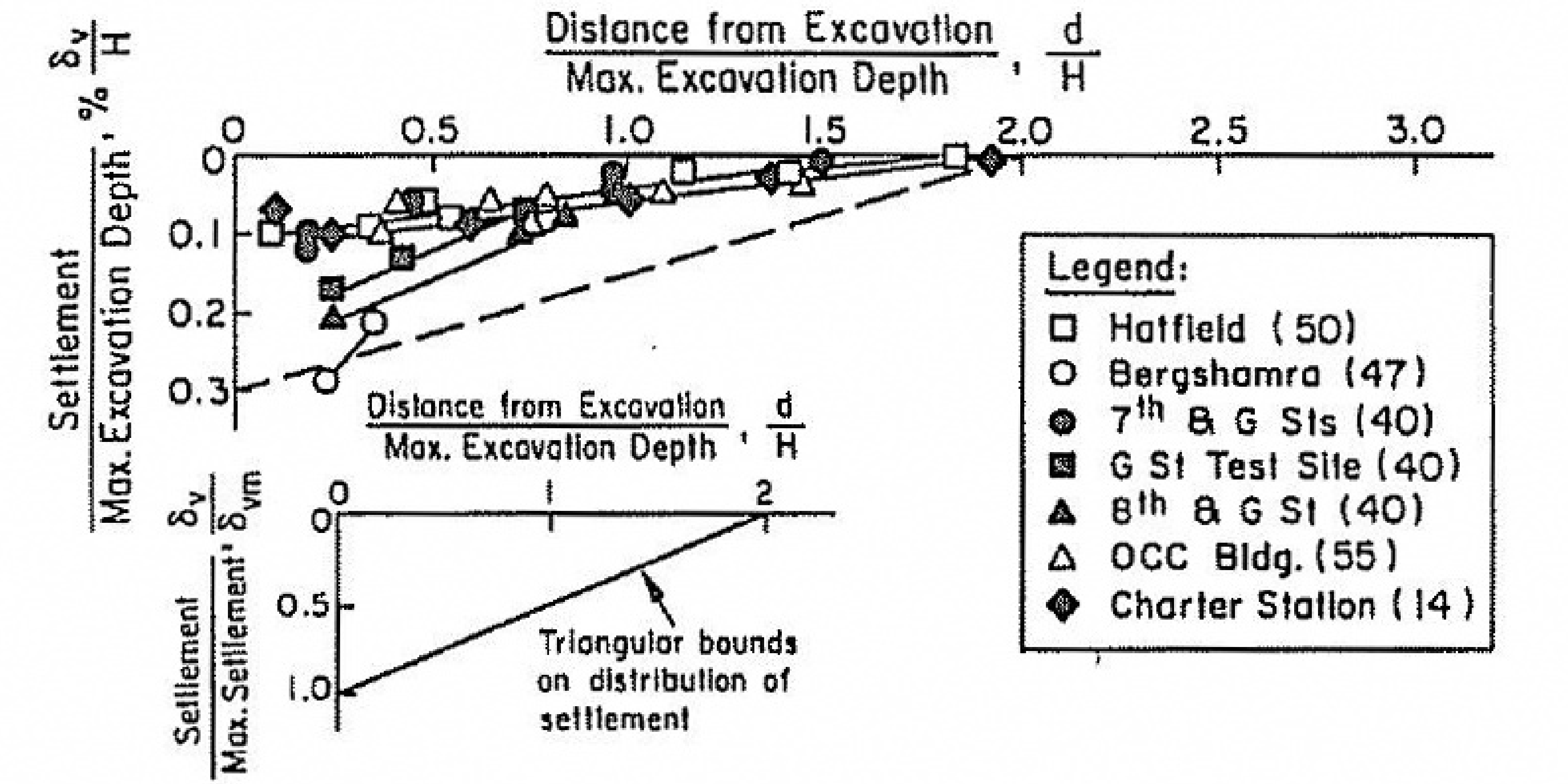
Maximum lateral movement

Empirical methods for evaluating movements

- Long (2001) database: causes of excessive movements (with respect to the majority of works in similar circumstances). 36 cases examined
  - Excessive movements in cantilever mode: 12 cases
  - Wall too flexible: 8 cases
  - Creep of anchors/props: 3 cases
  - Structural yielding: 2 cases
  - Water inflow: 1 case
  - Pile driving: 1 case
  - Unknown: 9 cases

Empirical methods for evaluating movements

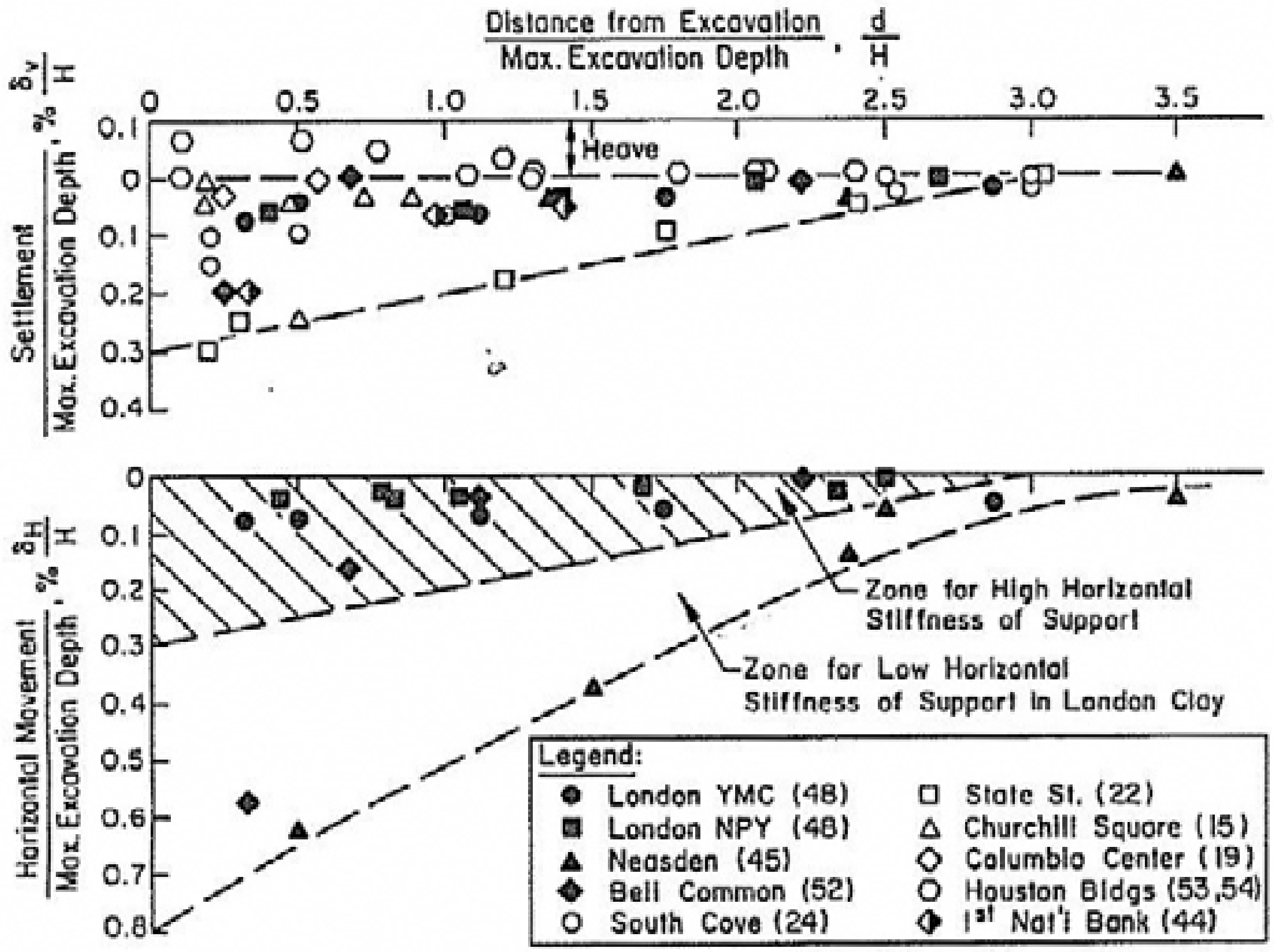
- Distribution of surface settlements (Clough & O'Rourke, 1990)



Sands

Empirical methods for evaluating movements

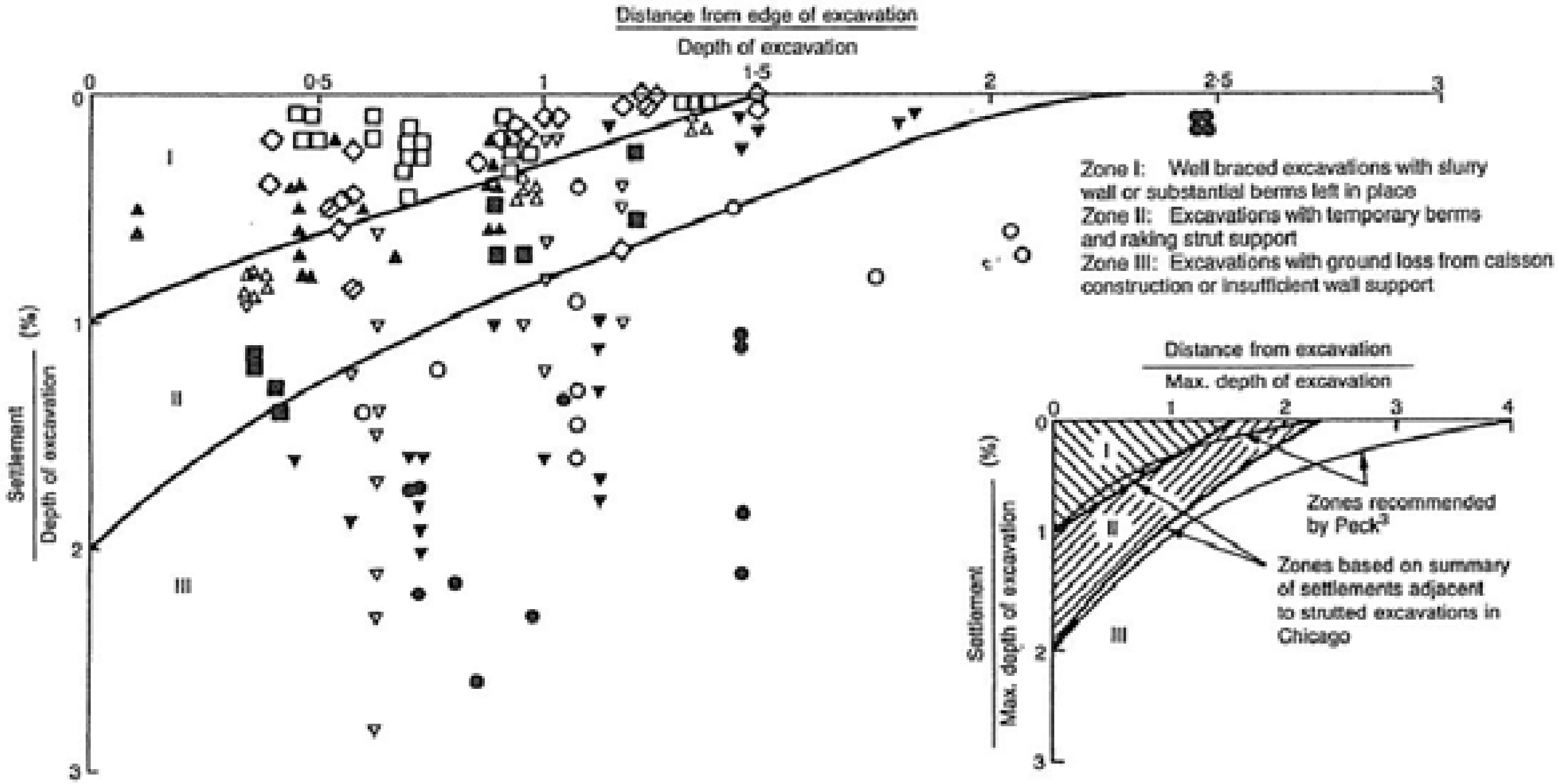
- Distribution of surface settlements (Clough & O'Rourke, 1990)



Stiff to hard clays

Empirical methods for evaluating movements

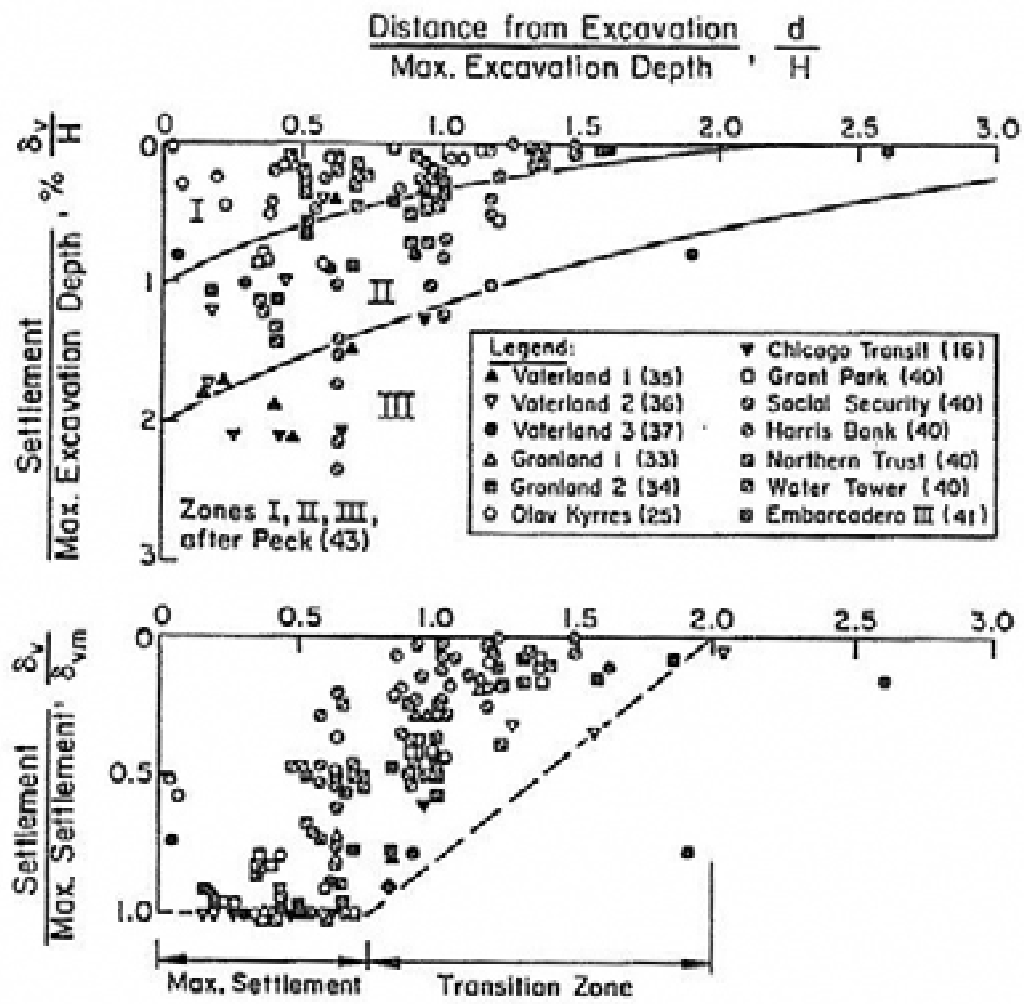
- Distribution of surface settlements (Clough & O'Rourke, 1990)



Chicago excavations (O´Rourke, 1976)

Empirical methods for evaluating movements

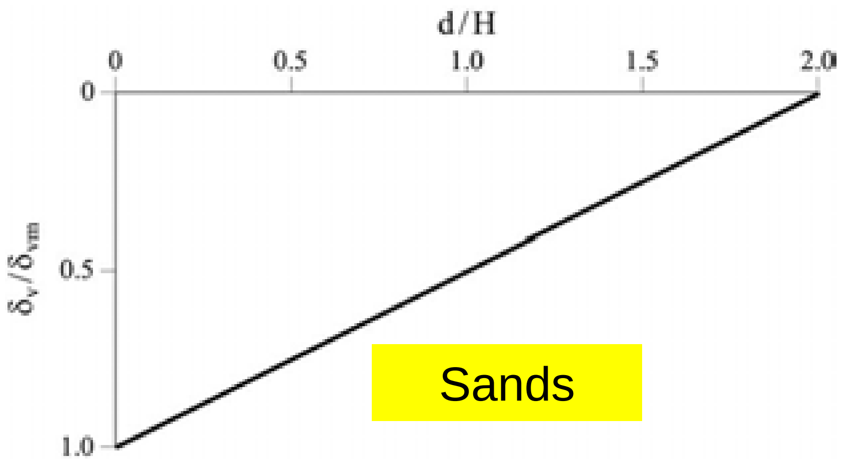
- Distribution of surface settlements (Clough & O'Rourke, 1990)

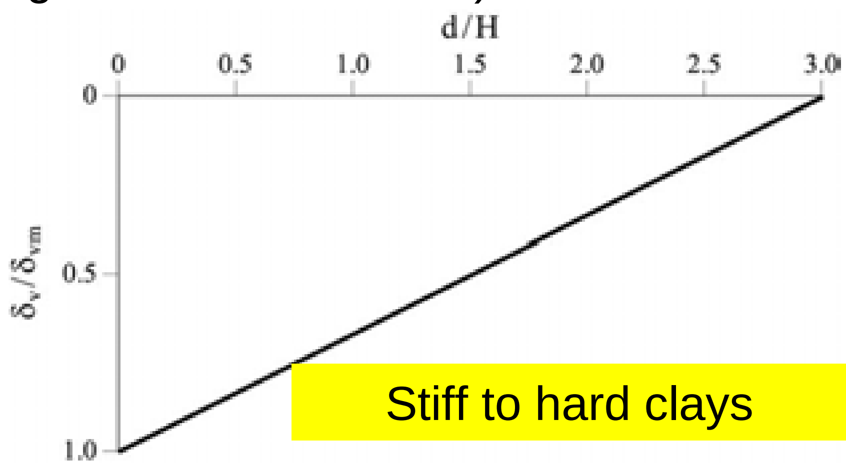


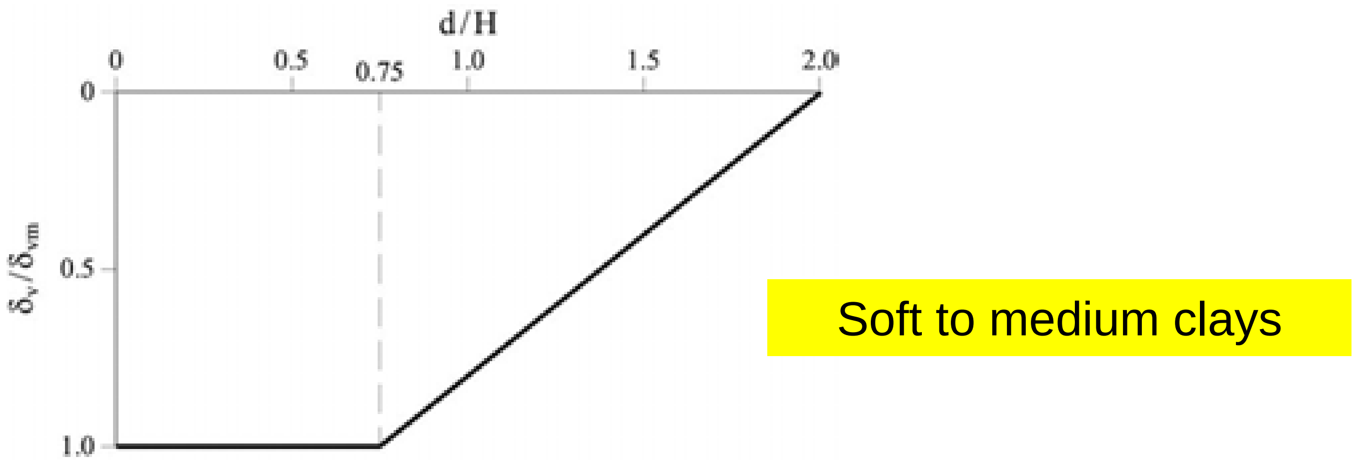
Soft to medium clays

Empirical methods for evaluating movements

- Distribution of surface settlements (Clough & O'Rourke, 1990)

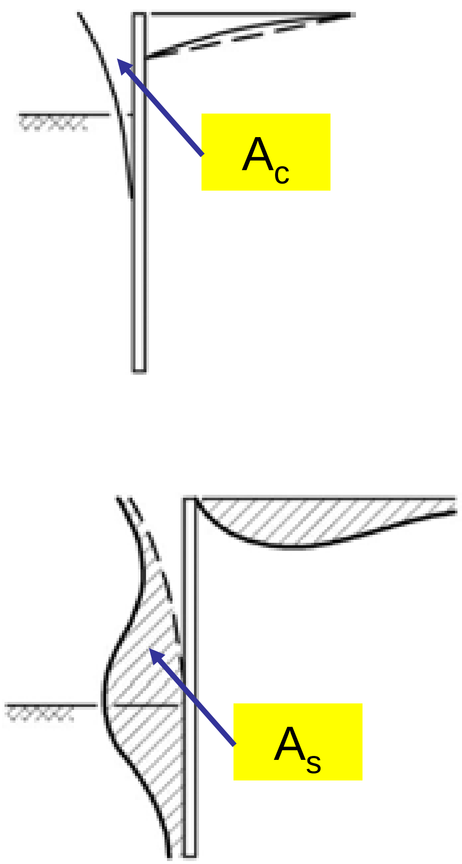


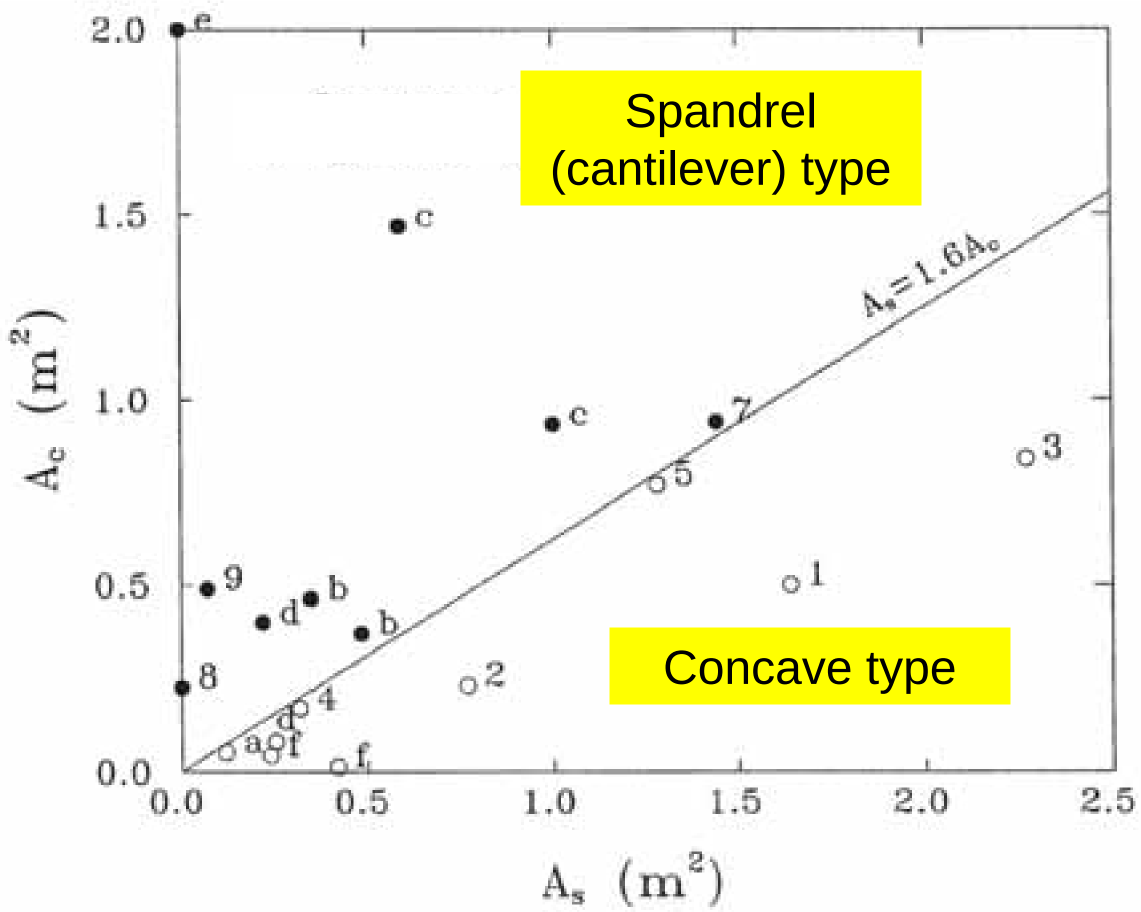




Empirical methods for evaluating movements

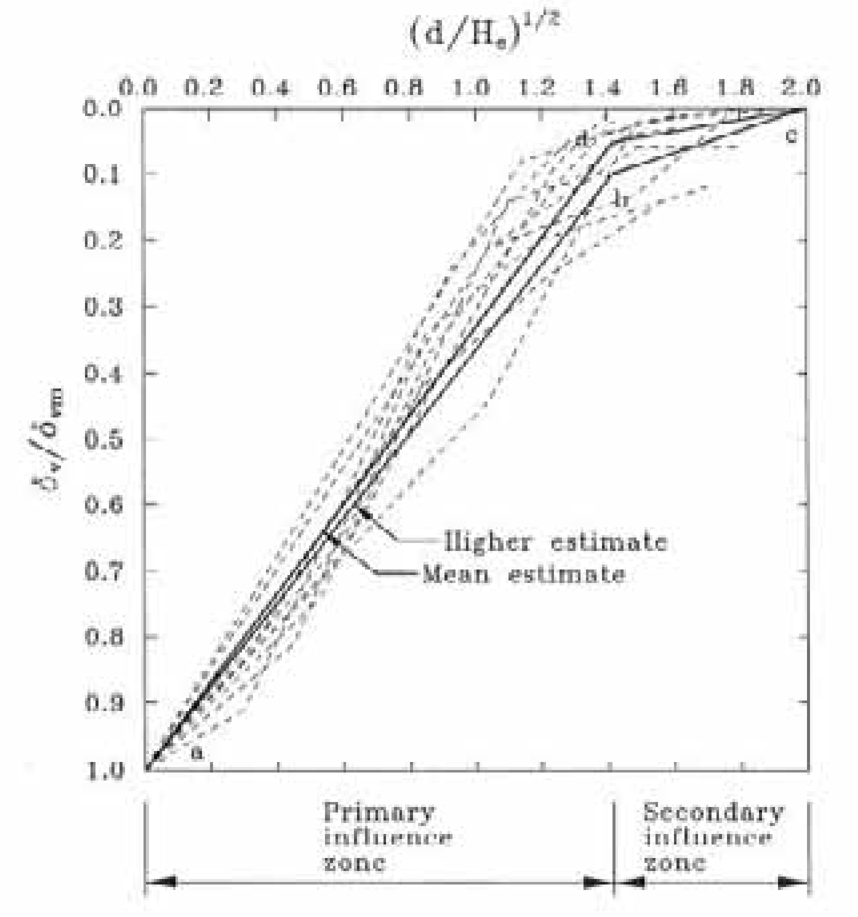
- Distribution of surface settlements (Hsieh and Ou, 1998)
  - They suggest that the shape of the settlement distribution is related to the type of wall deformation



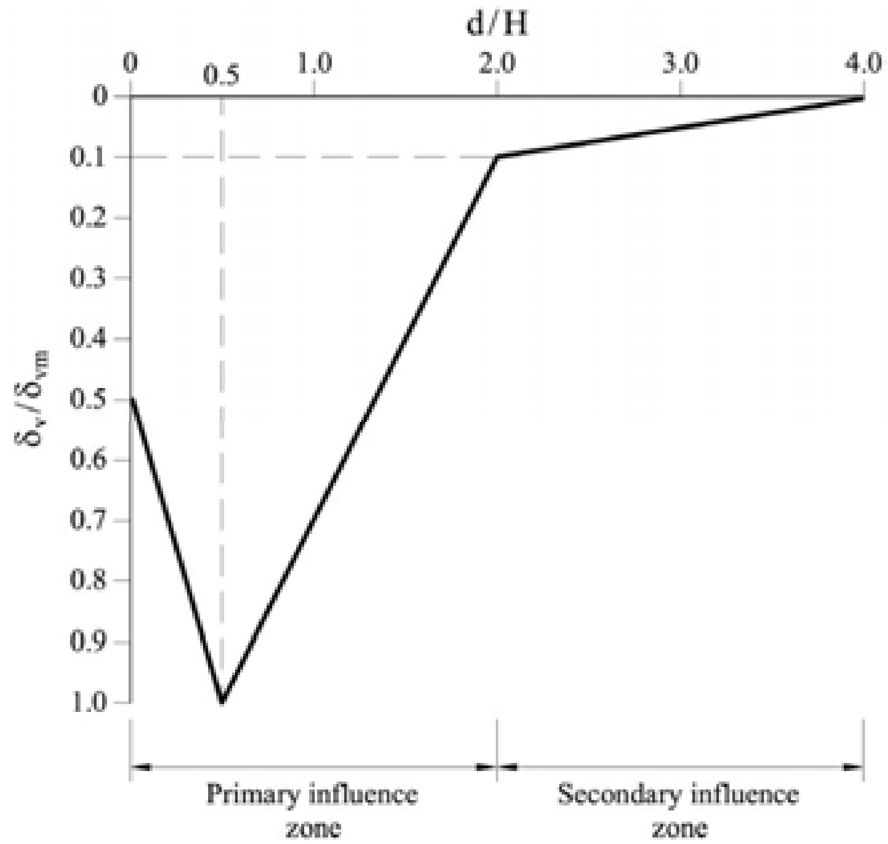


Empirical methods for evaluating movements

- Distribution of surface settlements (Hsieh and Ou, 1998)
  - Estimation method



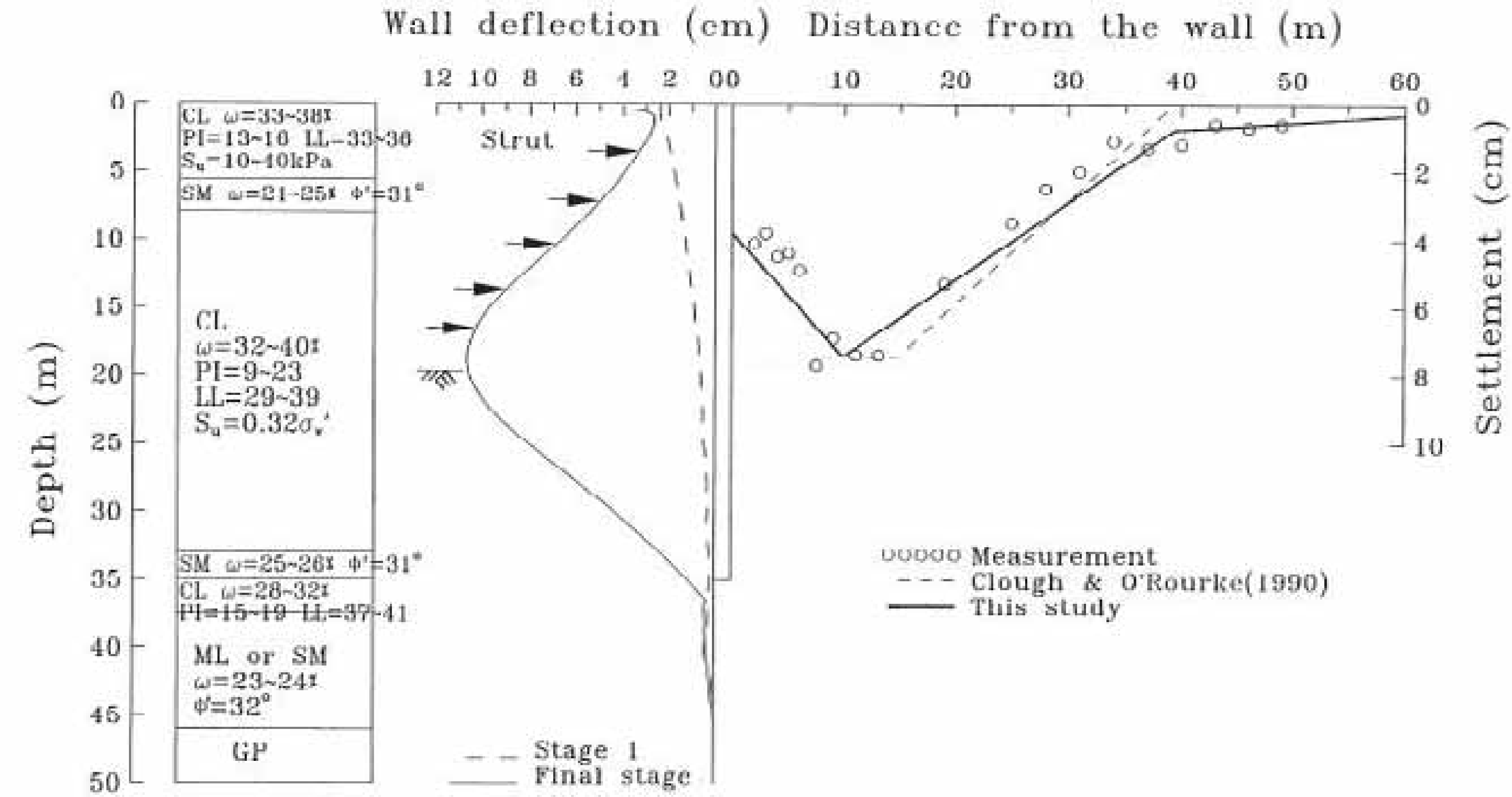
Spandrel (cantilever) type



Concave type

Empirical methods for evaluating movements

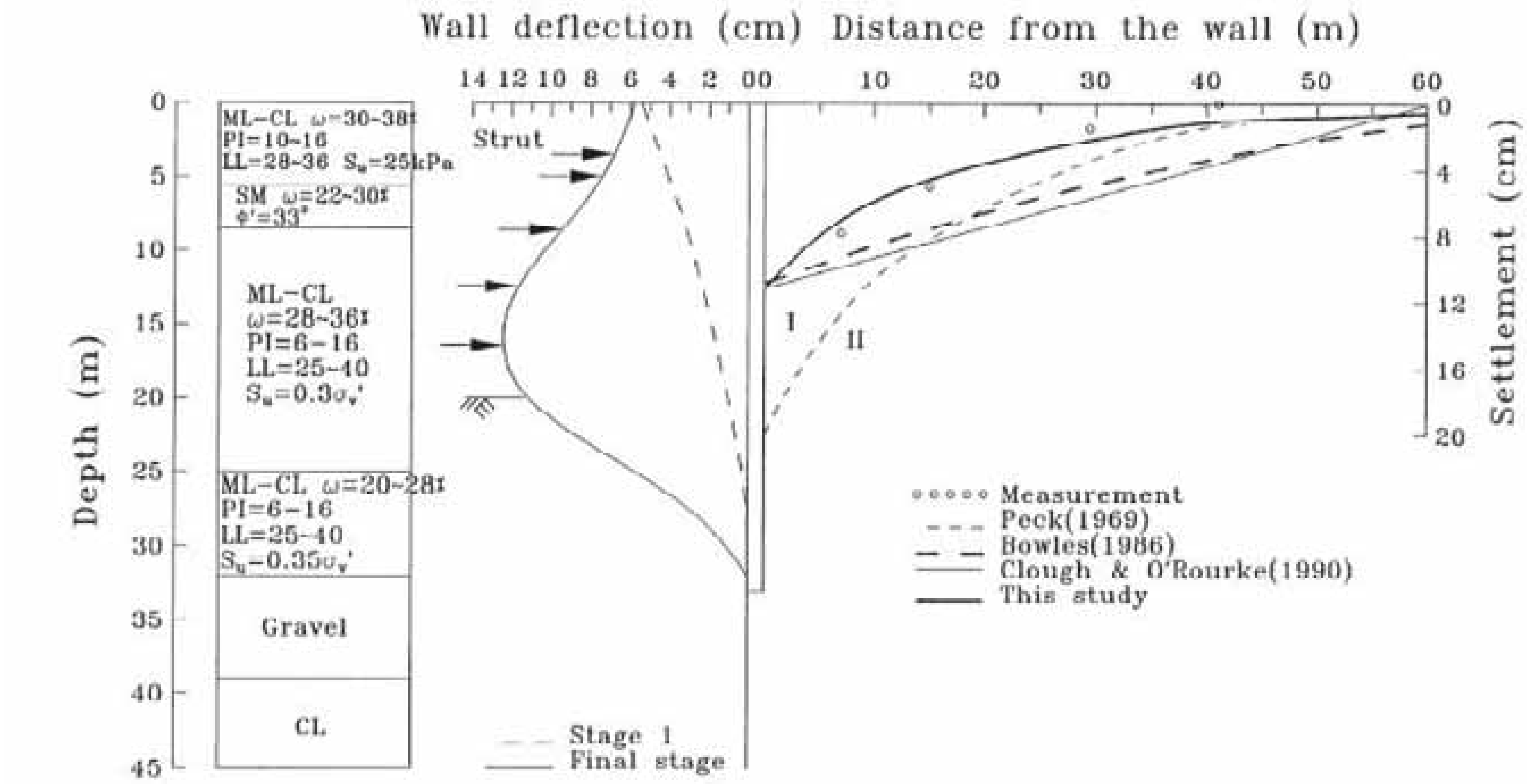
- Distribution of surface settlements (Hsieh and Ou, 1998)
  - Excavation in soft silty clay near the centre of the Taipei basin



Concave type

Empirical methods for evaluating movements

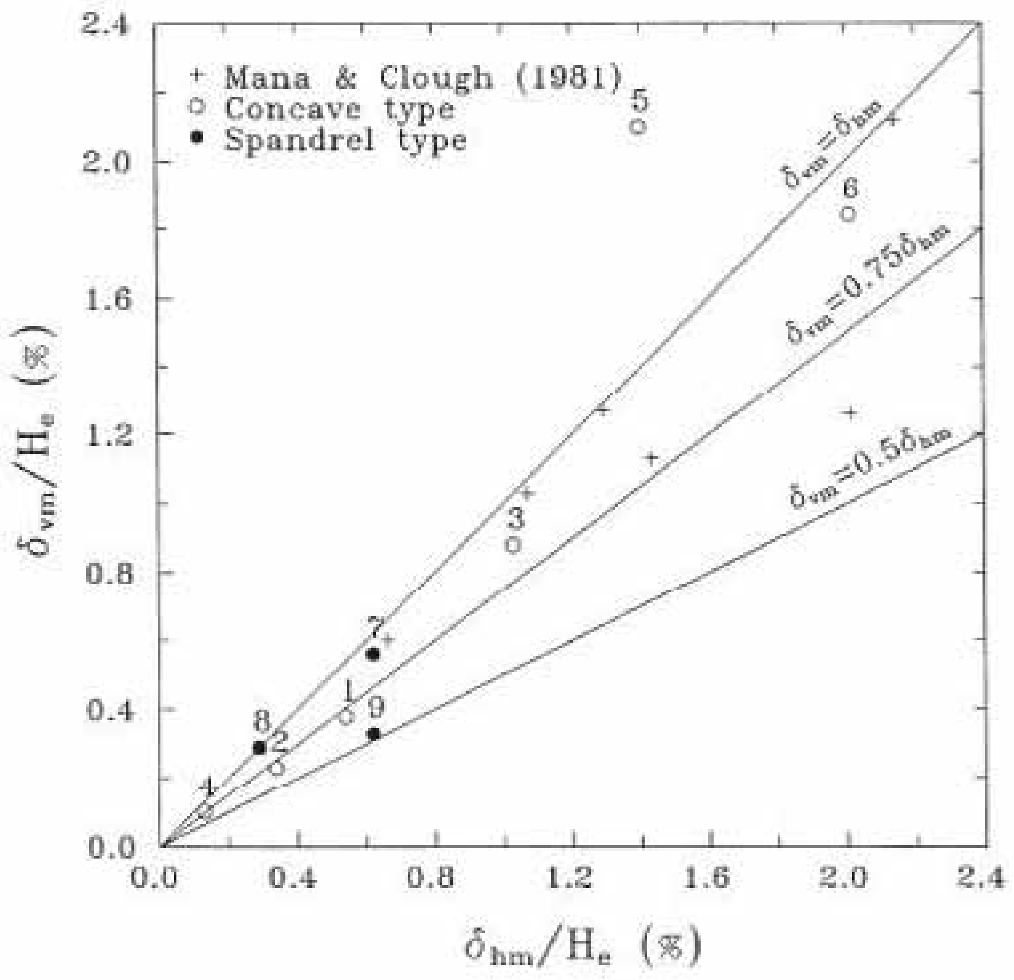
- Distribution of surface settlements (Hsieh and Ou, 1998)
  - Excavation in silty clay for the Far-East Enterprise Center project in Taipei



Spandrel (cantilever) type

Empirical methods for evaluating movements

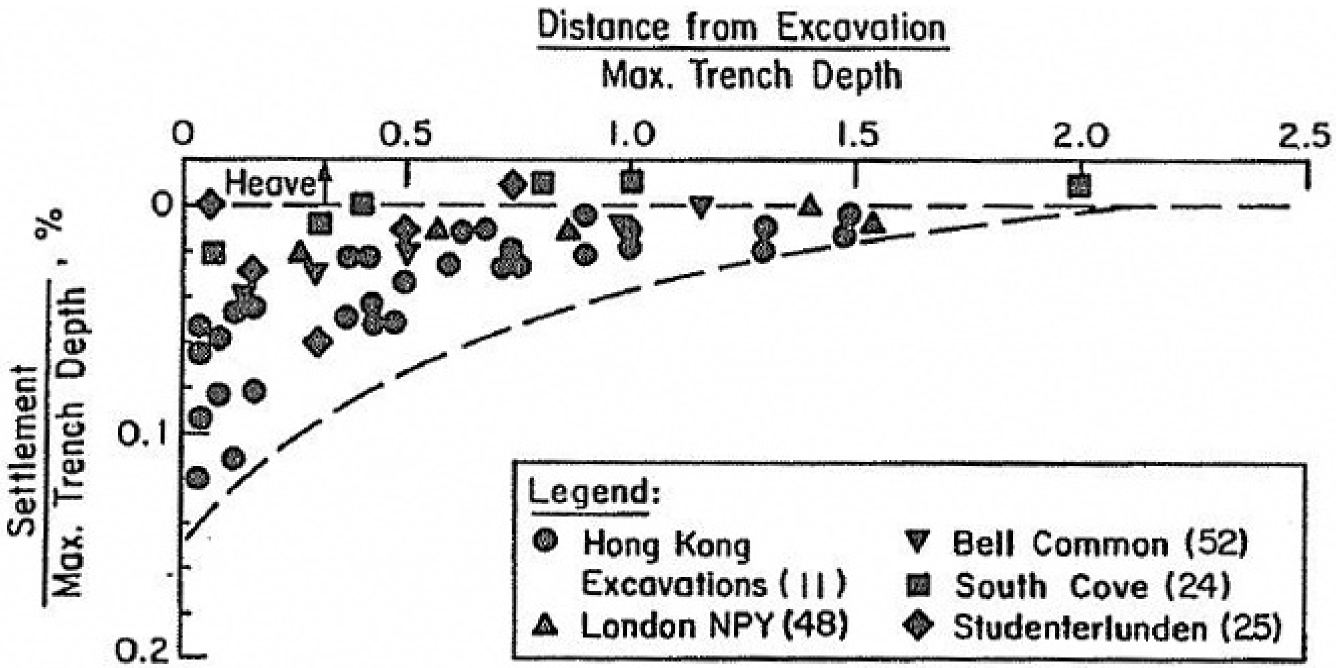
- Relationship between maximum vertical and lateral movement (Hsieh and Ou, 1998)



Independent of settlement distribution type

Empirical methods for evaluating movements

- Settlements caused by the installation of concrete diaphragm wall (Clough & O'Rourke, 1990



- Hong Kong, Charter Station: 50mm settlements for a 37m deep trench
- Normally 5 – 15 mm settlement in soft ground

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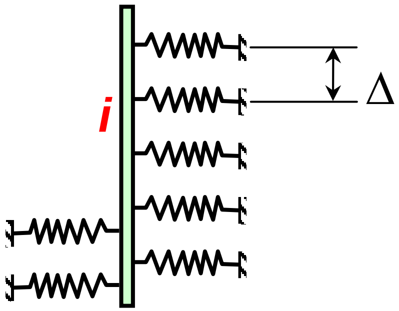
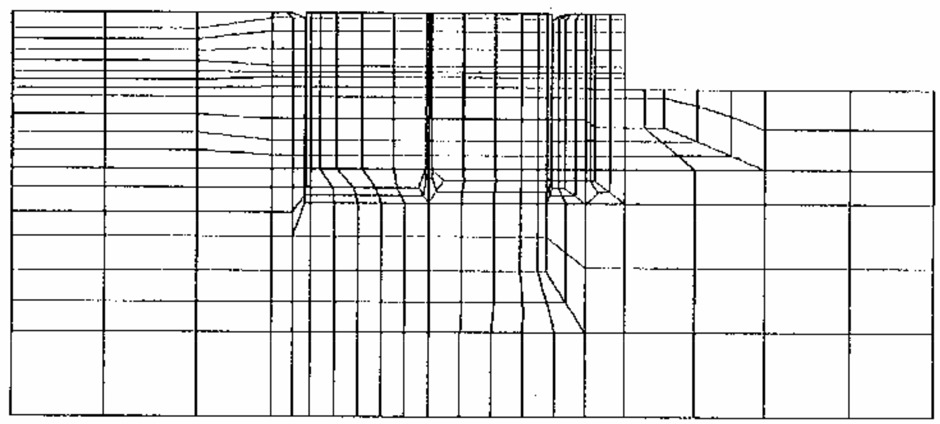
Methods for calculating ground movements

- Calculation methods
  - Limit equilibrium (no information on ground movements)
  - Diaphragm walls considered as elastic beams on springs (Winkler's model): RIDO, PARATIE, WALLOP…



  - Simualtion using finite elements or finite differences: ABAQUS, FLAC, PLAXIS



Methods for calculating ground movements

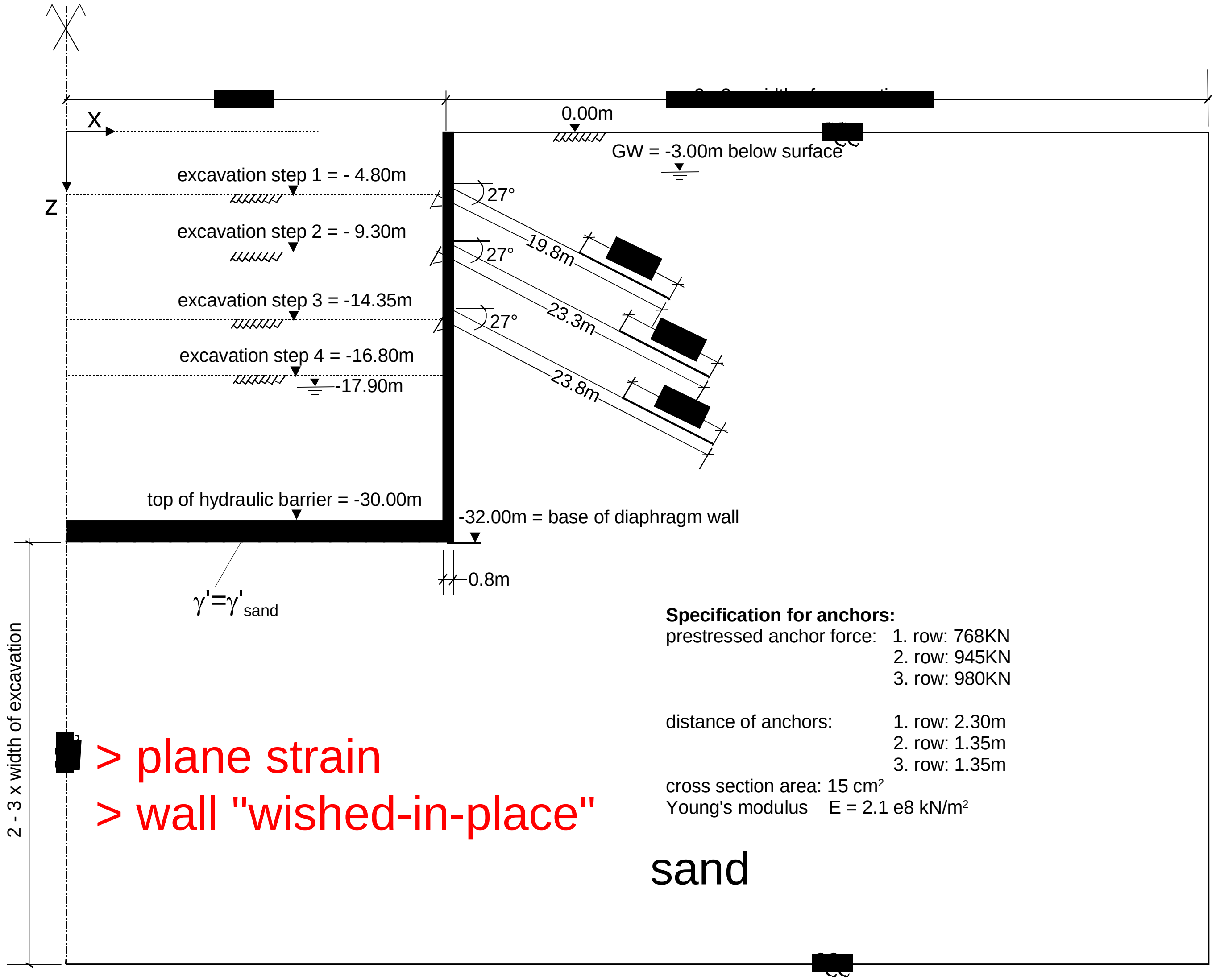
- Diaphragm wall considered as beams supported by springs
  - Relatively simple, they require a limited number of hypotheses and data
  - There is a wide experience of their use in practice
  - They allo the introduction of some nonlinearity
  - The subgrade modulus (a key parameter in this type of calculations) is a parameter with serous limitations
  - The global soil-interaction problem is not considered
  - The horizontal movements of the wall are computed, ground movemnts must be calculated separately

Methods for calculating ground movements

- Finite elements / Finite differences
  - More complex, they require a larger number of hypotheses and decisions (constitutive model, type of analysis, initial stresses, boundary conditions. domain size…)
  - There is less experience of use in practice (rapidly changing but…
  - Some models require an information level not always available
  - The allow the consideration of the global problem, they contribute to the better understanding of deformation and failure mechanisms
  - They provide a quite complete information on stresses, stains, displacements
  - They are progressively replacing simplified methods
  - Validation/calibration with field measurements are essential

Methods for calculating ground movements

- Effect of constitutive model (Schwiger, pers. comm.)

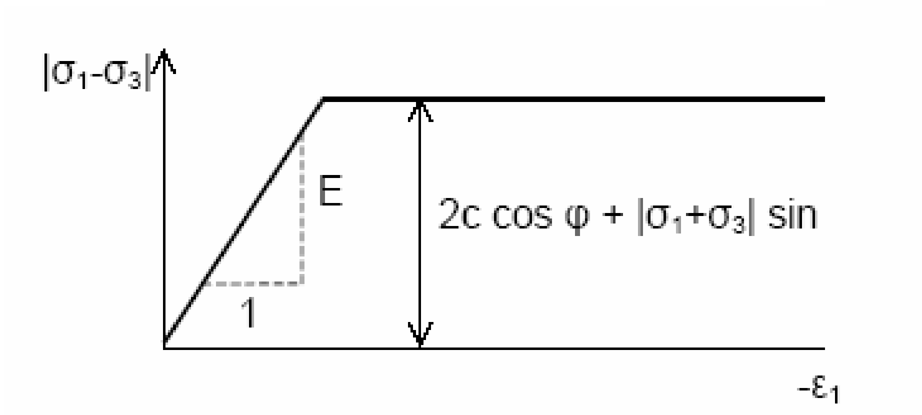


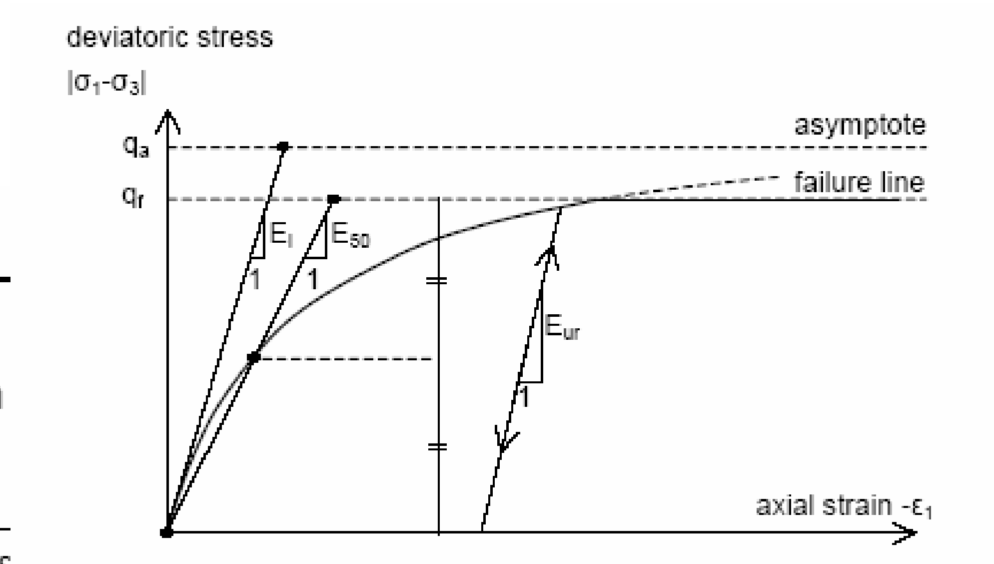
> plane strain

> wall "wished-in-place"

Methods for calculating ground movements

- Effect of constitutive model
  - Mohr Coulomb vs. Hardening Soil



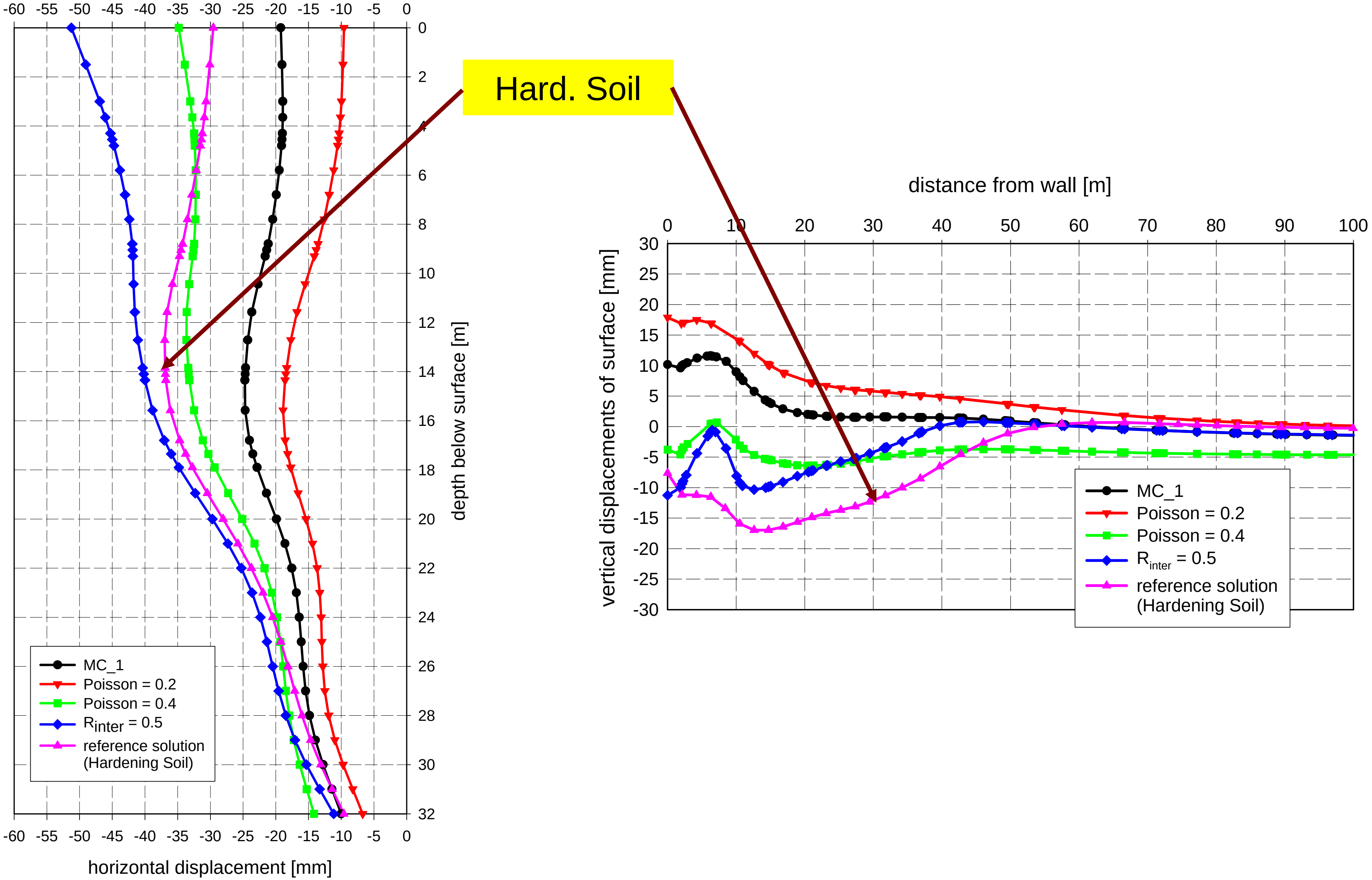


Mohr-Coulomb

Hardening Soil

Methods for calculating ground movements

- Effect of constitutive model
  - Mohr Coulomb vs. Hardening Soil

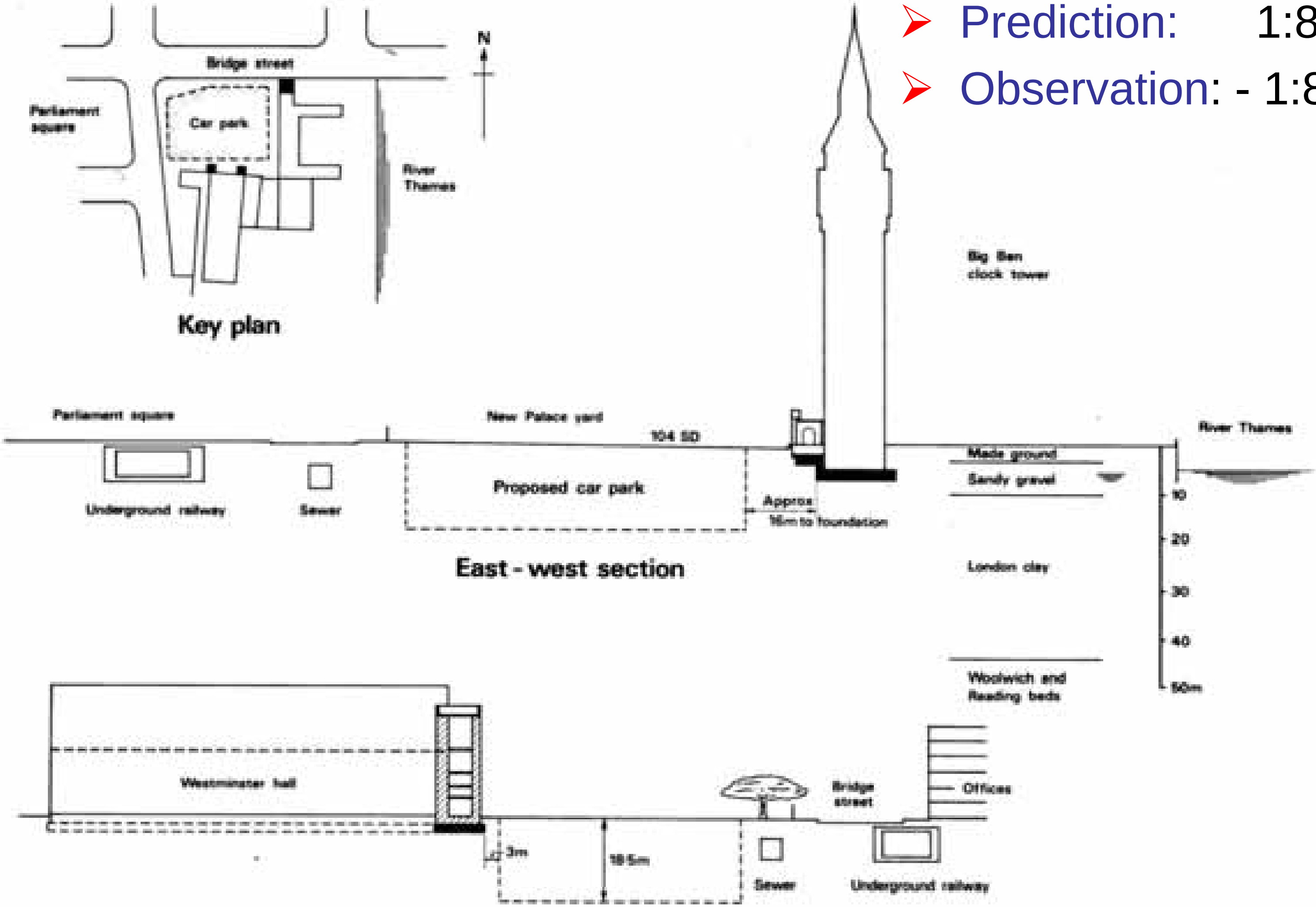


Methods for calculating ground movements

Wesminster Palace, London

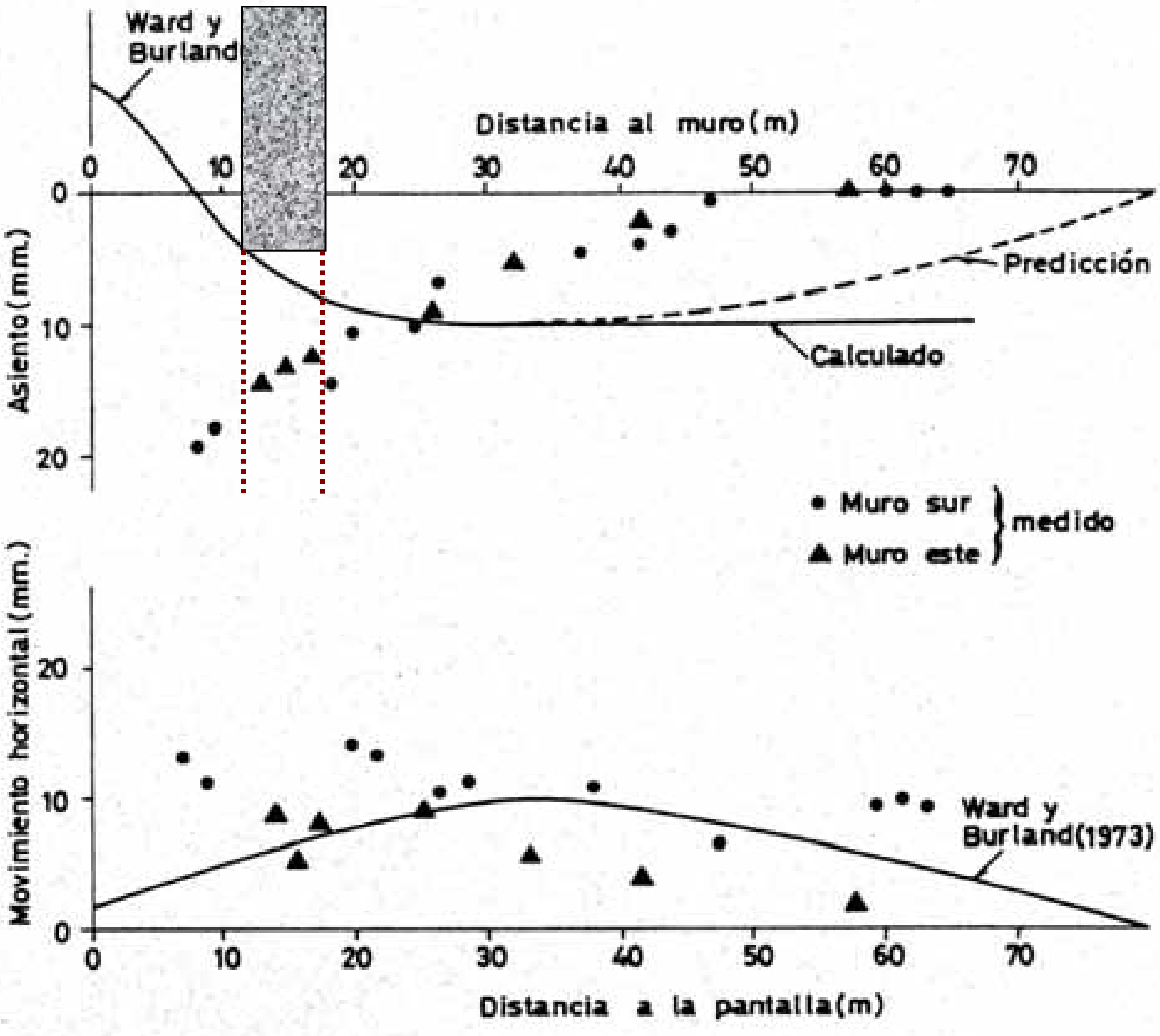
Methods for calculating ground movements

- Clock Tower inclination
  - Prediction: 1:8000
  - Observation: - 1:8600



Westminster Palce, London

Methods for calculating ground movements



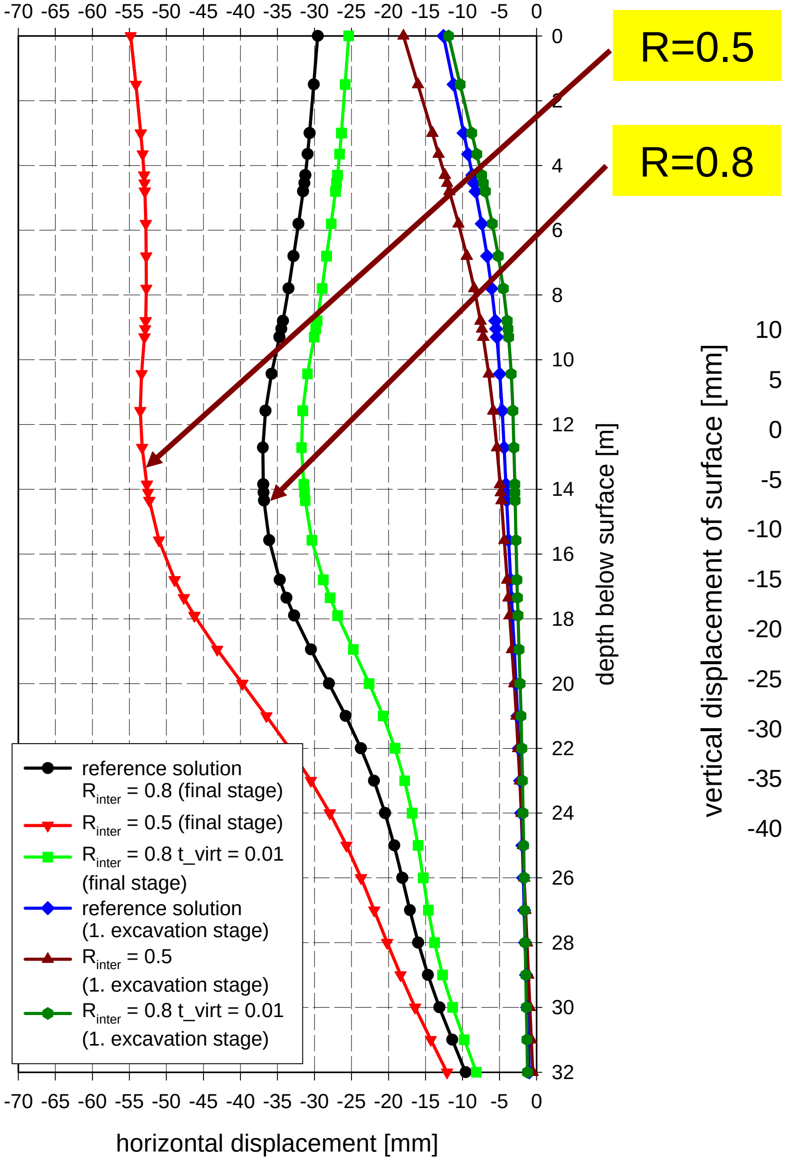
Horizontal and vertical displacements

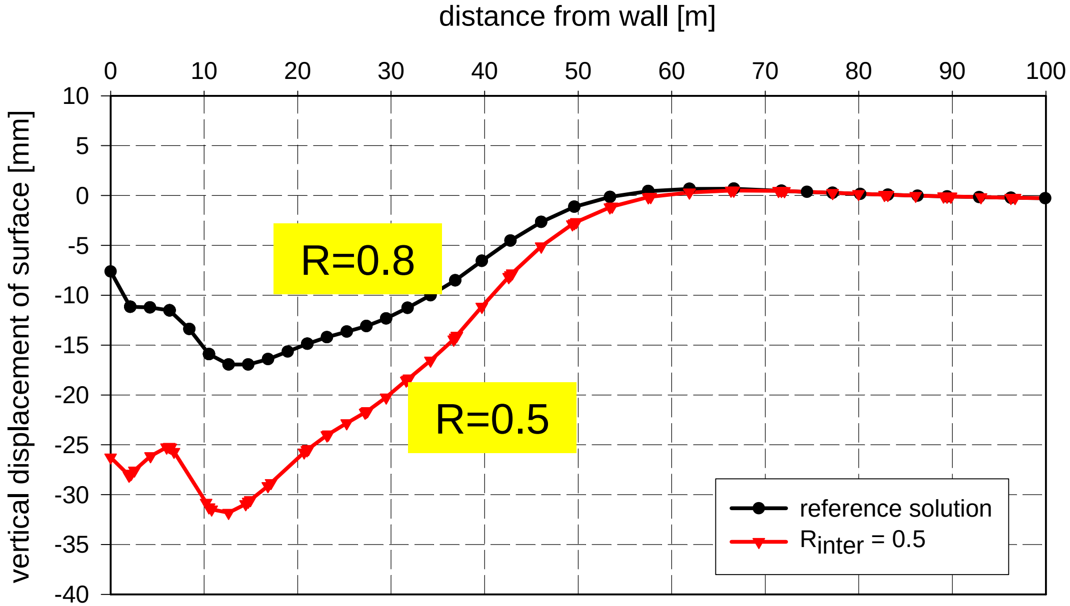
Methods for calculating ground movements

- Mohr-Coulomb model (or any other that incorporates a linear elastic component)
  - Although reasonable wall lateral movements can be obtained, computed settlements are often in error
  - Excavation bottom heave are considerably overestimated
  - The location of the lower boundary of the calculation domain has an decisive influence on computed displacements
  - In the case of excavations in soft soils, the effects are less marked because the soil shear strength plays a dominant role

Methods for calculating ground movements

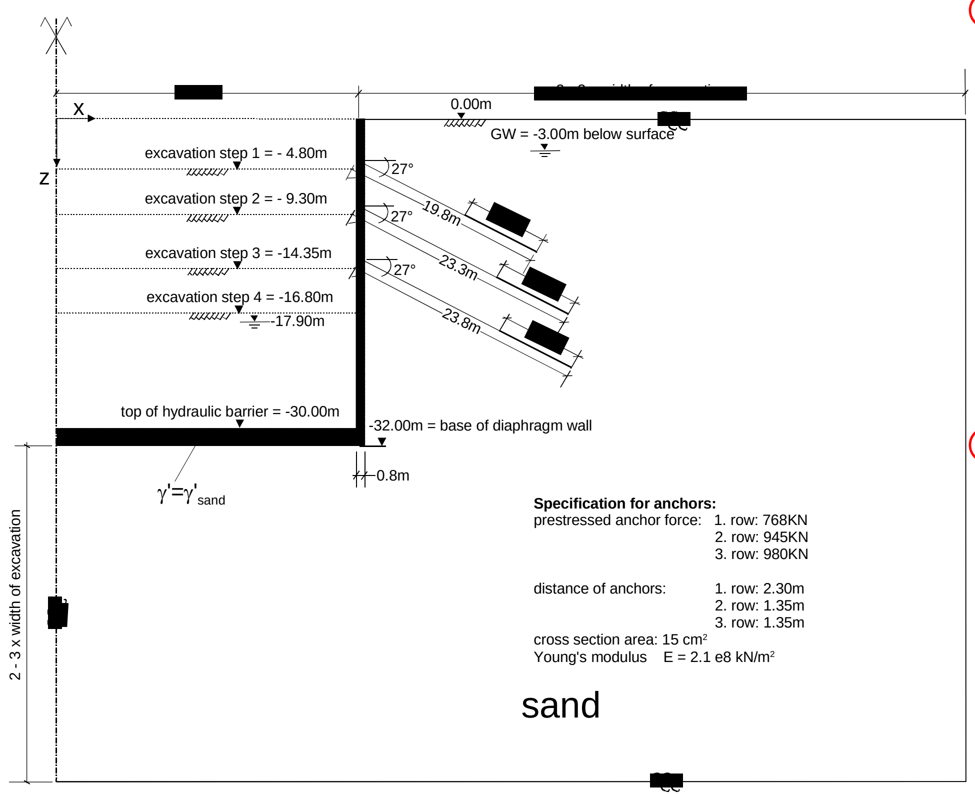
- Effect of the friction between soil and wall





Methods for calculating ground movements

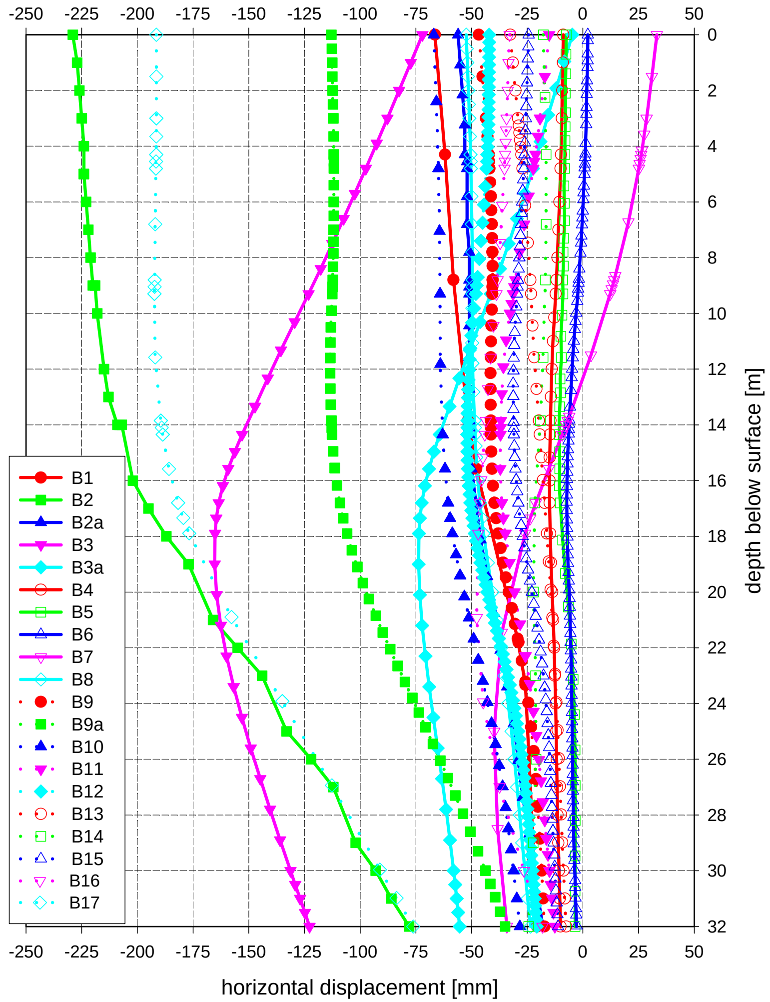
- Benchmark (Schwiger, 2006)

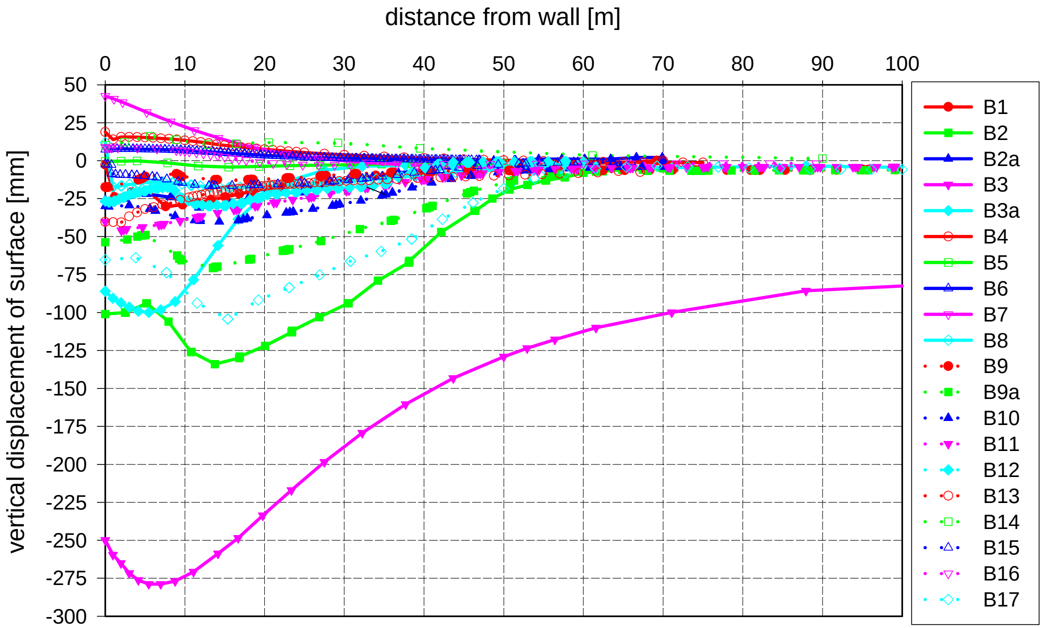


- 17 participants
  - domain size
  - structural elements, interfaces
  - Constitutive models: Mohr-Coulomb, nonlinear elastoplastic, hypoplastic
- similar strength parameters, more differences in stiffness parameters

Methods for calculating ground movements

- Benchmark (Schwiger, 2006)





Surface settlements

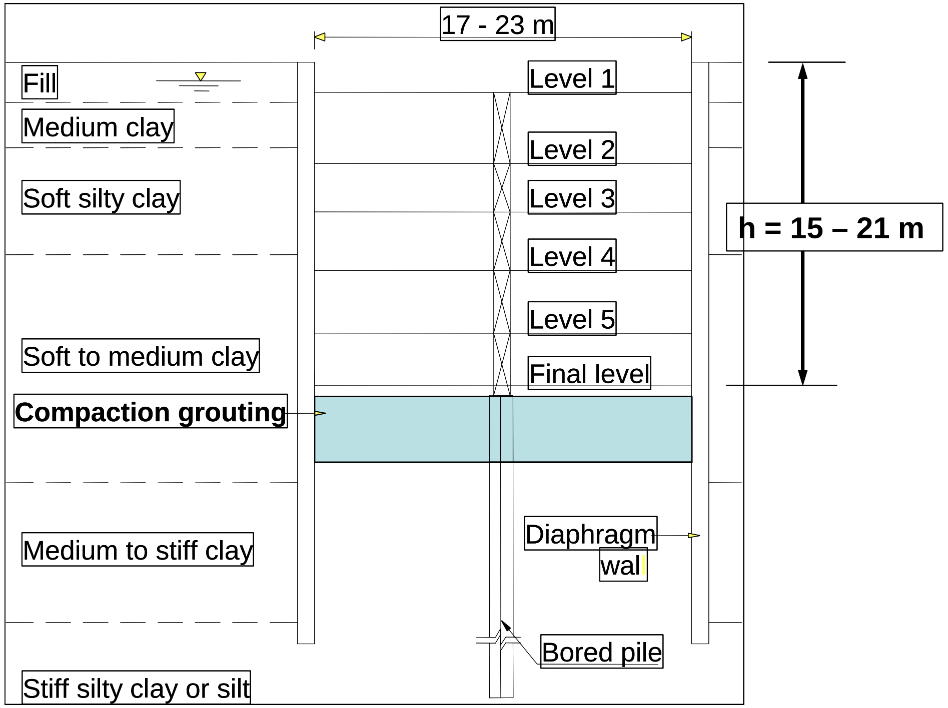
Horizontal wall displacements

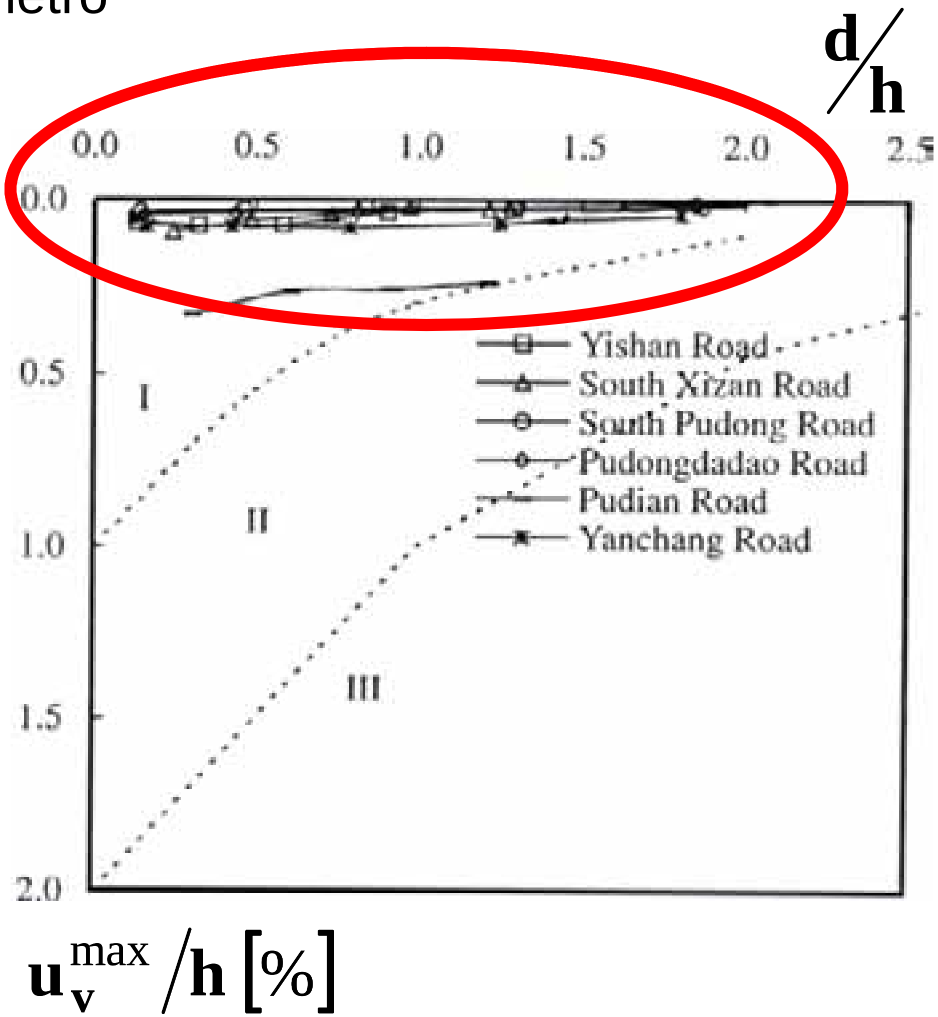
Esquema de la presentación

- Introduction. Generation of ground movements by deep excavations
- Empirical methods for estimating ground movements
- Methods for calculating ground movements
- Procedures for control and reduction of movements
- A case history
- Excavations with large movements: announcing failure?
- Conclusions

Procedures for control and reduction of movements

- Taking adequate measures, it is possible to minimize movements even in soft soils
  - A recent example: Shanghai metro





Wong et al. (2005)

Procedures for control and reduction of movements

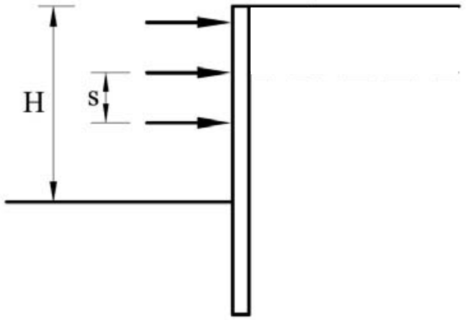
1. Increase stiffness of the retaining system (wall / bracing)
2. Early installation of bracing (especially the top one)
3. Attention to the contact between bracing and wall
4. Preloading the bracing
5. Avoid overexcavations
6. Embedding the wall in a stiff layer
7. Bracing below the maximum excavation depth
8. Impervious wall and water flow control
9. Compensation / correction grouting?

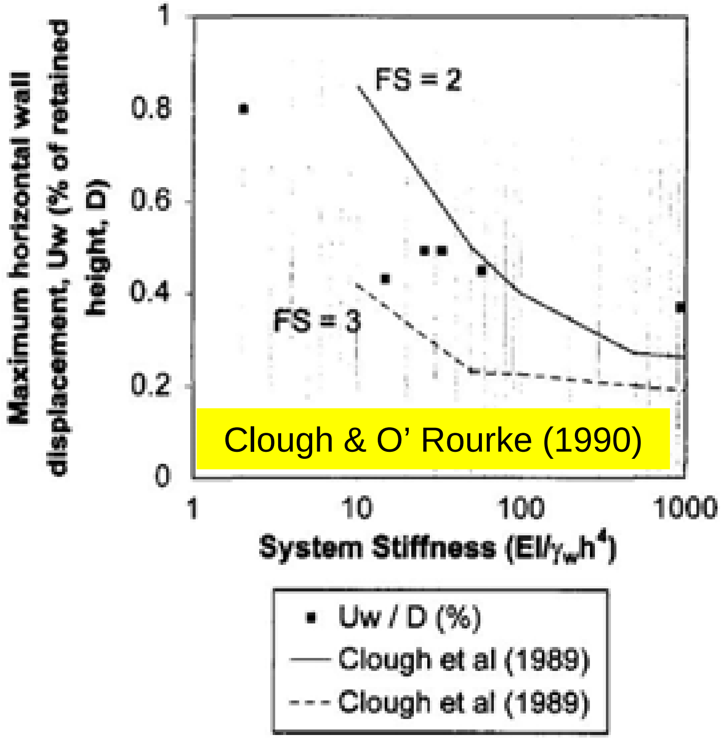
Procedures for control and reduction of movements

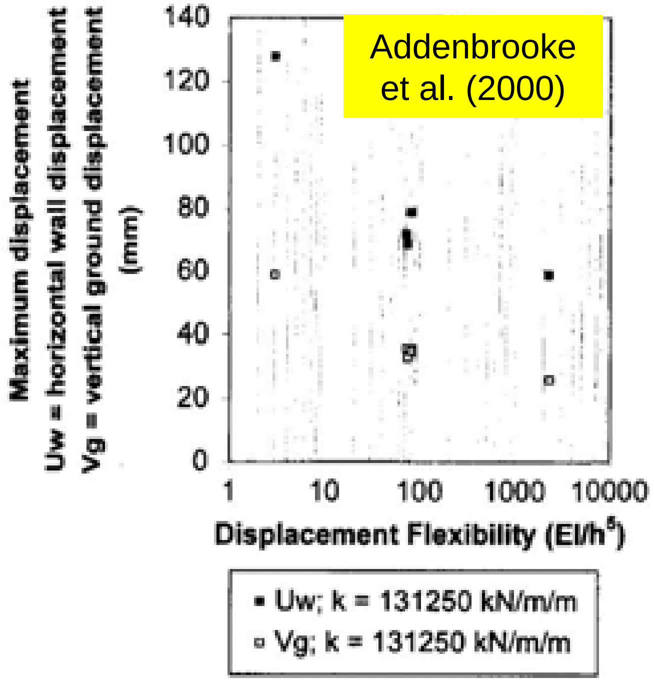
- Increase the stiffness of the retaining system
  - increase wall stiffness (thickness, counterforts)
  - increase bracing system (prop separation, prop stiffness)

System stiffness: $(EI)/(\gamma_w s^4)$ (Clough & O' Rourke, 1990)

Flexibility number: $(s^5)/(EI)$ (Addenbrooke et al., 2000)



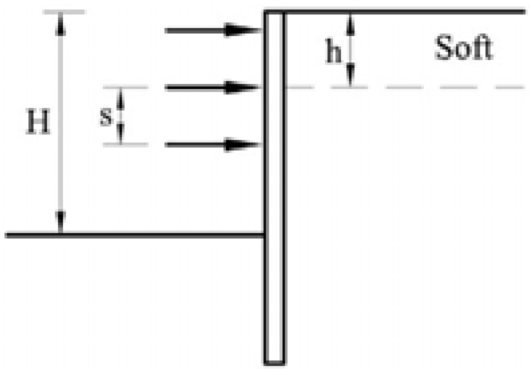




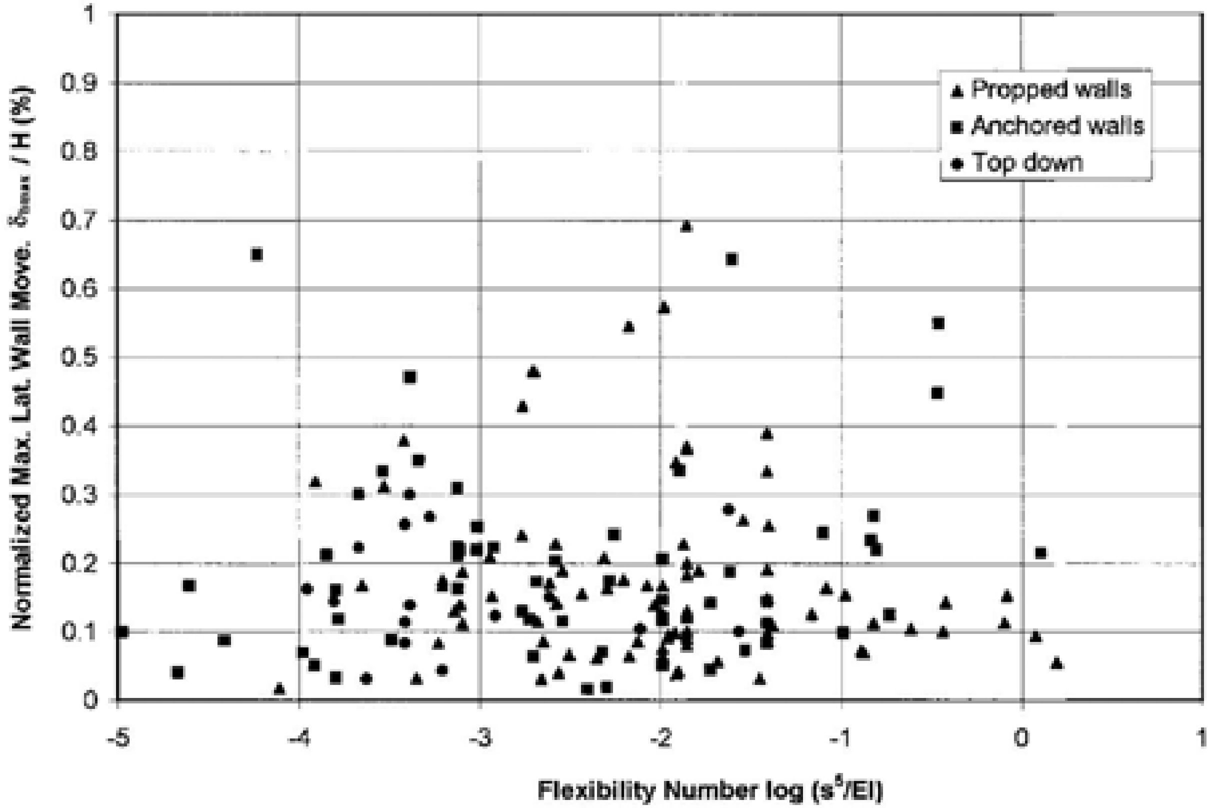
- based on finite elements calculations
  (nonlinear model with small strain stiffness)

Procedures for control and reduction of movements

- Influence of system stiffness
  - Long (2001) database. Excavations in stiff and medium soils



h < 0.6H

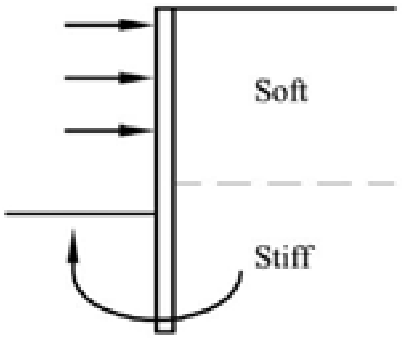


Maximum lateral wall movement

- System stiffness does not appear to be a dominant factor in these cases

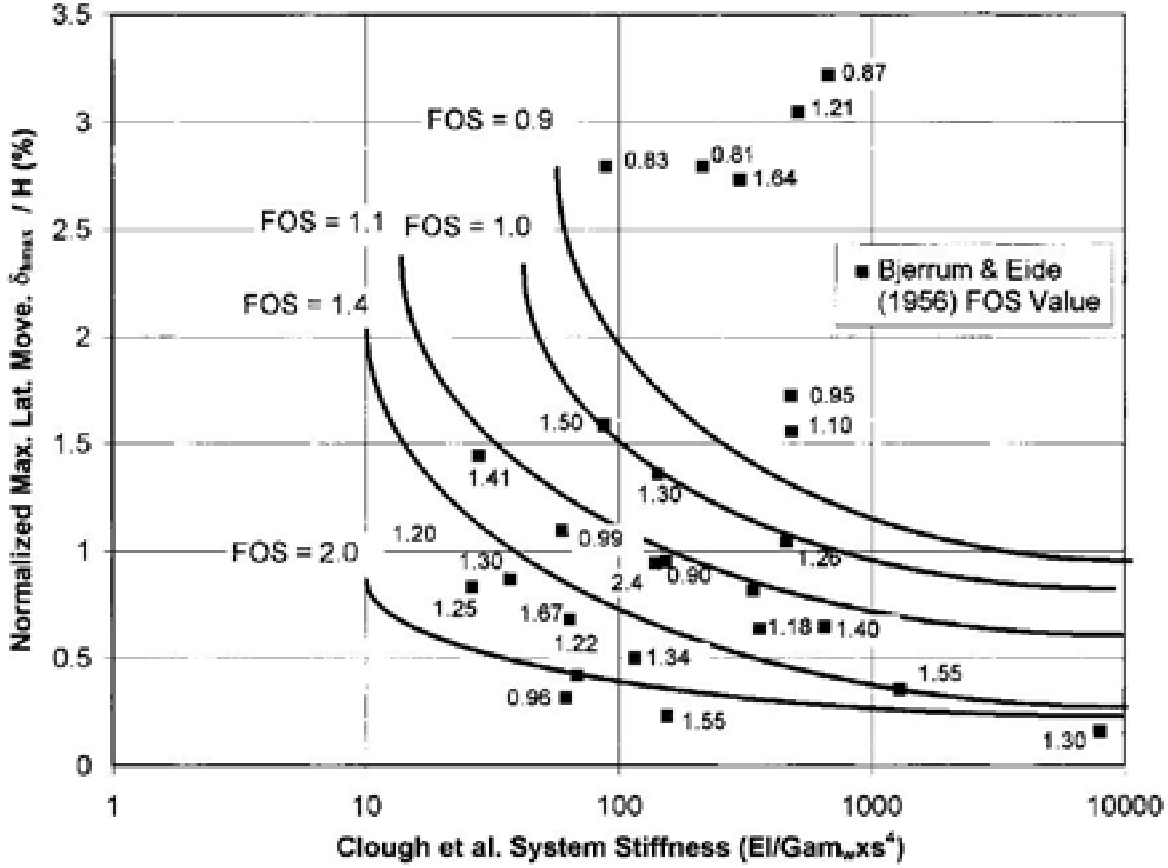
Procedures for control and reduction of movements

- Influence of system stiffness
  - Long (2001) database. Excavations in soft soils



h > 0.6H

Low FOS



Maximum lateral movement

- There appears to be some influence of the system stiffness for low factors fo safety

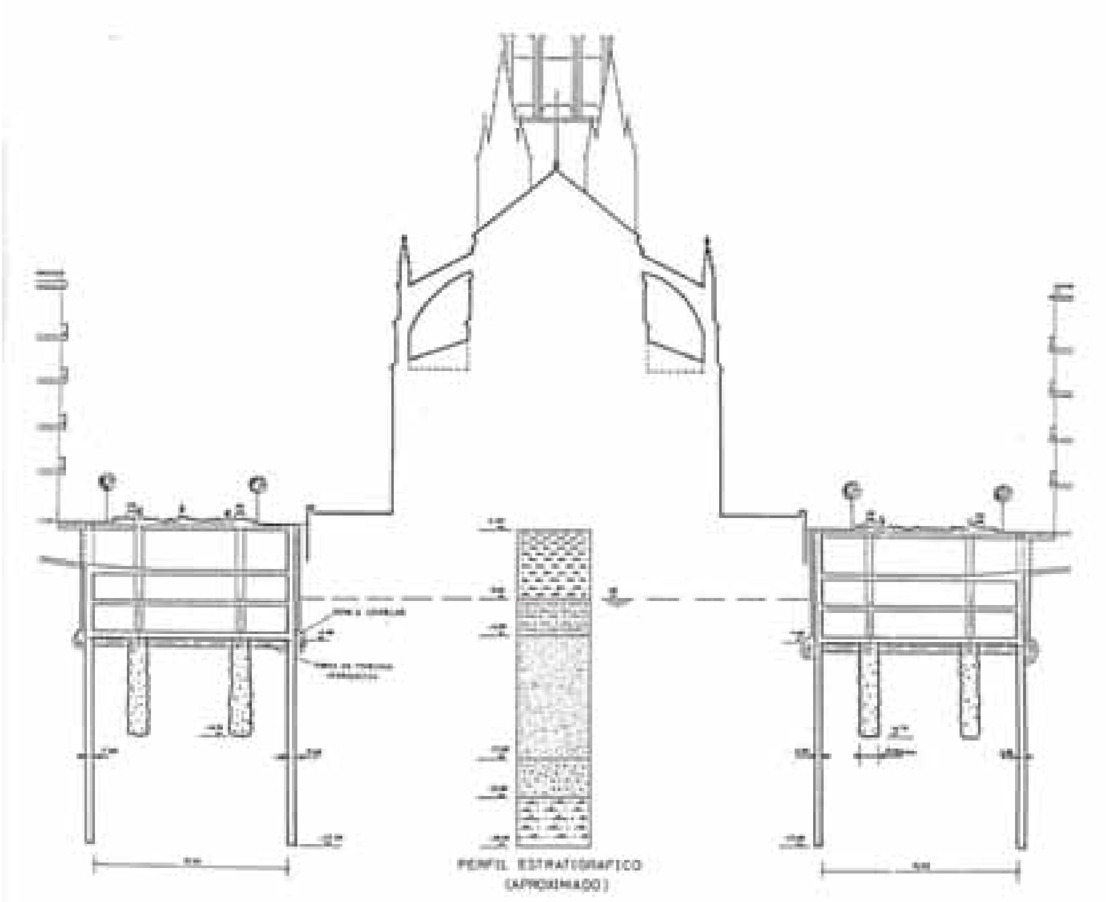
Procedures for control and reduction of movements

- Early installation of bracing
  - top-down construction

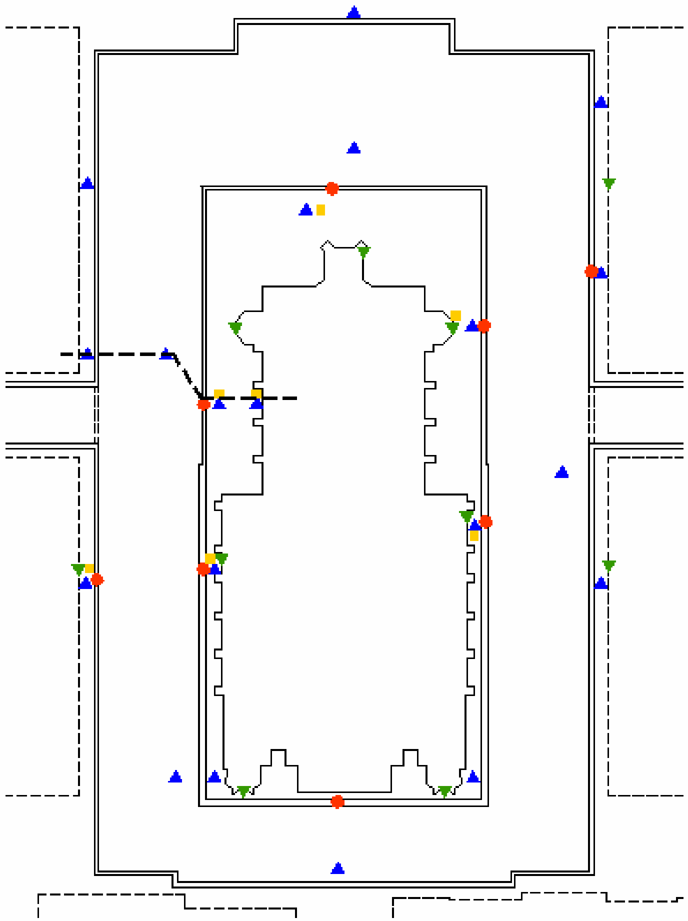
Buen Pastor Cathedral, San Sebastián, Spain

Procedures for control and reduction of movements

- Early installation of bracing
  - top-down construction



Section

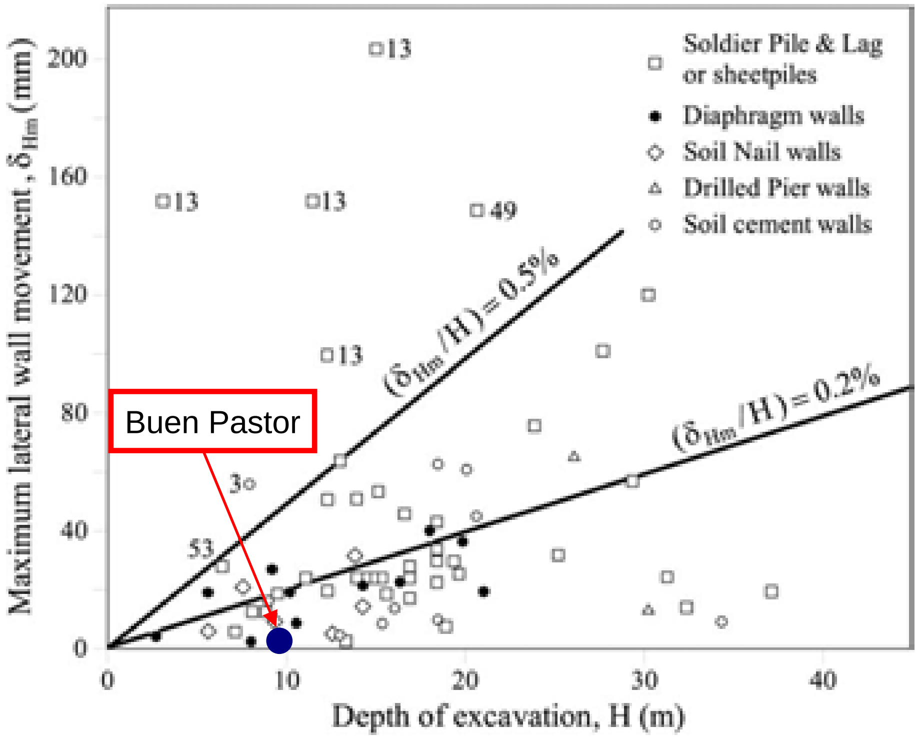


Plan view

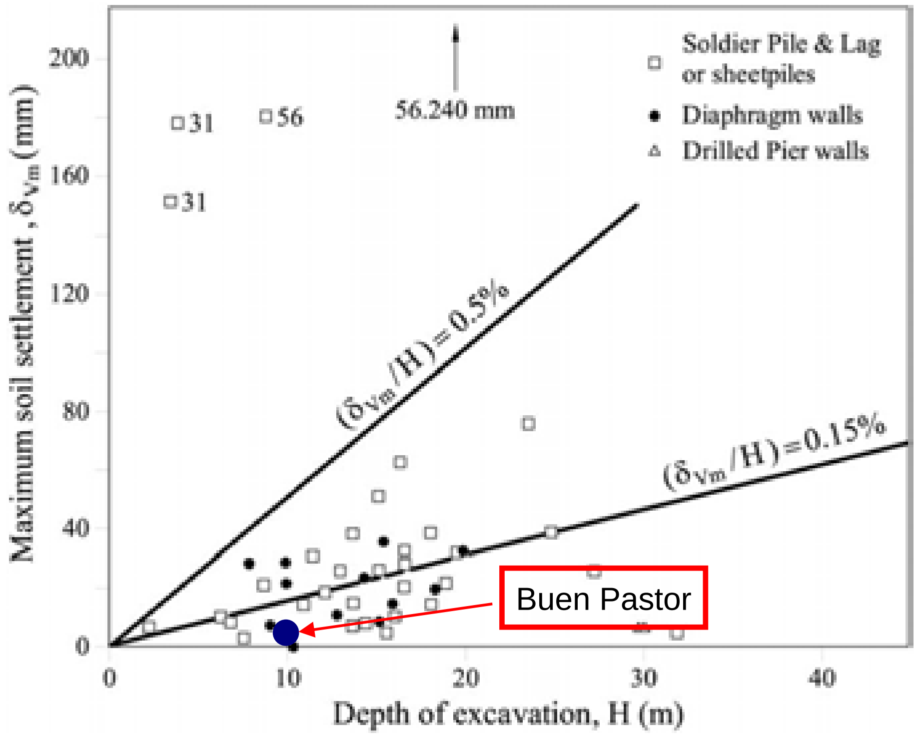
Buen Pastor Cathedral, San Sebastián, Spain

Procedures for control and reduction of movements

- Early installation of bracing
  - top-down construction



Maximum lateral movement



Maximum settlement

Buen Pastor Cathedral, San Sebastián, Spain

Procedures for control and reduction of movements

- Attention to the contact between bracing and wall

Lisbon Metro

Circle Line, Singapore Metro

Procedures for control and reduction of movements

- Preloading the bracing (props and anchors)

Lisbon Metro

Diagonal Mar, Barcelona

- prestressing reduces the movements caused by excavation
- prestressing does not increase the stiffness of the bracing

Procedures for control and reduction of movements

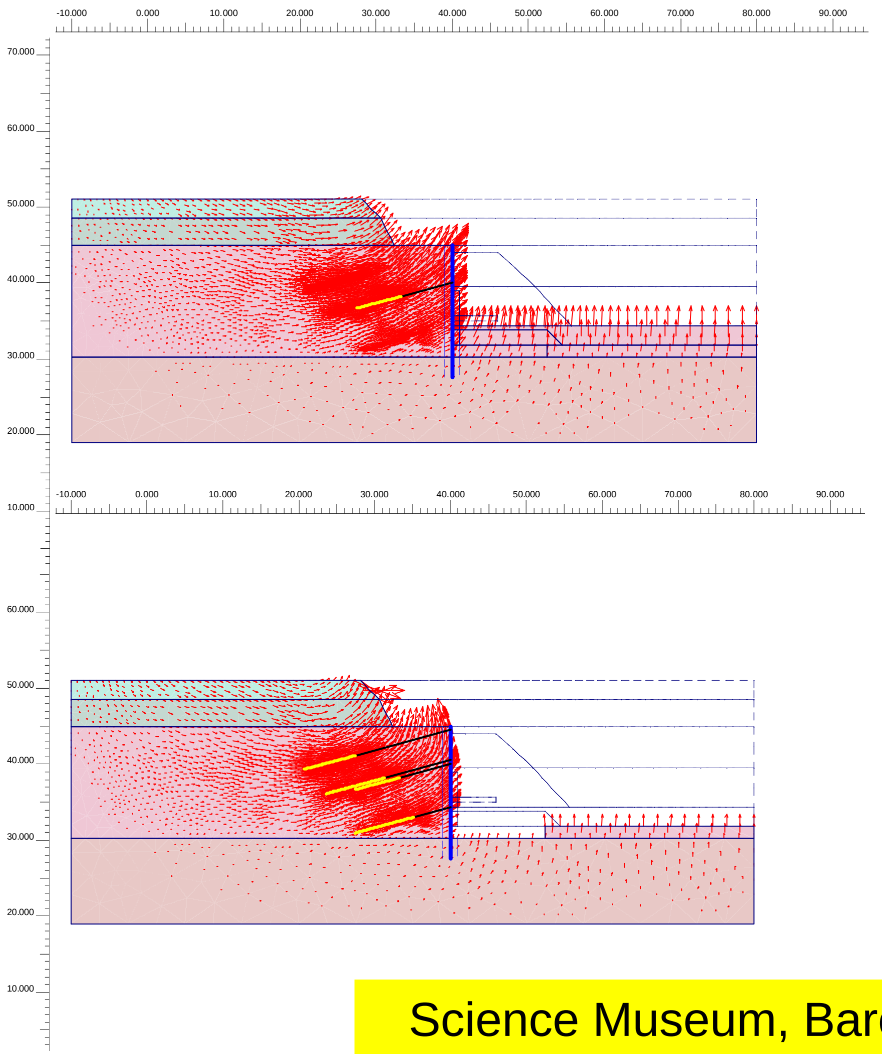
- Preloading of the bracing (props and anchors)
  - anchors with a considerable free length exhibit a significant deformability

- Pile wall (65 cm diameter)
- Wall length: 80 m
- Max. excavation depth: 20 m
- Excavation in weathered granite

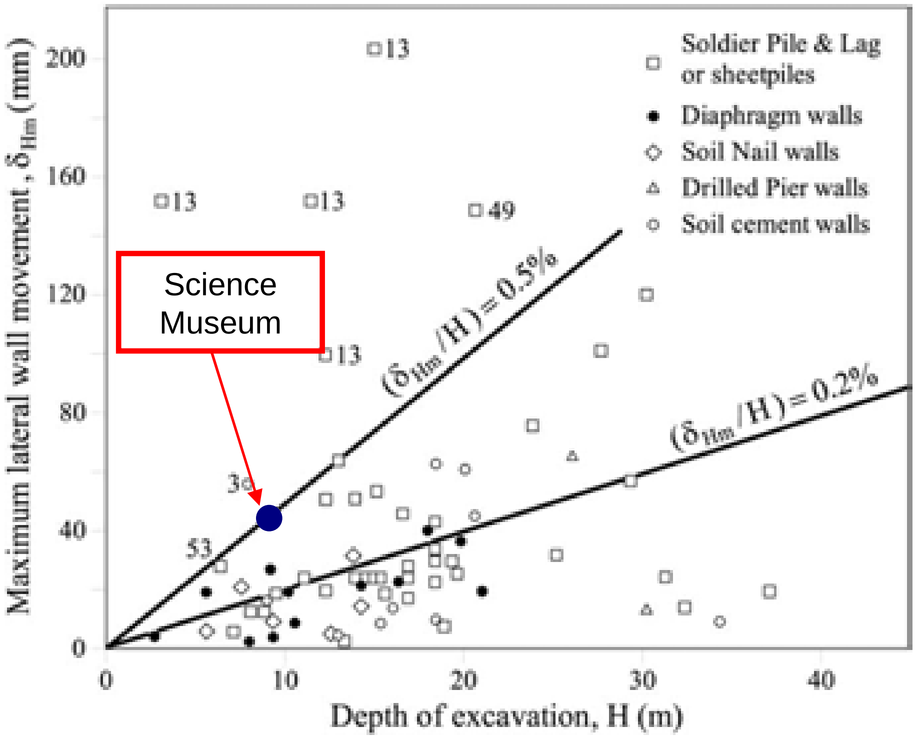
Science Museum, Barcelona

Procedures for control and reduction of movements

- Preloading of the bracing (props and anchors)
  - anchors with a considerable free length exhibit a significant deformability



Science Museum, Barcelona



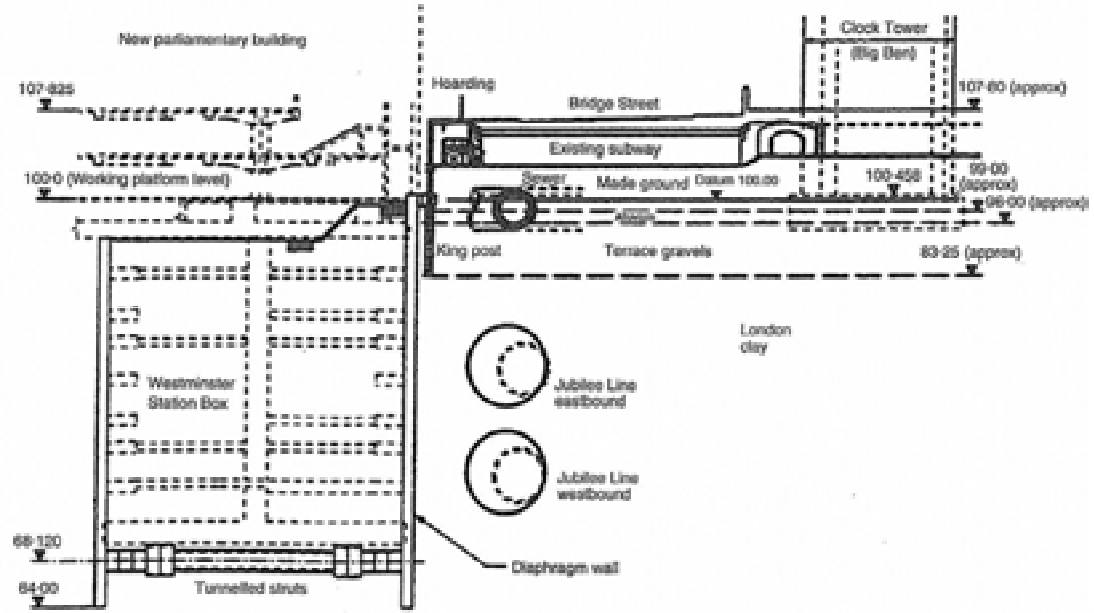
Maximum lateral displacement

Procedures for control and reduction of movements

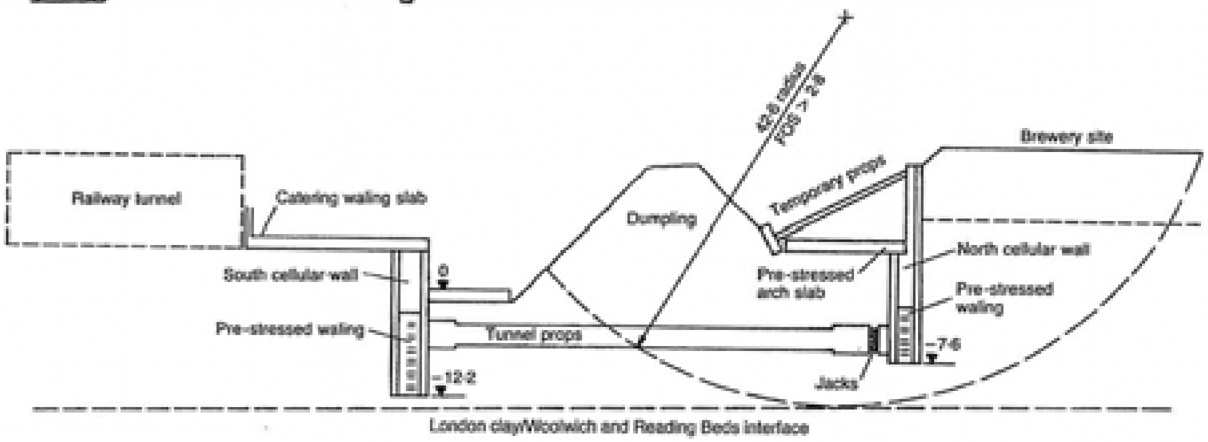
- Bracing below the maximum excavation depth
  - Procedures:
    - Props placed in trenches or tunnels previously excavated
    - Rows of barrettes (diaphragm walls segments)
    - Jet grouting slabs or props
    - Slabs of props constructed with deep soil mixing
    - Slabs of props constructed with compaction grouting
  - For bracing constructed using soil improvement techniques
    - There is no consensus whether it is better to use slabs or thicker discontinuous props
    - Ground improvement techniques often produce brittle materials that can lose strength if failure strain is exceeded
    - Constructing the bracing may weaken the overlying soil

Procedures for control and reduction of movements

- Bracing below the maximum excavation depth
  - Props placed in pre-excavated trenches or tunnels



Westminster Station
London

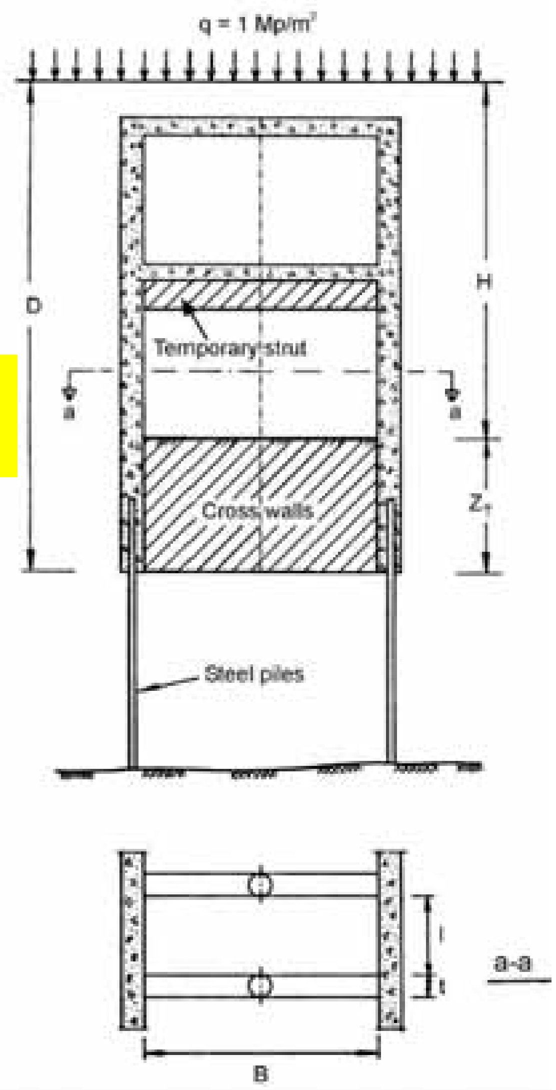


Barbican Arts Centre
London

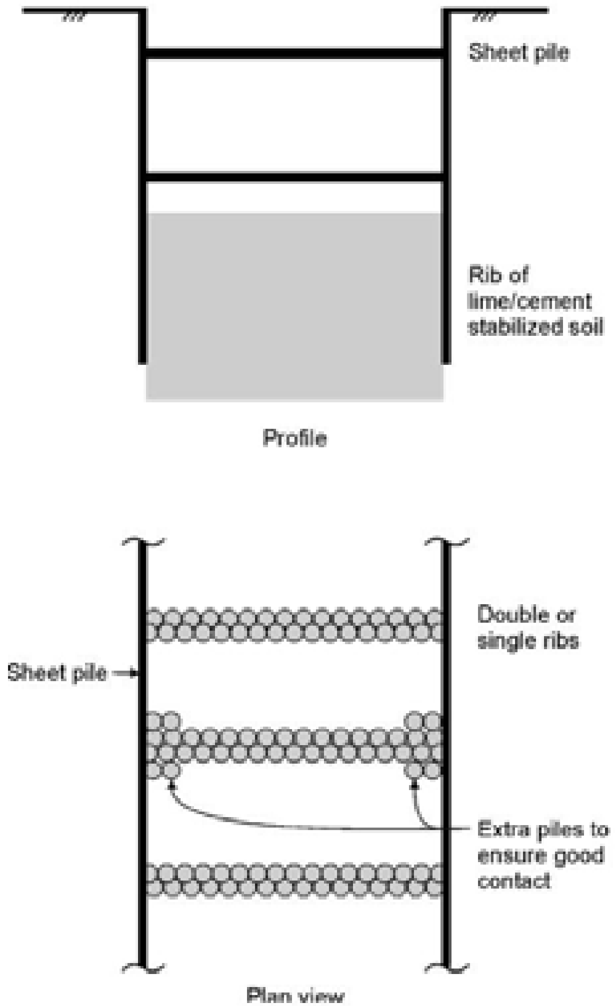
Procedures for control and reduction of movements

- Bracing below the maximum excavation depth

Studenterlinden Oslo



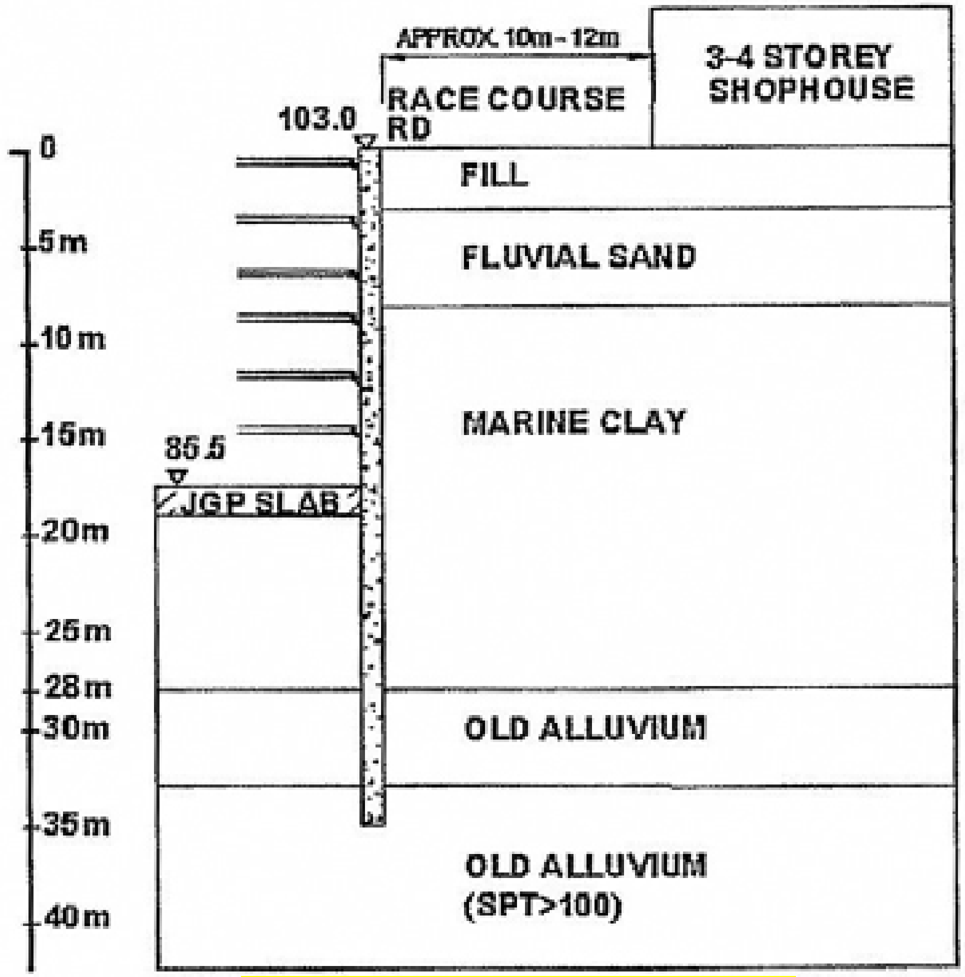
Diaphragm wall segments



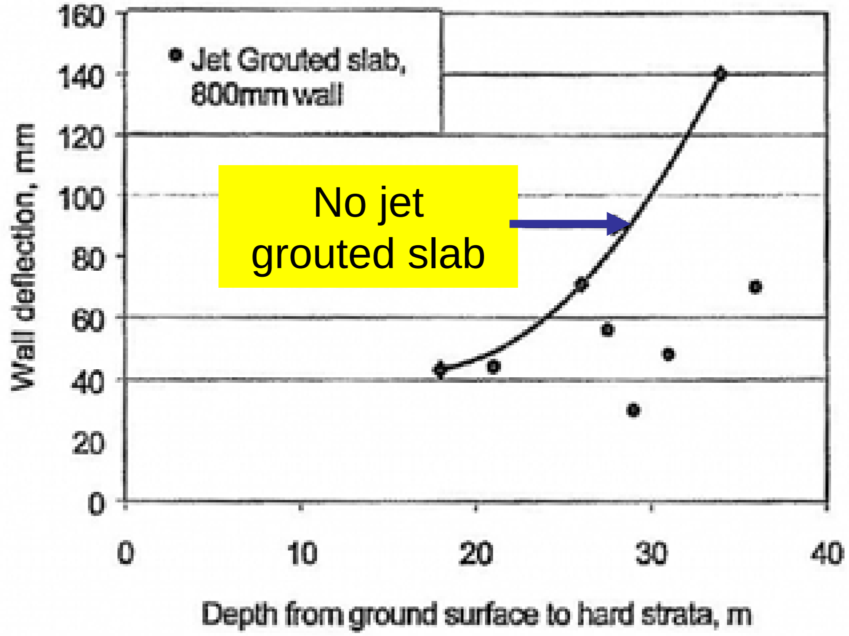
Lime-cement columns

Procedures for control and reduction of movements

- Bracing below the maximum excavation depth
  - Jet grouting slabs or props



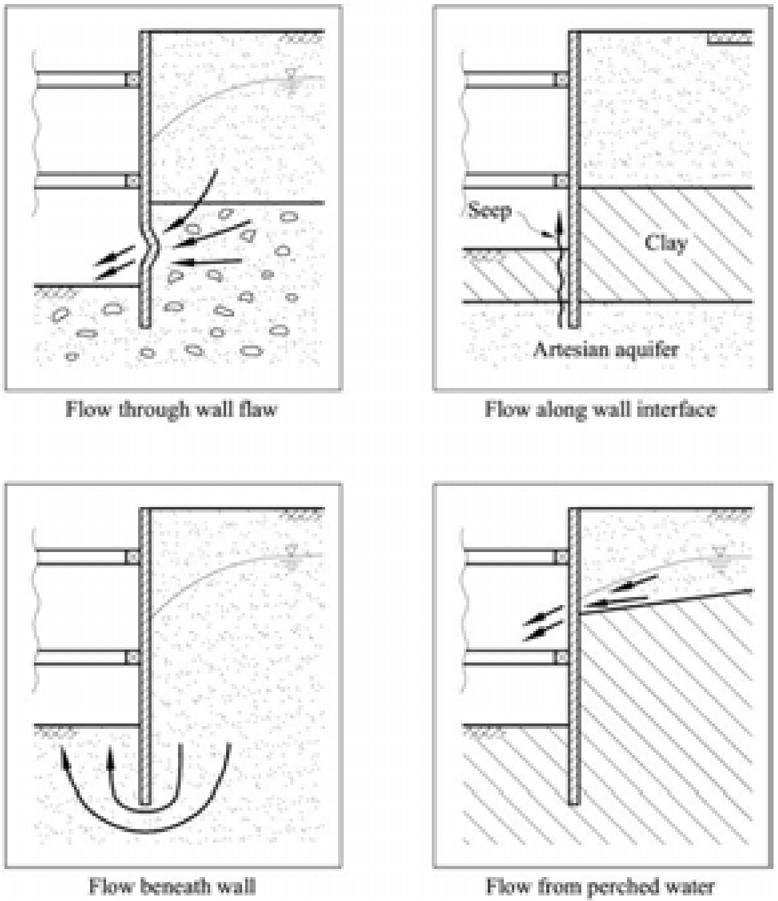
Race Course Road Metro Singapore



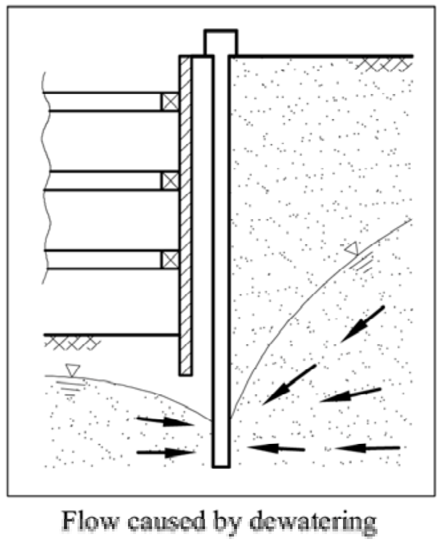
Lateral excavation movements in Singapore (Shirlaw, 2006)

Procedures for control and reduction of movements

- Impervious wall and water flow control
  - The lack of water flow control or the changes in hydraulic conditions cause sort and long term ground movements



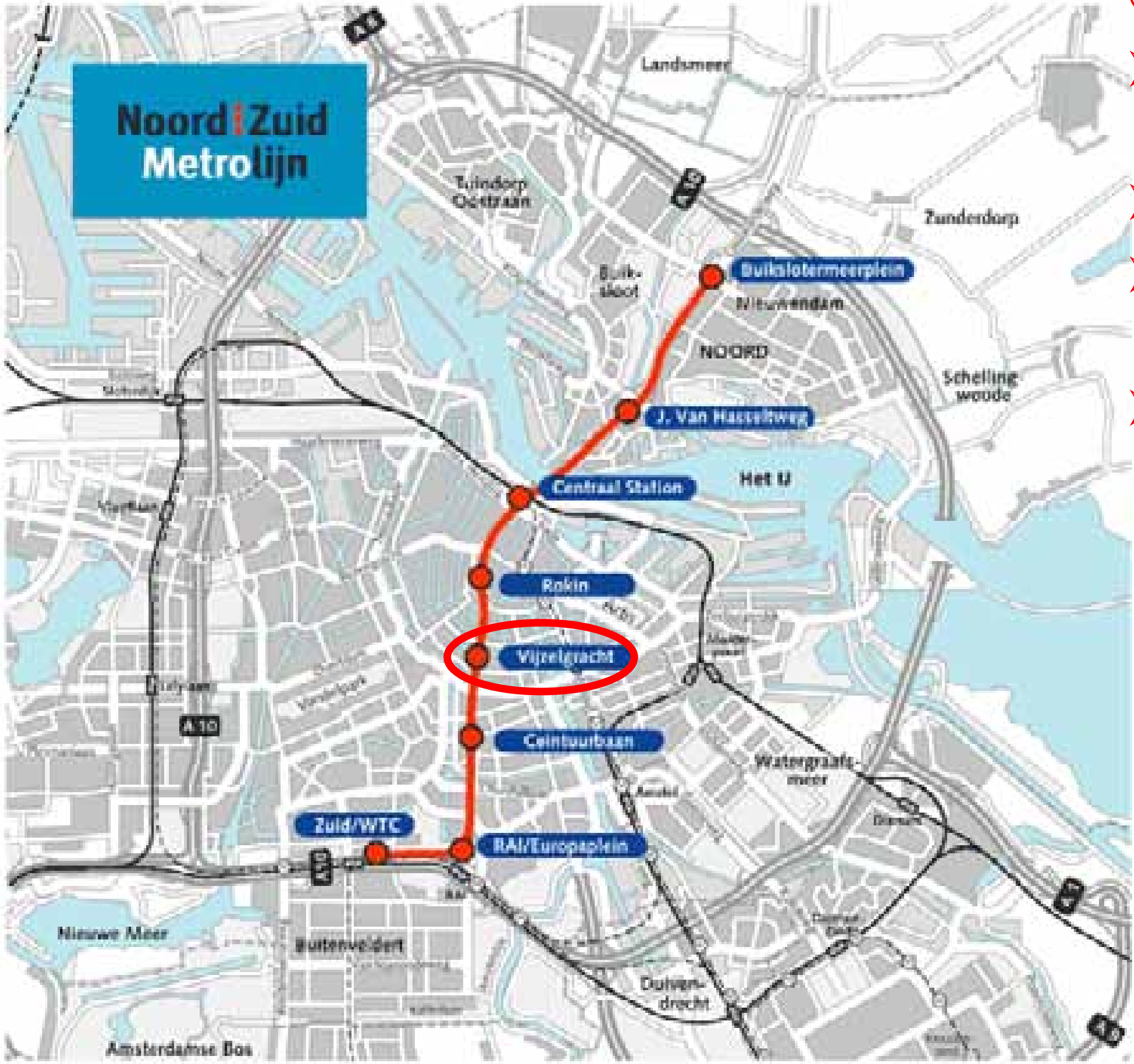
Sealing defects



Pumping

Procedures for control and reduction of movements

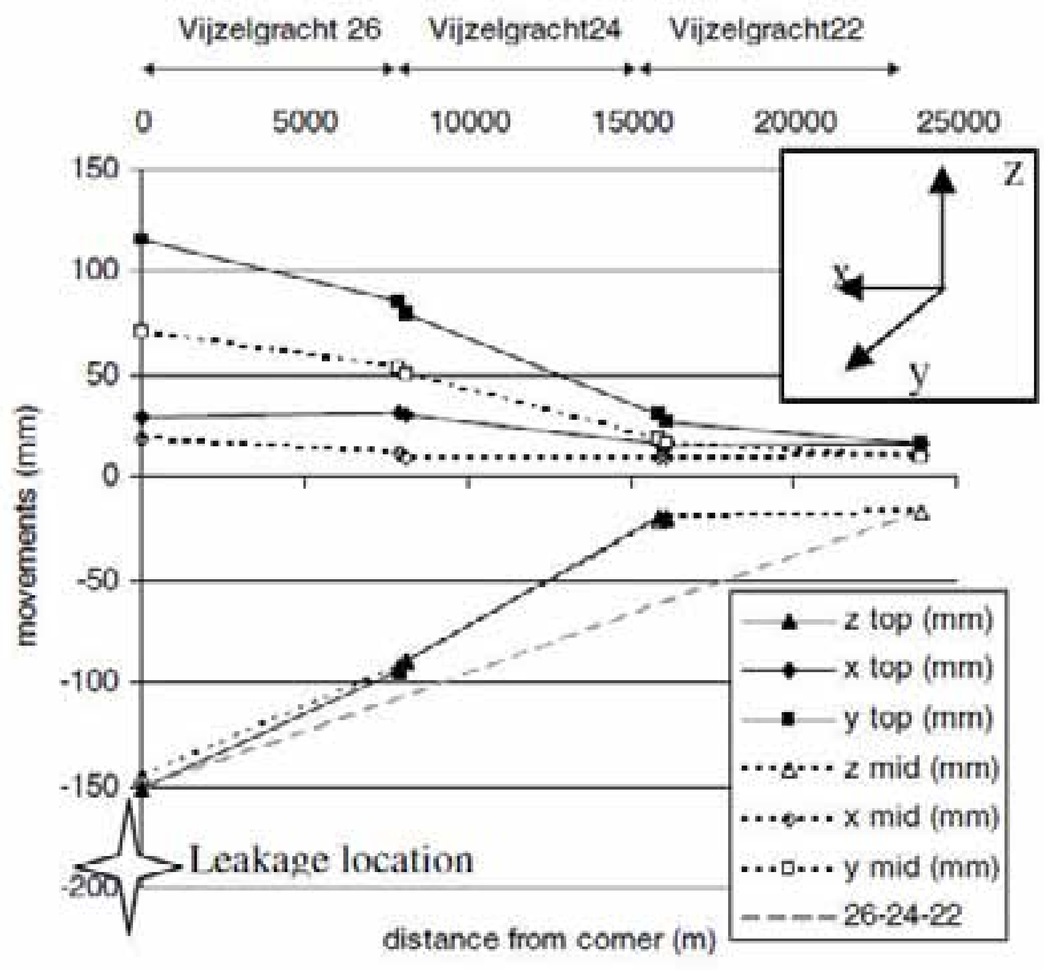
- Amsterdam. North-South line



- Vijzelgracht station
  - 250 m long, 22 m wide, 31 m deep
  - Top down construction
  - 1.2 m thick diaphragm walls 45 m deep
  - 5.1 m long panels with steel stop ends

Procedures for control and reduction of movements

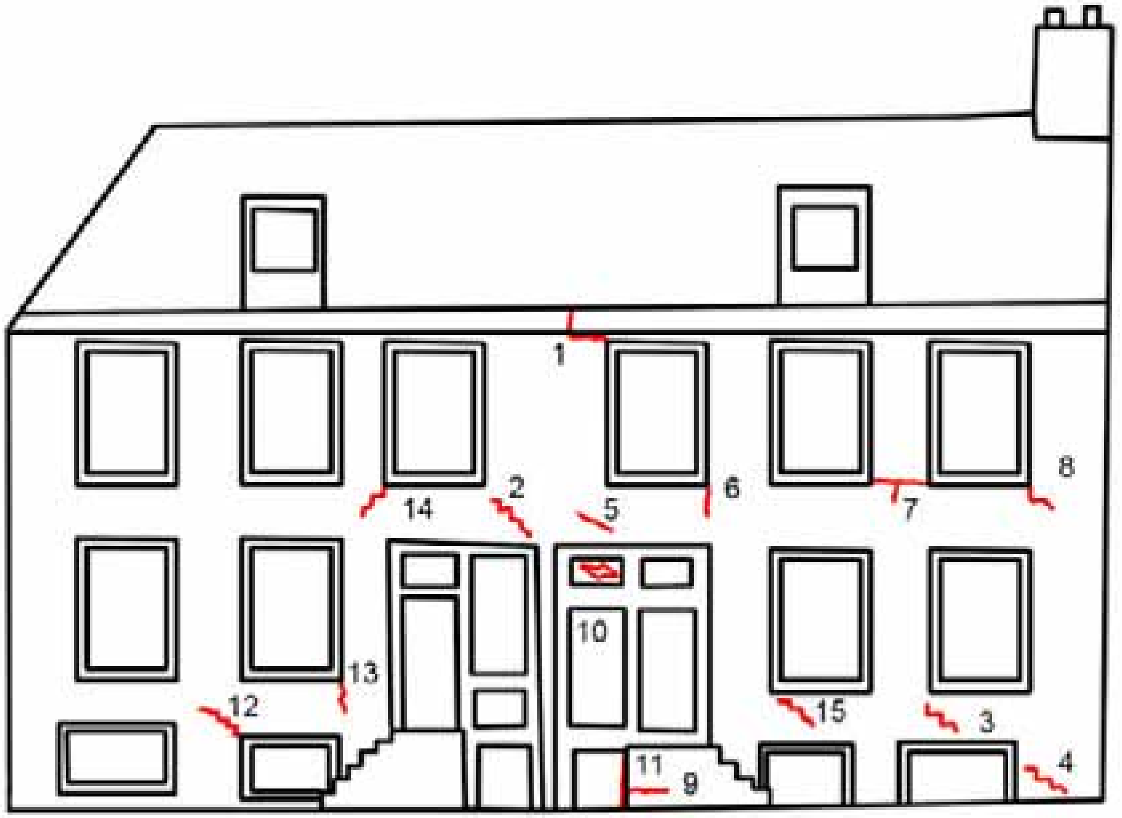
- Vijzelgracht station, North-South line, Amsterdam
  - Vijzelgracht, 26. Leakage due to a steel stop not being removed



(Korff et al., 2009)

Procedures for control and reduction of movements

- Vijzelgracht station, North-South line, Amsterdam
  - Vijzelgracht, 26. Leakage due to a steel stop not being removed

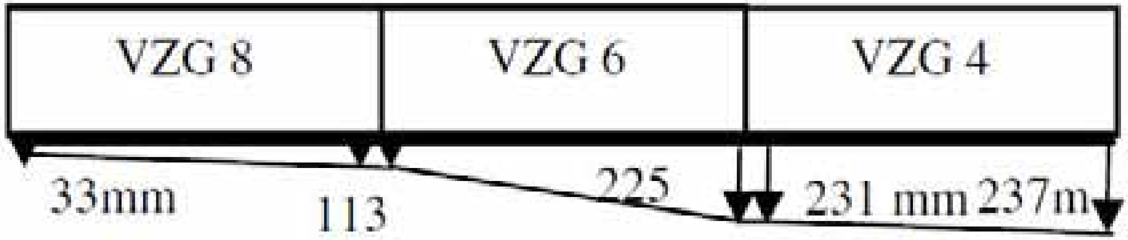


- Settlement due to ground loss
  - Tilt 1/78 and 1/184. *Severe* to *very severe* damage

(Korff et al., 2009)

Procedures for control and reduction of movements

- Vijzelgracht station, North-South line, Amsterdam
  - Vijzelgracht, 4. Leakage due a large bentonite inclusion in the wall

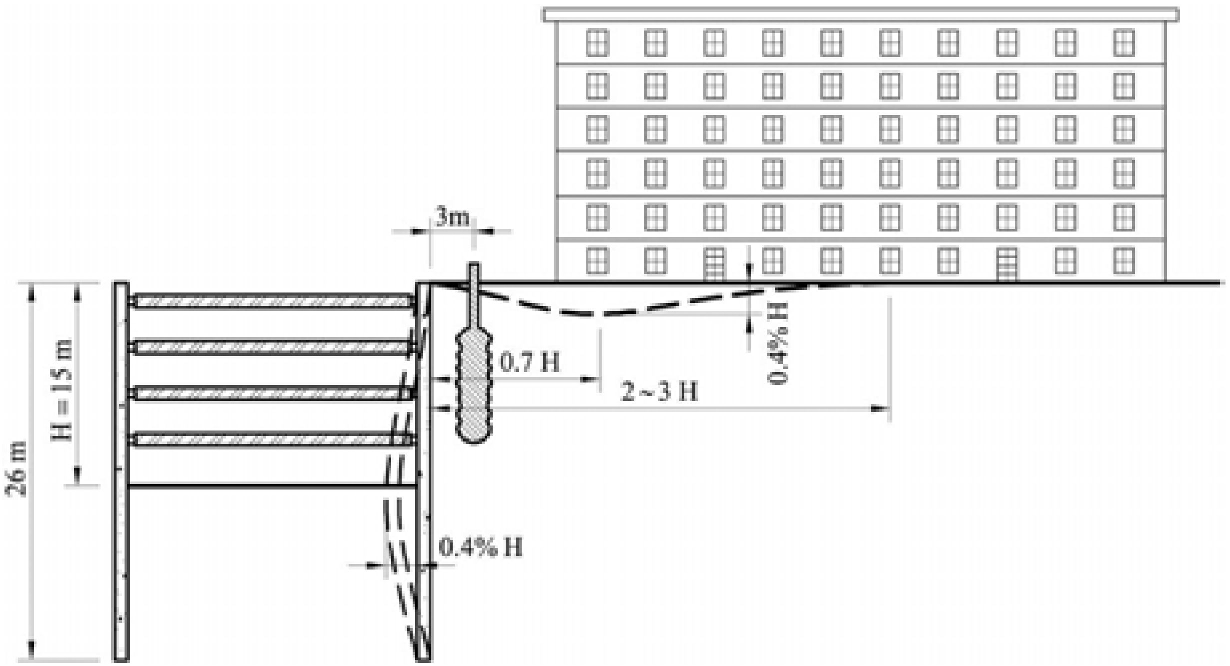


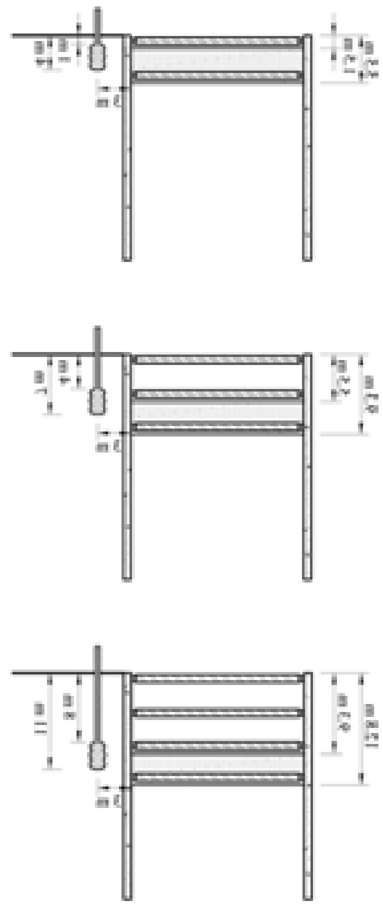
- Settlement due to ground loss
  - Tilt 1/38 and 1/70. *Severe* to *very severe* damage

(Korff et al., 2009)

Procedures for control and reduction of movements

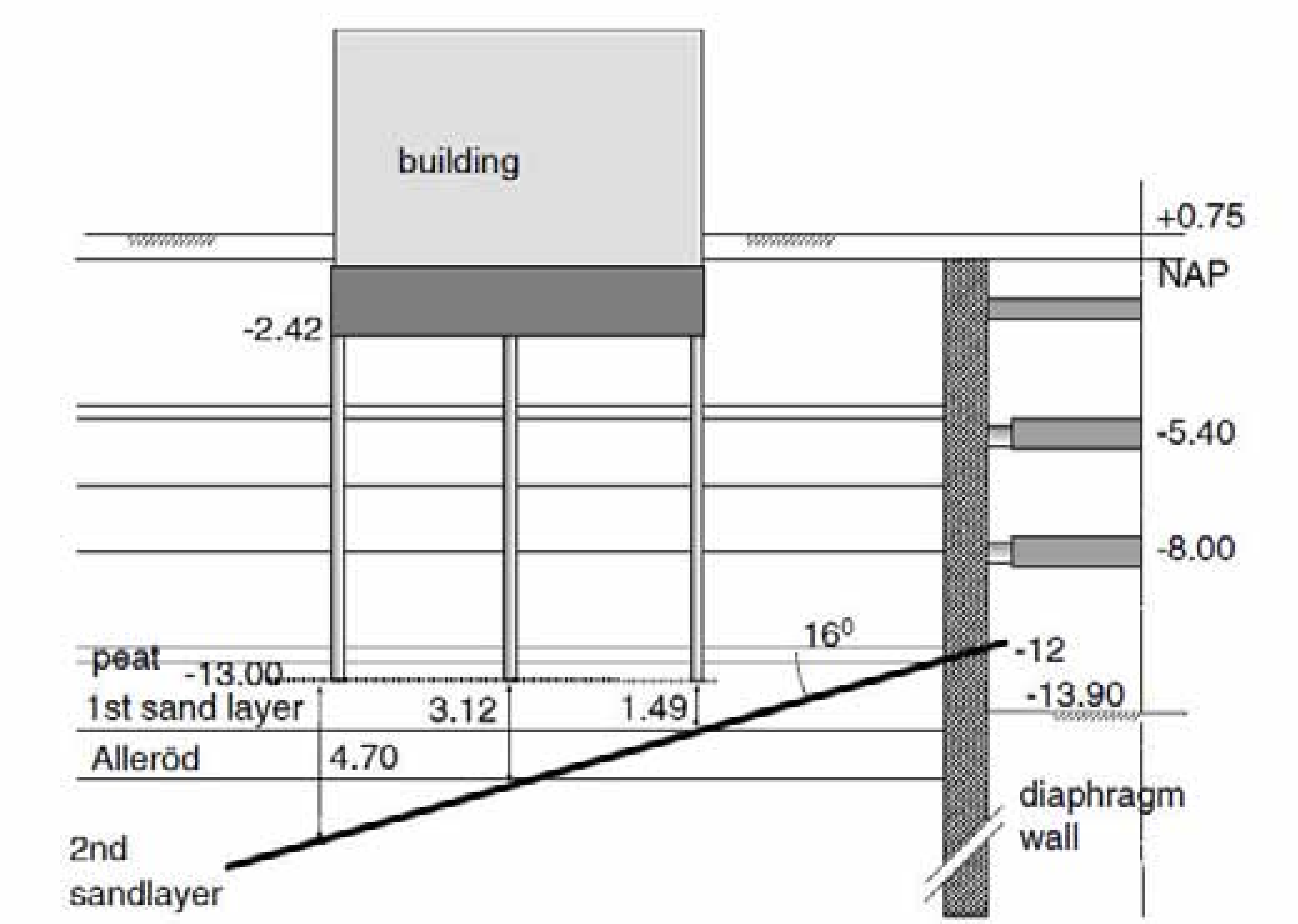
- Compensation grouting
- Excavation in soft clay in Shanghai (Liu, 2003)
  - Risk of affecting the wall (injection is performed after the props have been installed)
  - It is generally counterproductive to perform compensation grouting in soft clays





Procedures for control and reduction of movements

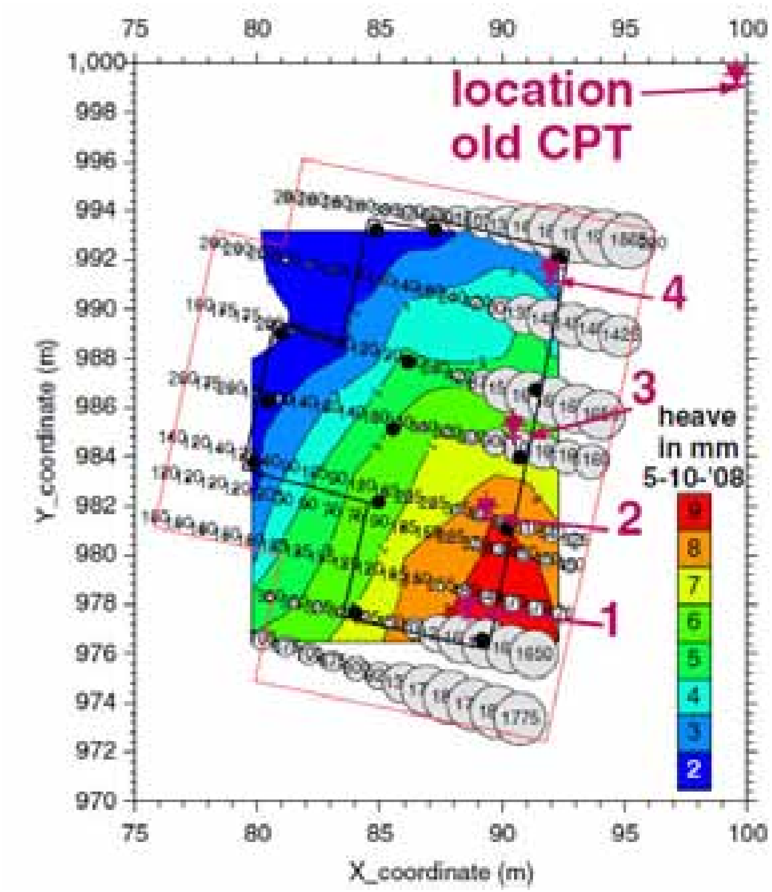
- Vijzelgracht station, North-South line, Amsterdam
  - Corrective grouting at Vijzelgracht, 22, 24, 26

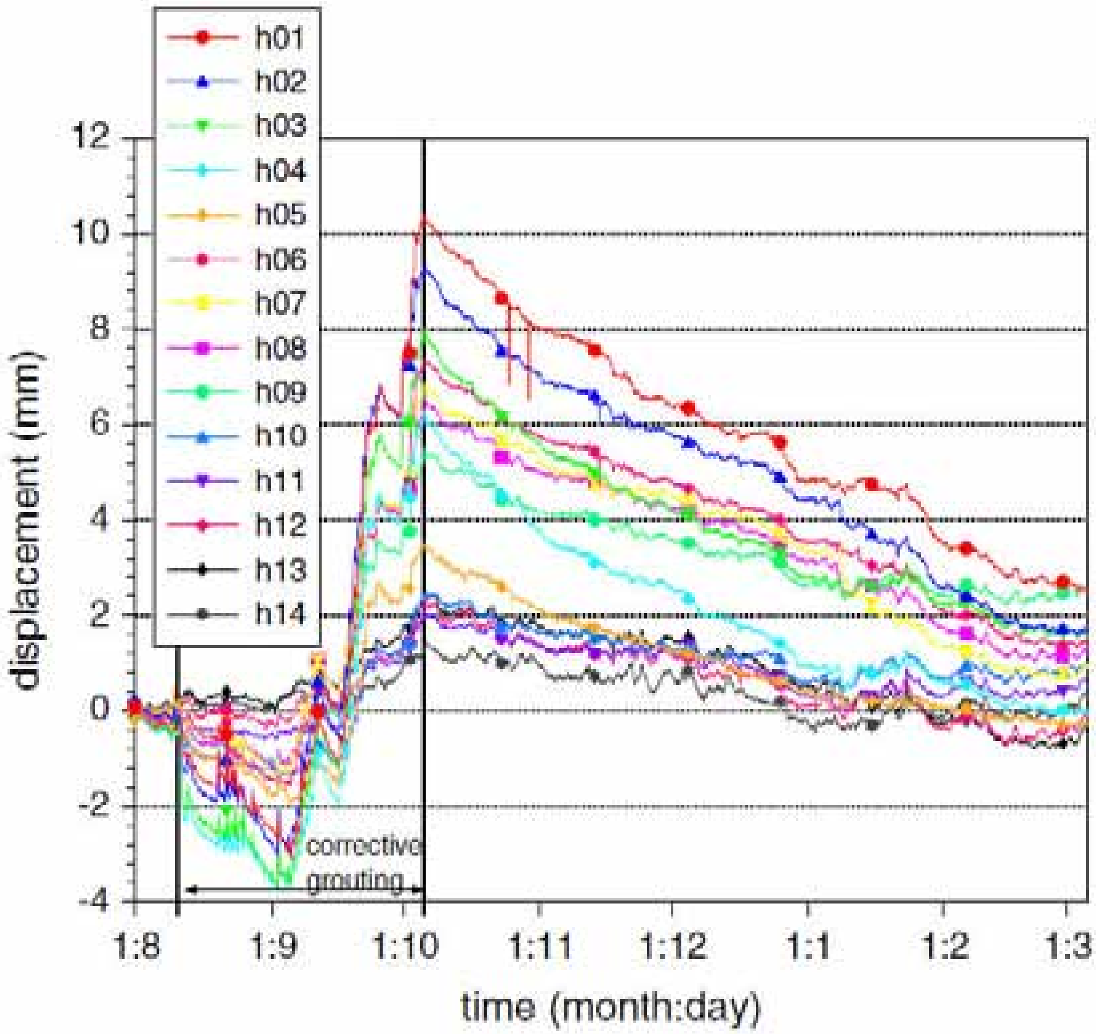


(Bezuijen et al., 2009)

Procedures for control and reduction of movements

- Vijzelgracht station, North-South line, Amsterdam
  - Corrective grouting at Vijzelgracht, 22, 24, 26





(Bezuijen et al., 2009)

Esquema de la presentación

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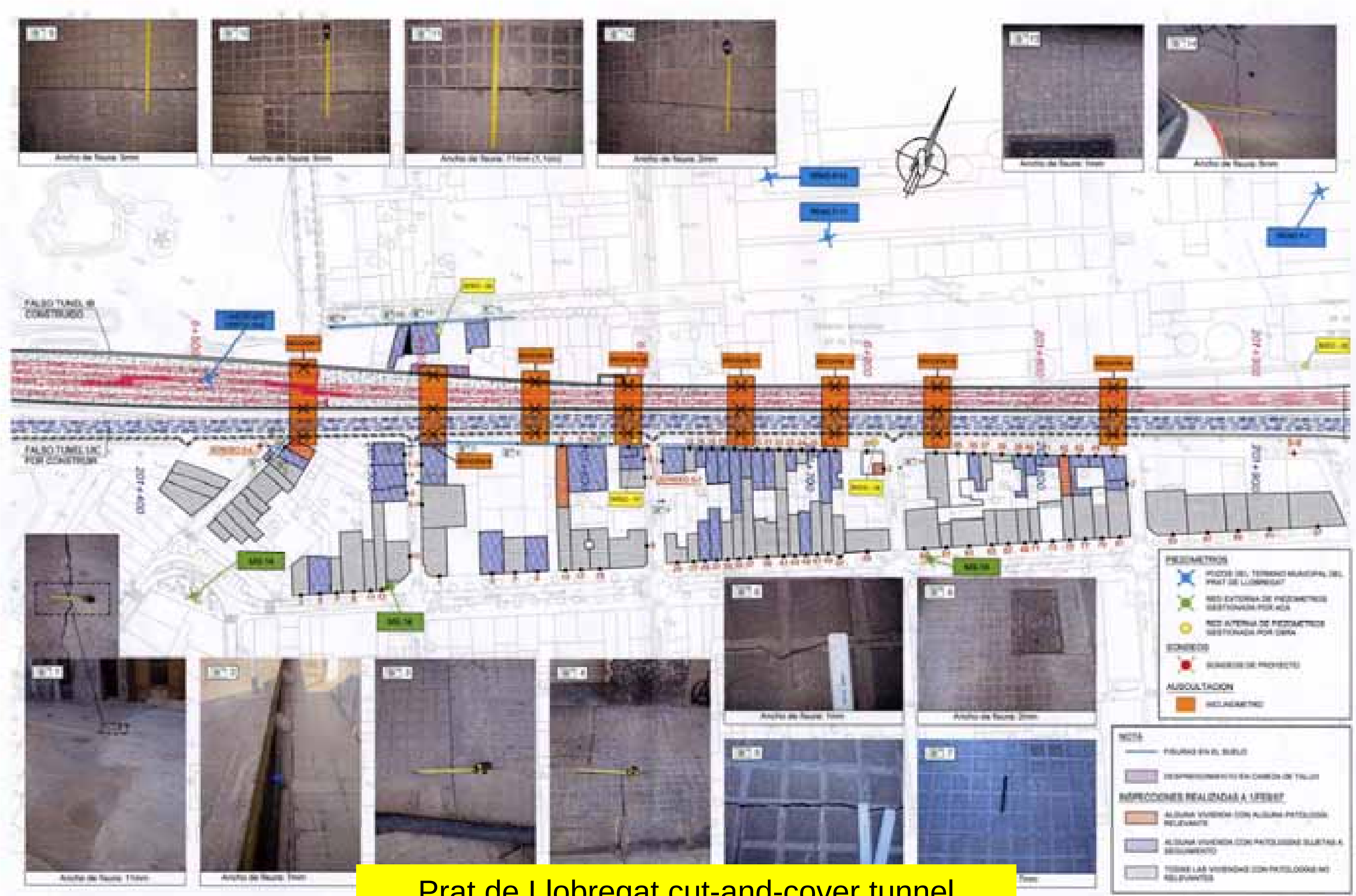
Procedures for control and reduction of movements

Prat de Llobregat cut-and-cover tunnel

Procedures for control and reduction of movements



Prat de Llobregat cut-and-cover tunnel

Procedures for control and reduction of movements

Prat de Llobregat cut-and-cover tunnel

What the papers say…

►► Un tren passa davant les cases del carrer Major del Prat, ahir.

TEMOR ... ELS HABITANTS DEL BAIX LLOBREGAT

Les garanties dels tècnics no tranquil.litzen els veïns

Els afectats denuncien que cada dia surten noves fissures

EDWIN WINKELS
EL PRAT DE LLOBREGAT

Diguin el que diguin tècnics i altres experts sobre l'absència de perill, els veïns del Prat que dia darrere dia veuen aparèixer noves esquerdes i eixamplar-se les existents dins i fora dels seus pisos, ja no estan tranquils. «Aquest matí m'he aixecat a les cinc i he sortit al carrer. No podia dormir més. Tant al bany com a la cuina, l'alumini s'està separant de les parets cada vegada més», deia ahir Pepi Bautista, veïna del número 2 del carrer de Manuel Bertrand, un dels edificis més malmesos.

A la paret mitgera que dóna a les vies del tren, Joan Ribas assenyalava quatre noves esquerdes que un parell de dies abans encara no es veien. Pot ser que no totes les fissures siguin noves; que la gent, fixant-s'hi molt, trobi de sobte moltes més esquerdes que abans no veia, però l'entorn de l'epicentre no ofereix dubtes que la zona afectada està cruixint de manera preocupant.

INVENTARI MUNICIPAL // Després que el cas sortís dissabte a la llum pública, cada vegada són més els veïns que s'acosten a l'ajuntament per denunciar esquerdes a les seves vivendes. Fins divendres passat hi constaven 14 casos concrets, però aquest nombre ja va créixer ahir i segurament anirà en augment en els pròxims dies. L'ajuntament diu que cada denúncia és revisada in situ per tècnics municipals per fer així un inventari de les esquerdes. Segons el tinent d'alcalde i regidor d'Urbanisme, Sergi Alegre, que va reconèixer l'extraordinària complexitat del subsòl del Prat –«però això ho saben totes les constructores»–, les inspeccions han descartat danys estructurals.

Però a més de les esquerdes aparegudes ara, la gran preocupació és la segona fase de les obres, quan s'excavarà un altre fals túnel. Mentre que el primer, acabat al novembre, discorre a 15 metres dels blocs del Nucli Antic, el segon passarà a tot just tres metres. ■

Los vecinos de El Prat afectados por el AVE amenazan

de El Prat reab

...cinal por los informes ... las grietas por el AVE

...ños relevantes en siete inmuebles

...daños "no preocupan». La mayoría, más de dos ...s, tienen lesiones "no ...antes", como manchas ...medad o microfisuras, o ...na patología.

...stos datos no convencen ...vecinos. Según la presi... de la Asociación del ... Antic, Rosario Ama... **"nos dicen que hay siete ...ndas afectadas cuando ...untamiento tiene más ... censadas con proble...** La indignación vecinal ...ién radica en que se ha... hecho públicos los resul... del informe sin haberlos hecho llegar antes ni a vecinos ni a Ayuntamiento.

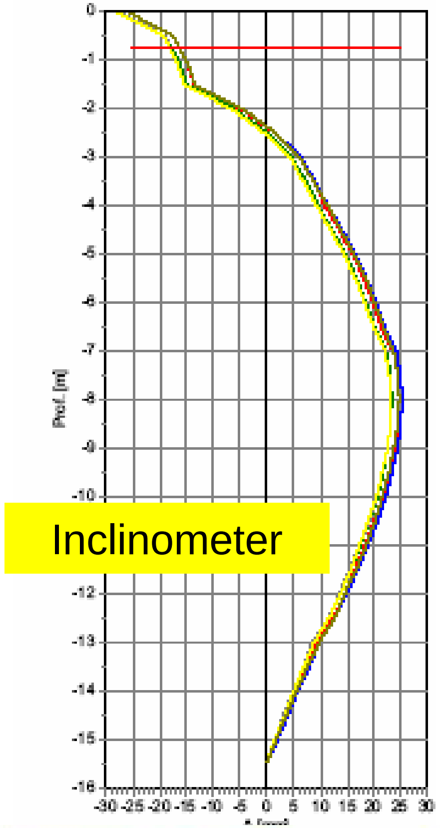
En cuanto al estudio encargado a la Universitat Politècnica de Catalunya, constata que las lesiones de las viviendas tienen origen en las obras, concretamente en los **"movimientos de tierra inducidos por la deformación de las pantallas"** colocadas para la construcción de los túneles, pero concluye que no entrañan **"riesgo de ruptura o de fallo estructural"** en los edificios examinados. Además, todas las lesiones **"no superan la categoría de ligeras"** y se han producido en edificios de planta baja construidos en los años 50, **"de estructura muy simple y posiblemente de cimentación sucinta"**. El presidente de Adif se comprometió a reparar todos los daños ocasionados si se constataba su responsabilidad, como así ha sido.

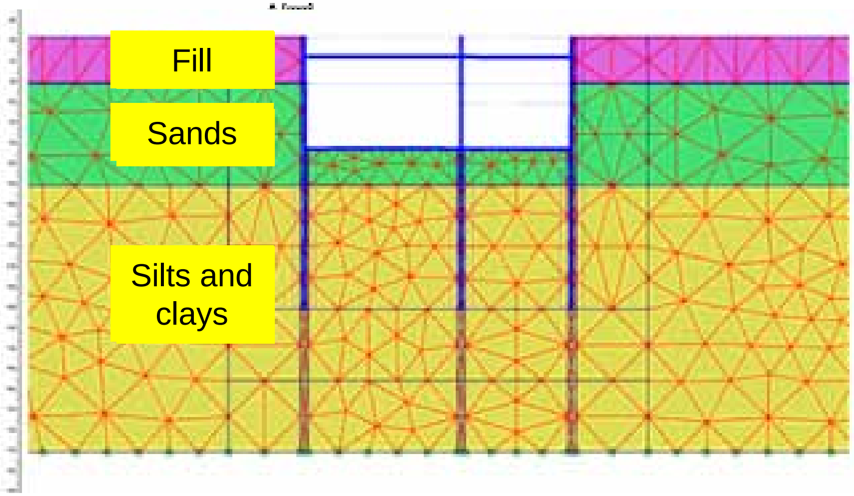
El estudio propone que para la construcción del próximo túnel se controle mejor el nivel freático, que es muy elevado en la zona, y que se refuerce el sistema constructivo con barras horizontales para que el problema no se reproduzca. González avanzó que se mantendrá toda la instrumentalización de pantallas prevista en el proyecto y la obra se seguirá mediante la observación **"continua"** de las pantallas existentes.

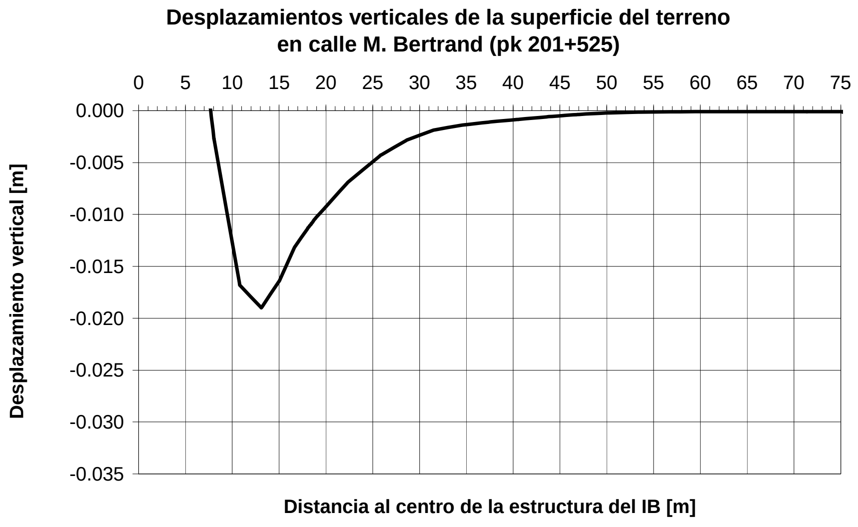
...ida con lo que pue... en Barcelona, don... ...ntament recuerda ...arán inspecciones ...a Generalitat no va... ...razado. JULIO BRAVO

...ano muestra la amplitud de una grieta aparecida en

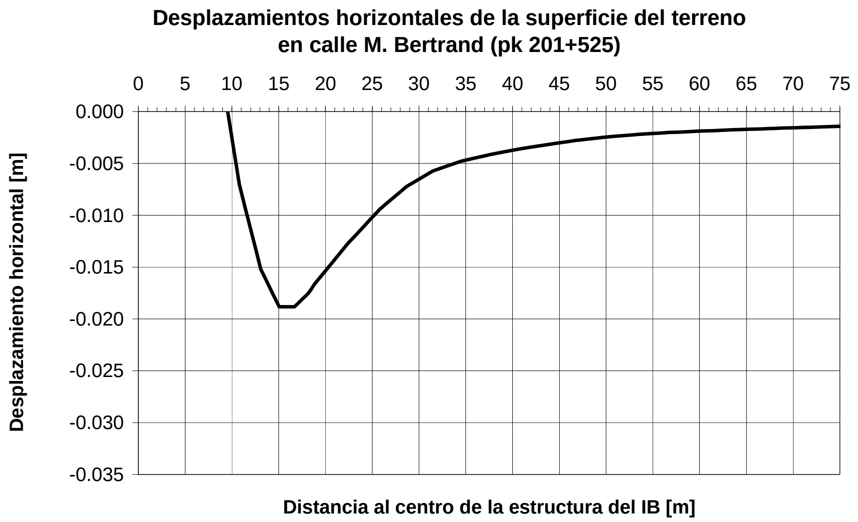
Procedures for control and reduction of movements





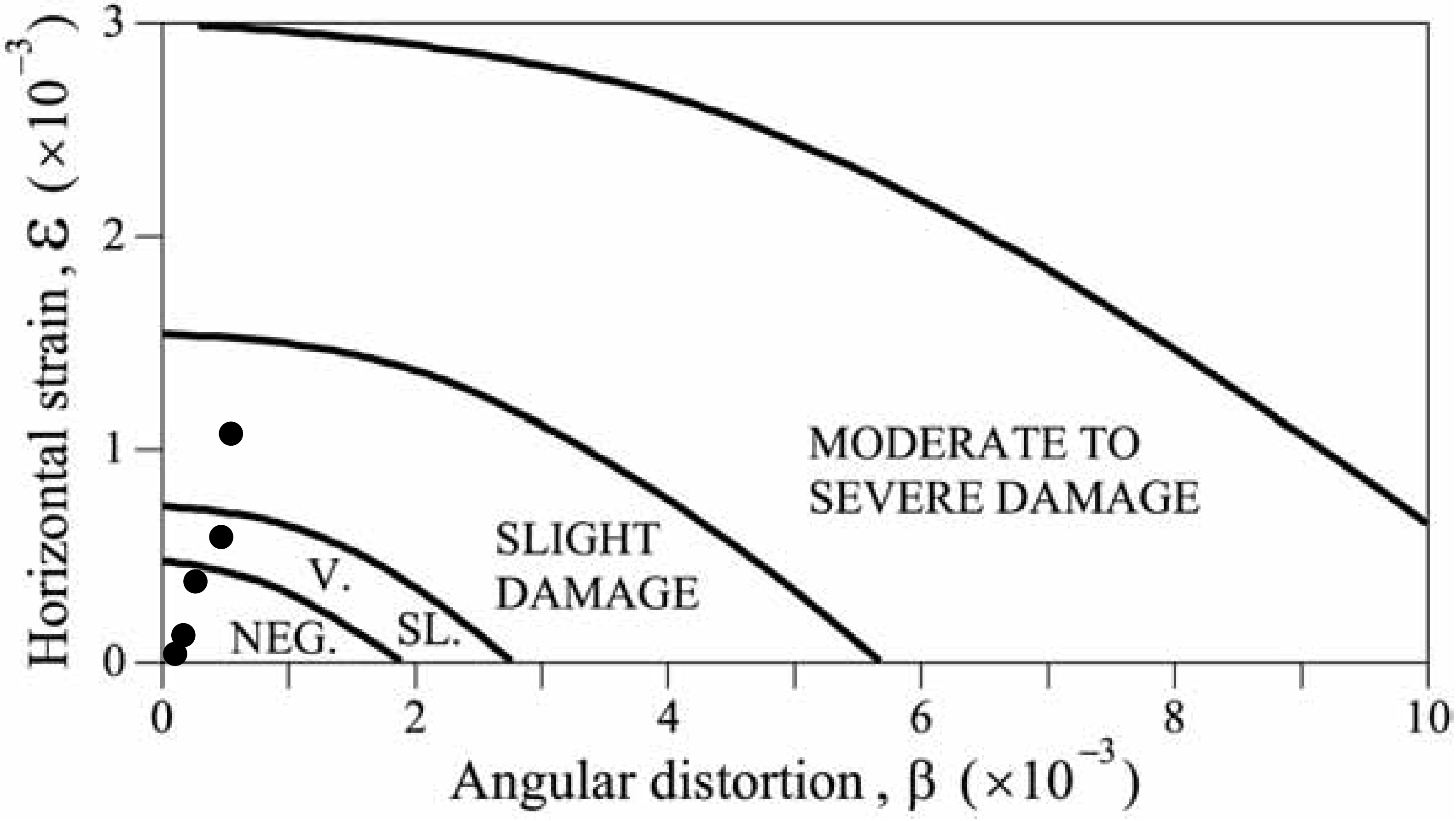


Computed settlements

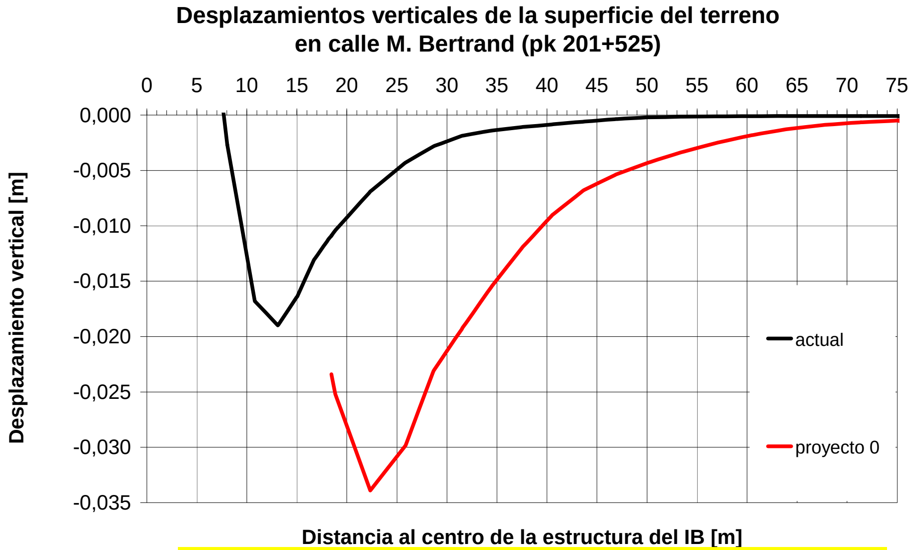


Computed horizontal displacements

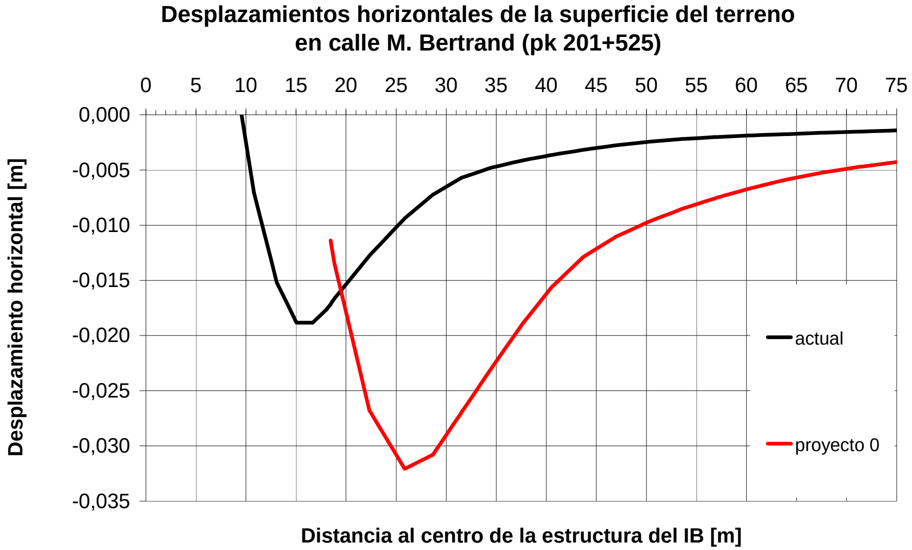
Procedures for control and reduction of movements



Procedures for control and reduction of movements

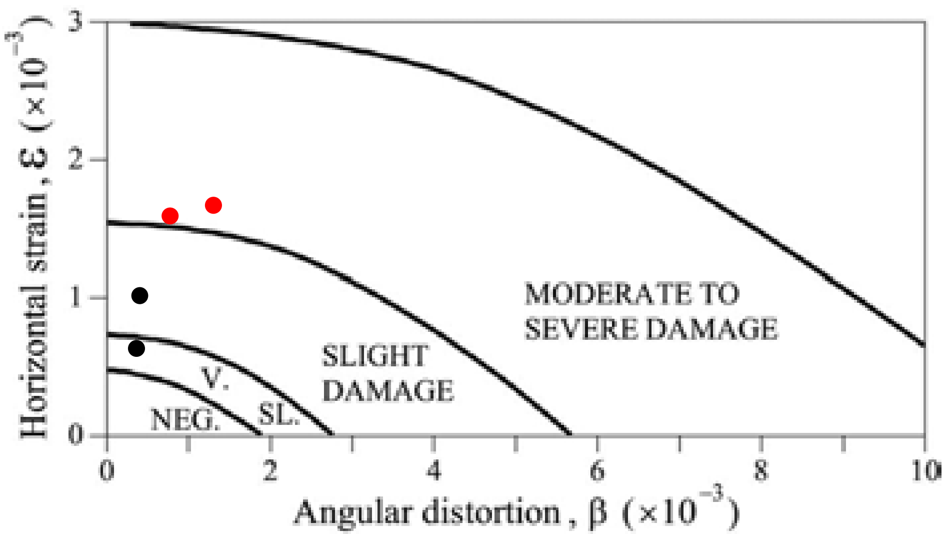


Computed settlements



Computed horizontal displacements

- Project 0
  - No additional measures

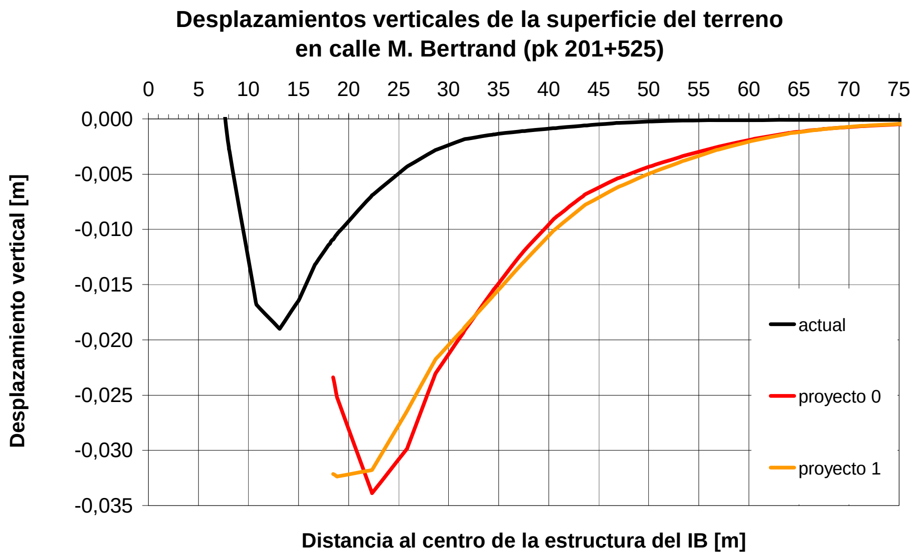


Procedures for control and reduction of movements

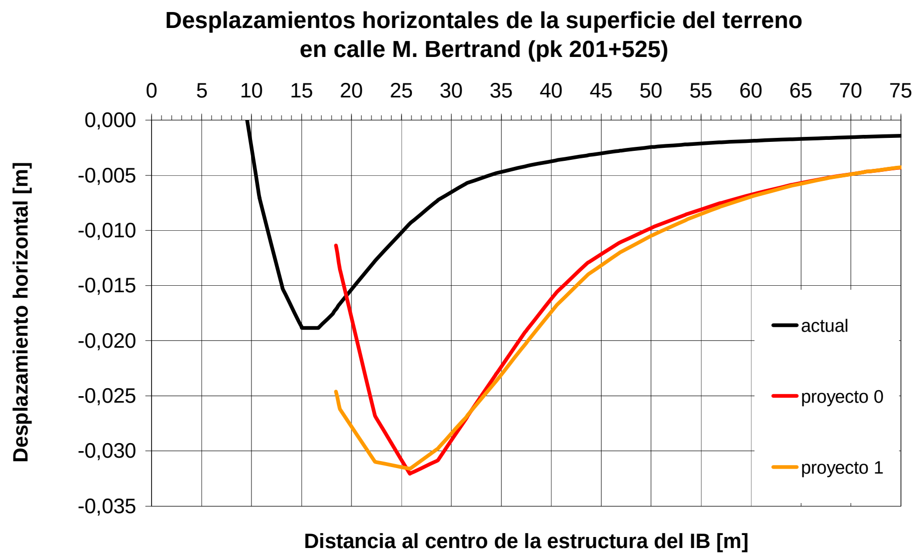
- Possible additional measures
  - Increase wall thickness
  - Install additional props
  - Increase wall length
  - Embed the diaphragm wall in a stiff layer
  - Install bracing below the maximum excavation depth (jet grouting)

- Cases examined
  - Project 0: No additional measure
  - Project 1: 1.20 m wall thickness (UIC2)
  - Project 2: Project 1 + Temporary intermediate prop
  - Project 3: Project 2 + wall depth to elevation -27
  - Project 4: Project 2 + wall depth to elevation -34
  - Project 5: Project 3 + bracing below the maximum excavation depth

Procedures for control and reduction of movements

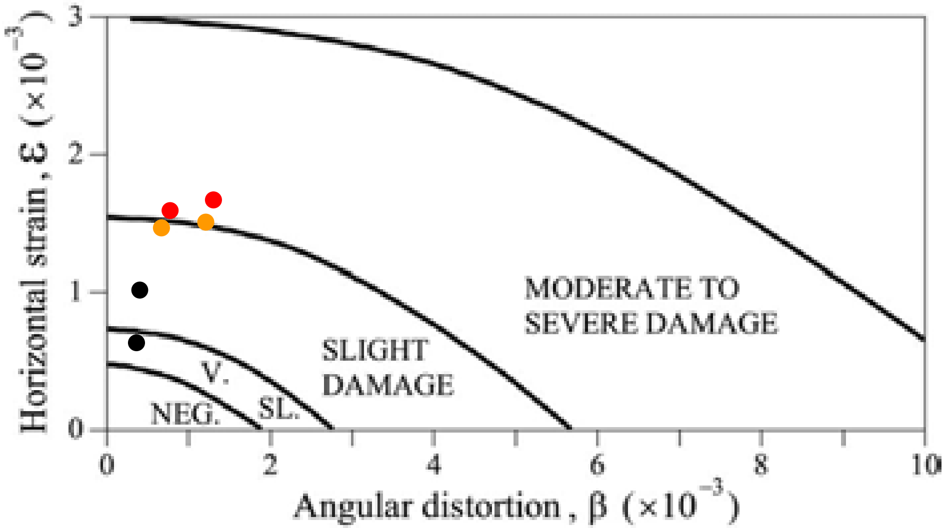


Computed settlements

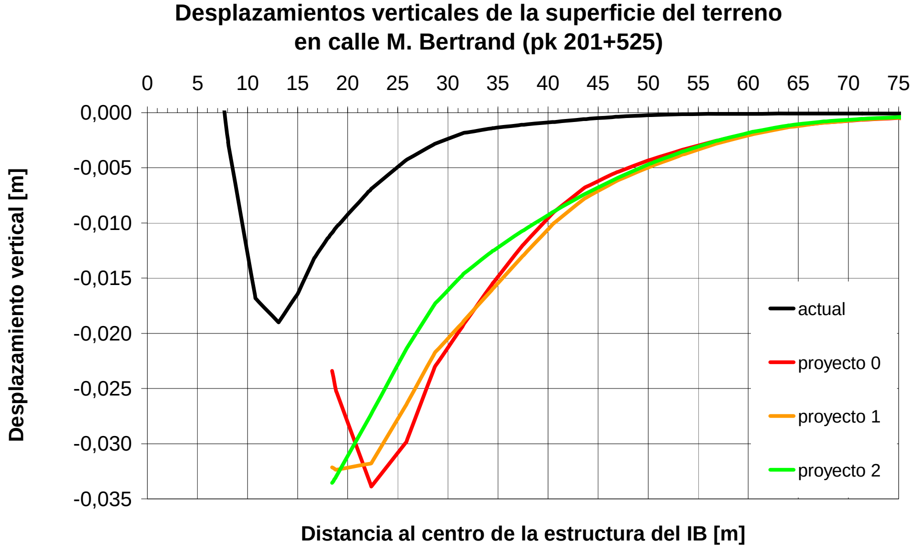


Computed horizontal displacements

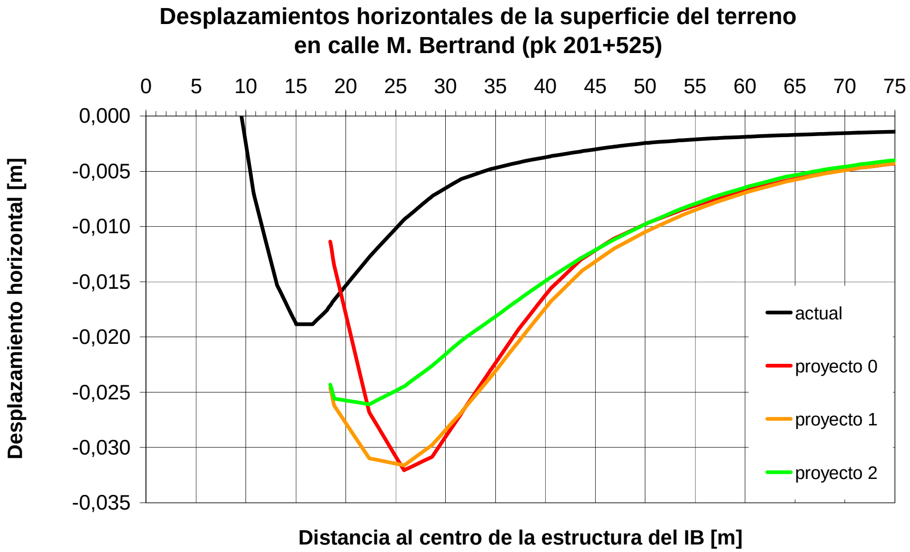
- Project 0
  - No additional measures
- Project 1
  - Wall thickness:1.2 m



Procedures for control and reduction of movements

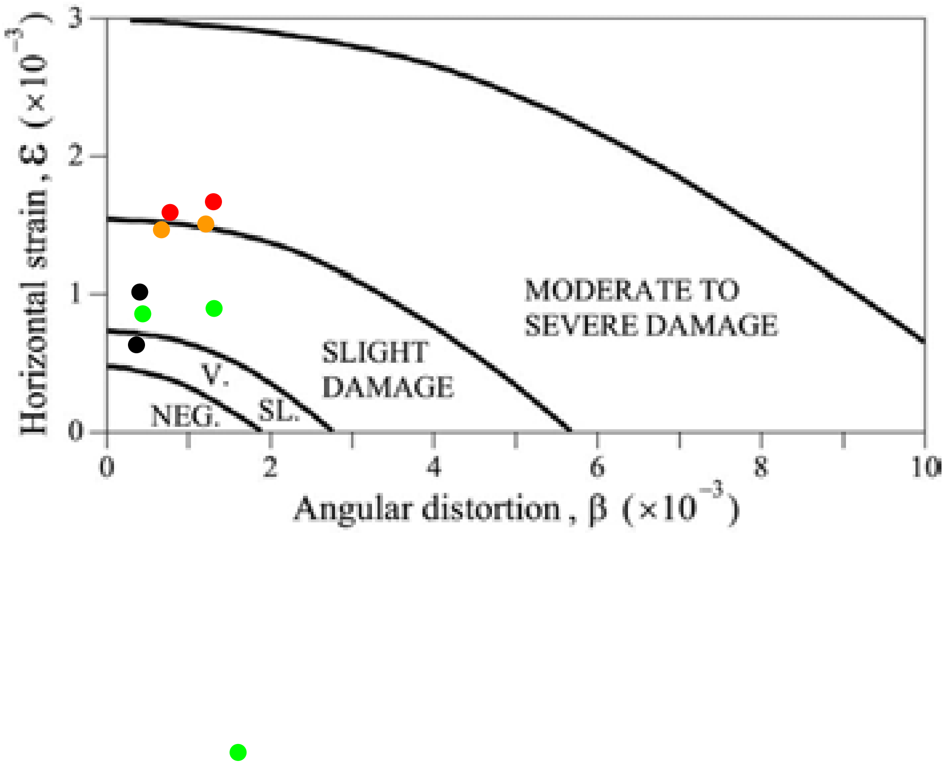


Computed settlements

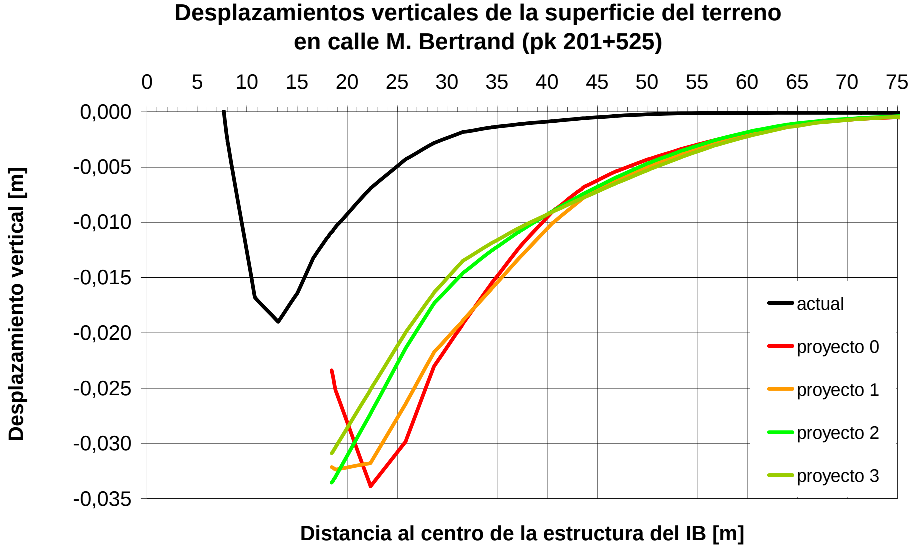


Computed horizontal displacements

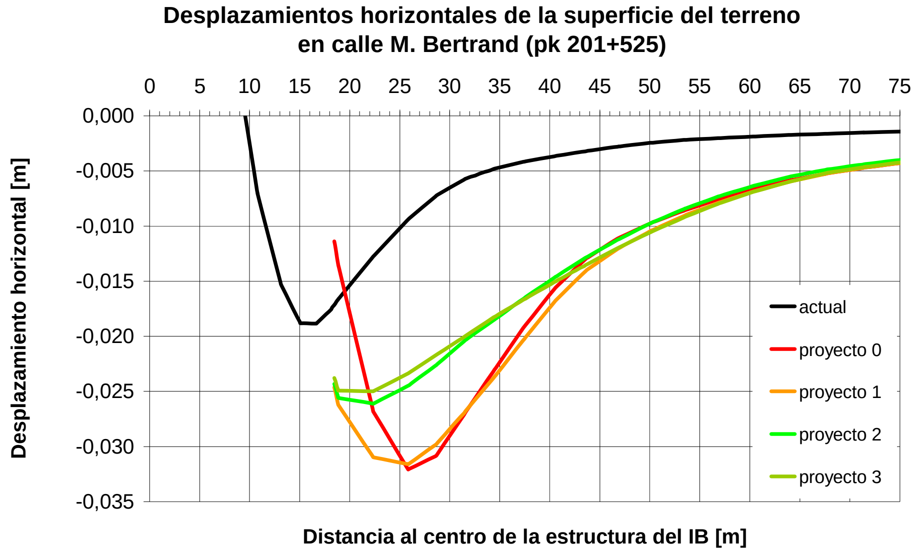
- Project 0
  - No additional measures
- Project 1
  - Wall thickness: 1.2m
- Project 2
  - Project 1 + additional prop



Procedures for control and reduction of movements

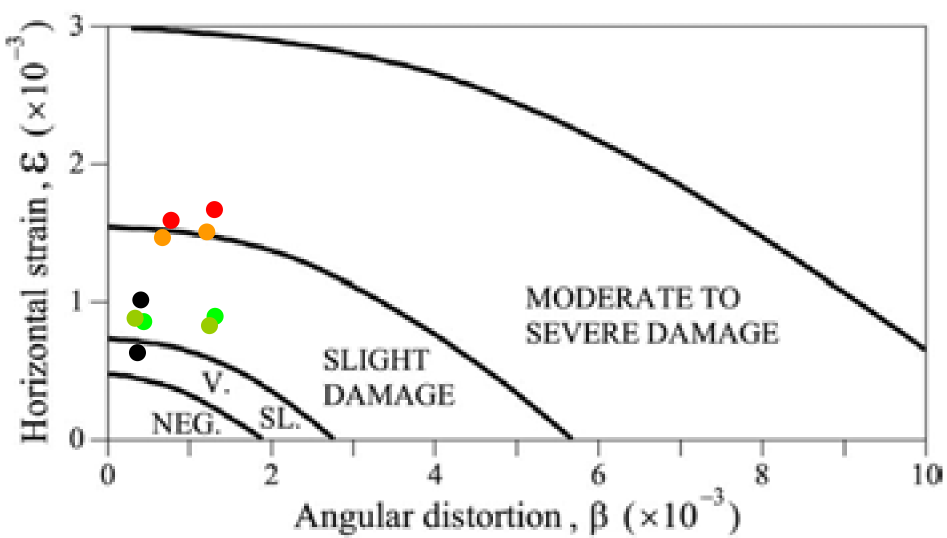


Computed settlements

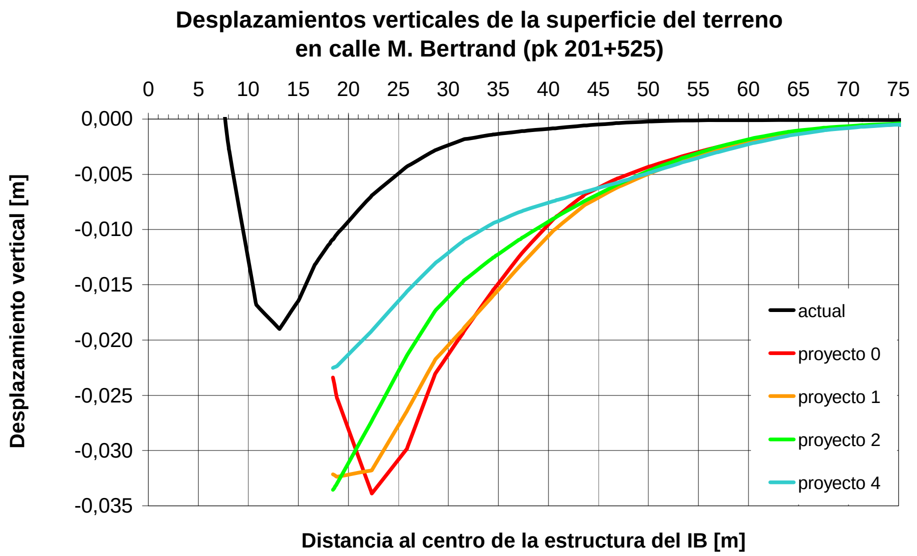


Computed horizontal displacements

- Project 0
  - No additional measures
- Project 1
  - Wall thickness: 1.2m
- Project 2
  - Project 1 + additional prop
- Project 3
  - Project 2 + wall to elevation -27

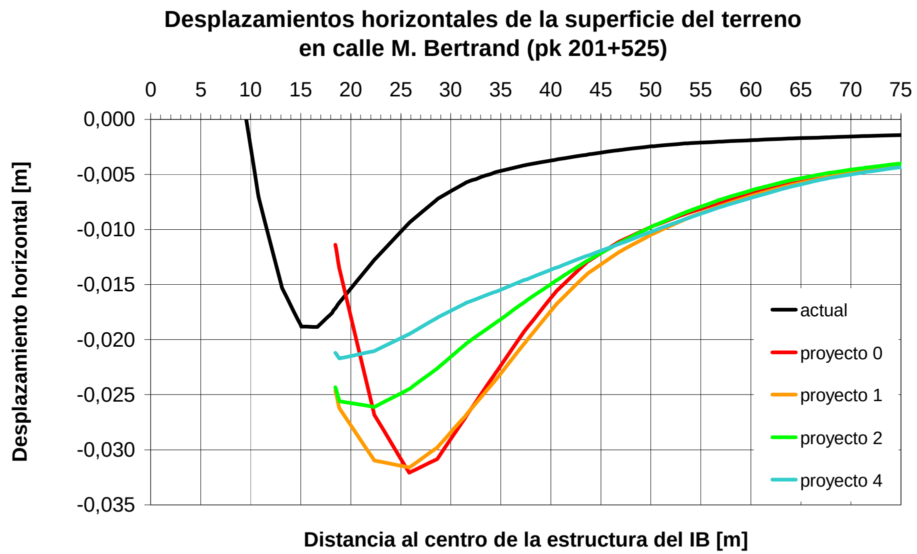


Procedures for control and reduction of movements

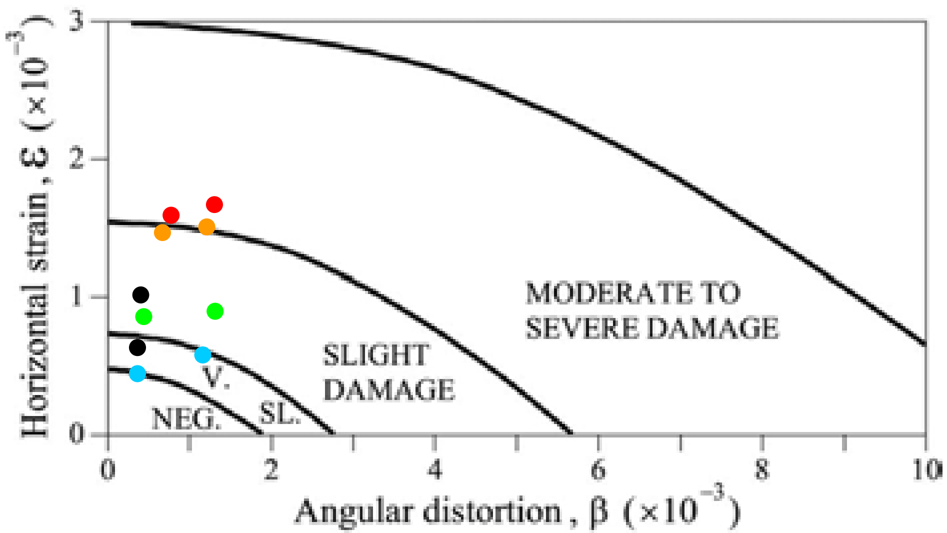


Computed settlements

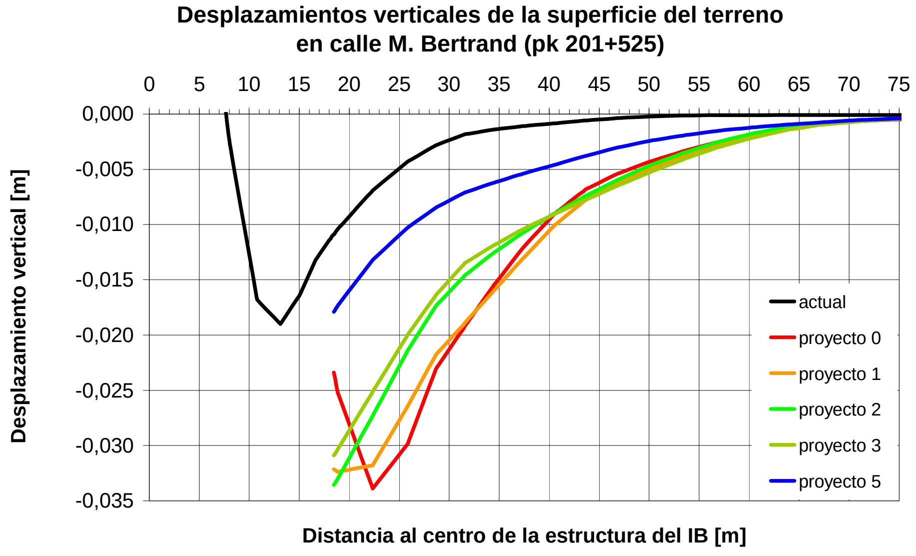
- Project 0
  - No additional measures
- Project 1
  - Wall thickness: 1.2m
- Project 2
  - Project 1 + additional prop
- Project 4
  - Project 2 + wall to elevation -34



Computed horizontal displacements

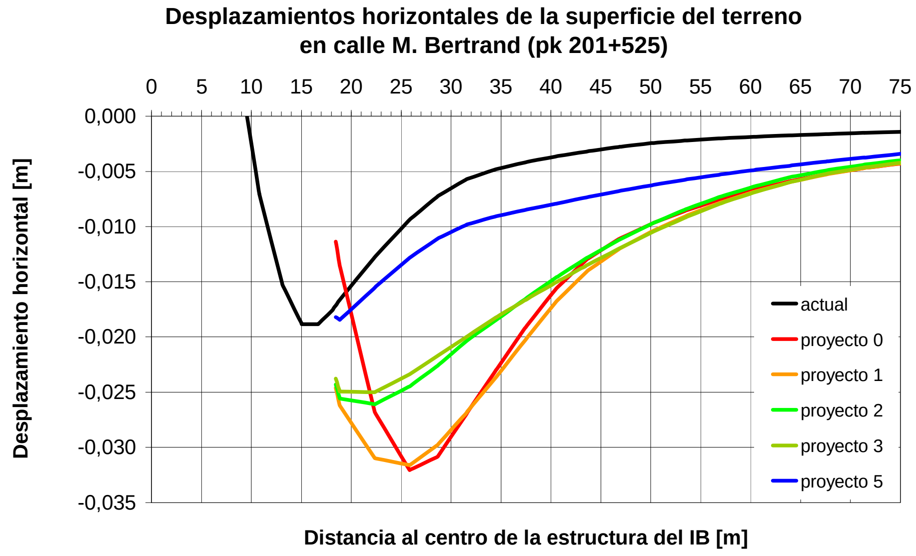


Procedures for control and reduction of movements

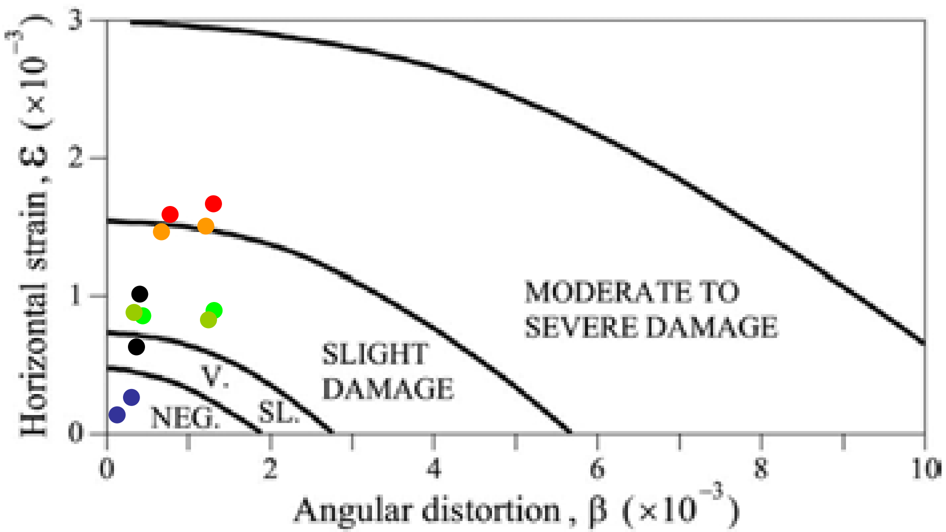


Computed settlements

- Project 0
  - No additional measures
- Project 1
  - Wall thickness: 1.2m
- Project 2
  - Project 1 + additional prop
- Project 3
  - Project 2 + wall to elevation -27
- Project 5
  - Project 3 + Jet grouting prop



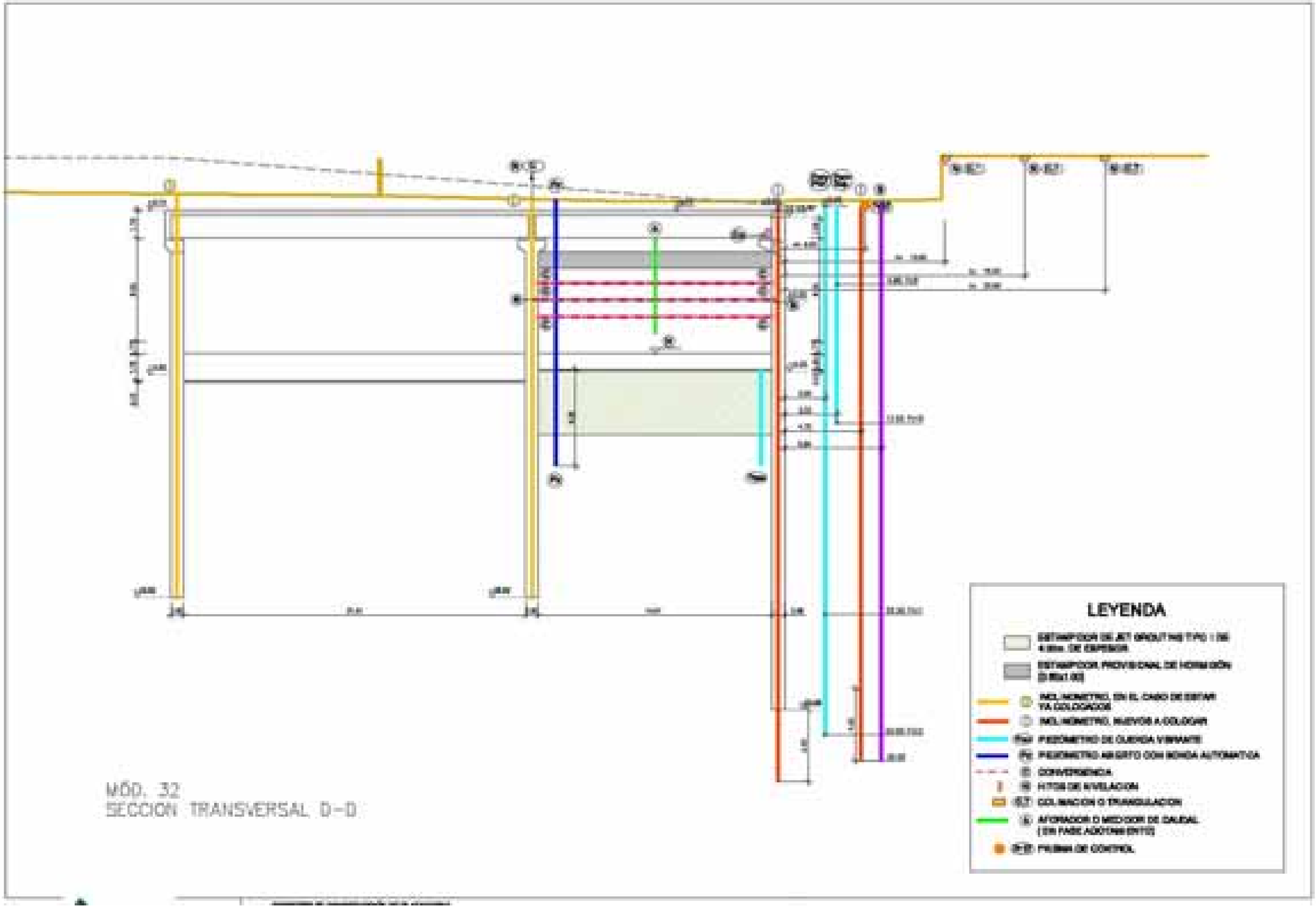
Computed horizontal displacements



Procedures for control and reduction of movements

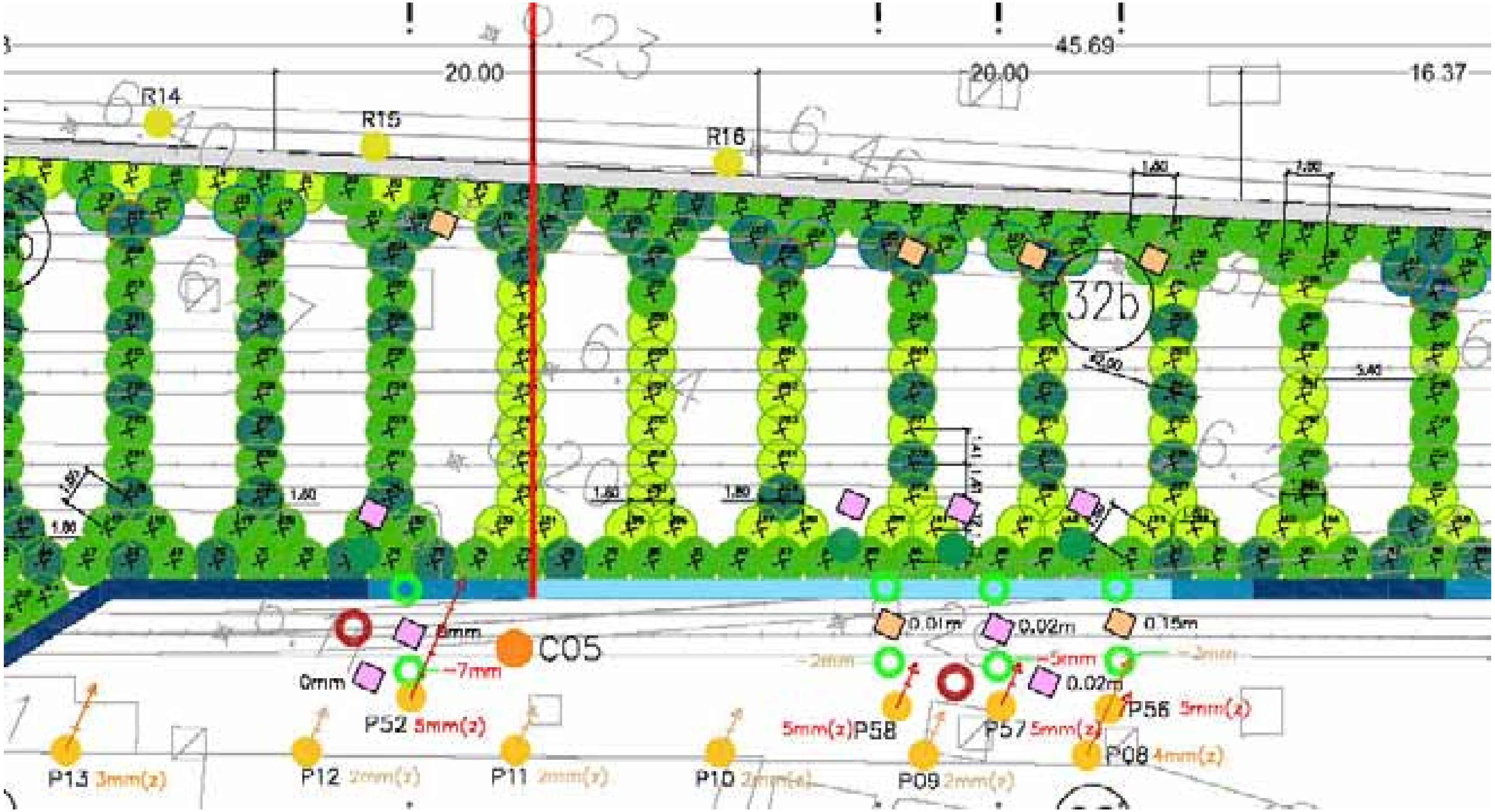
Trial sections

Procedures for control and reduction of movements



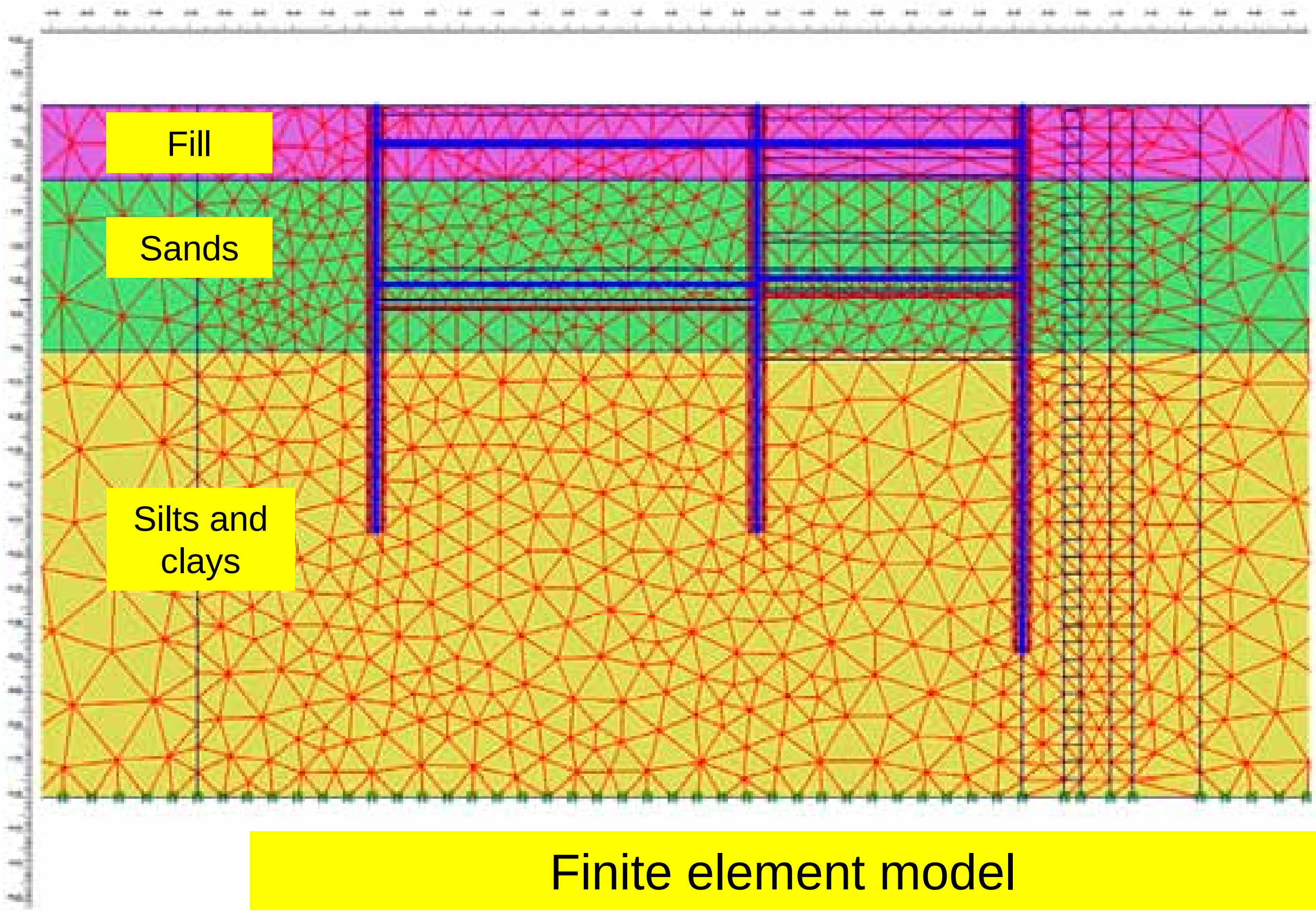
Adopted construction procedure

Procedures for control and reduction of movements



Jet grouting props below maximum excavation depth

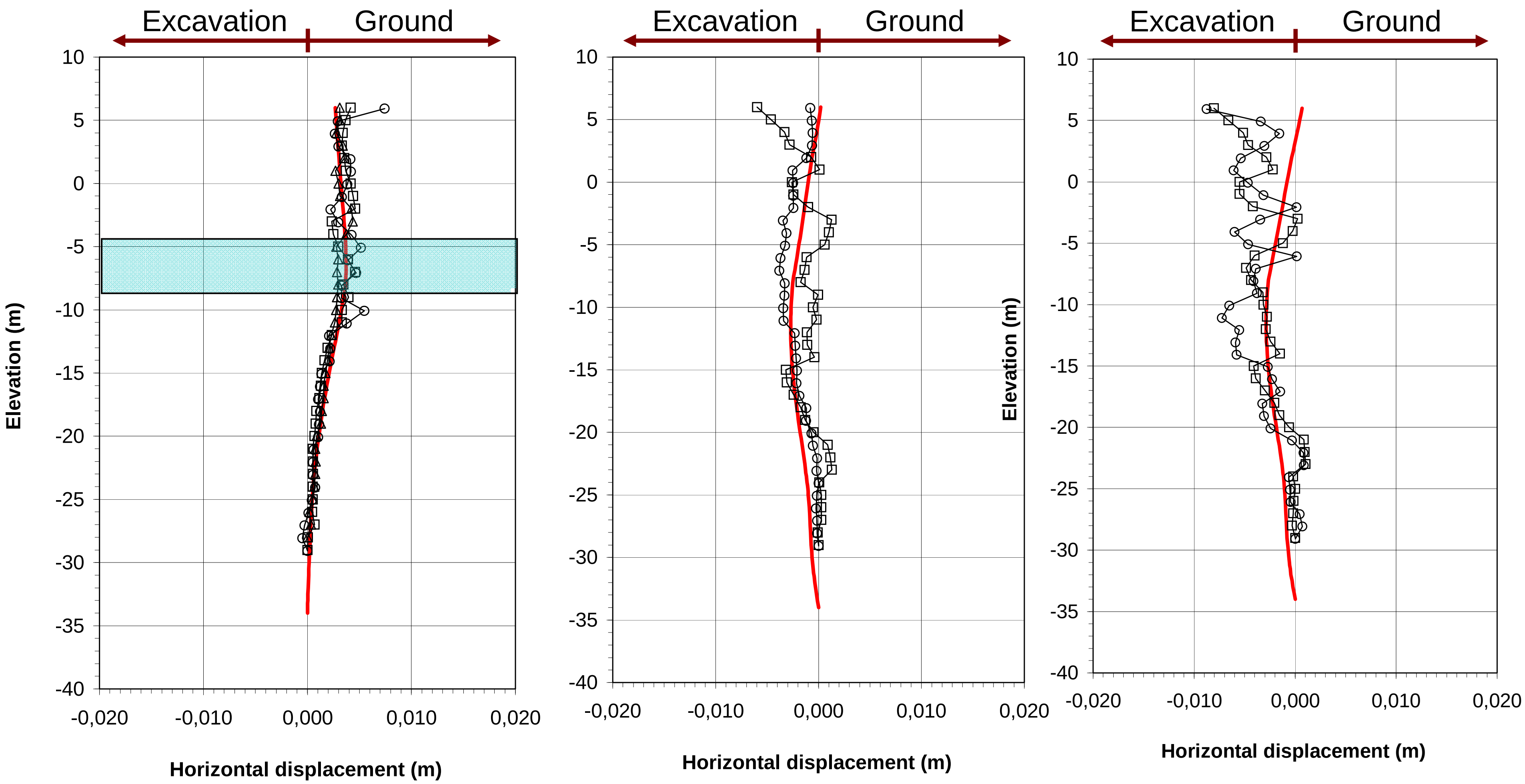
Procedures for control and reduction of movements



- "Hardening Soil model" for all layers

Procedures for control and reduction of movements

- Observations and model calibration. Ground inclinometers

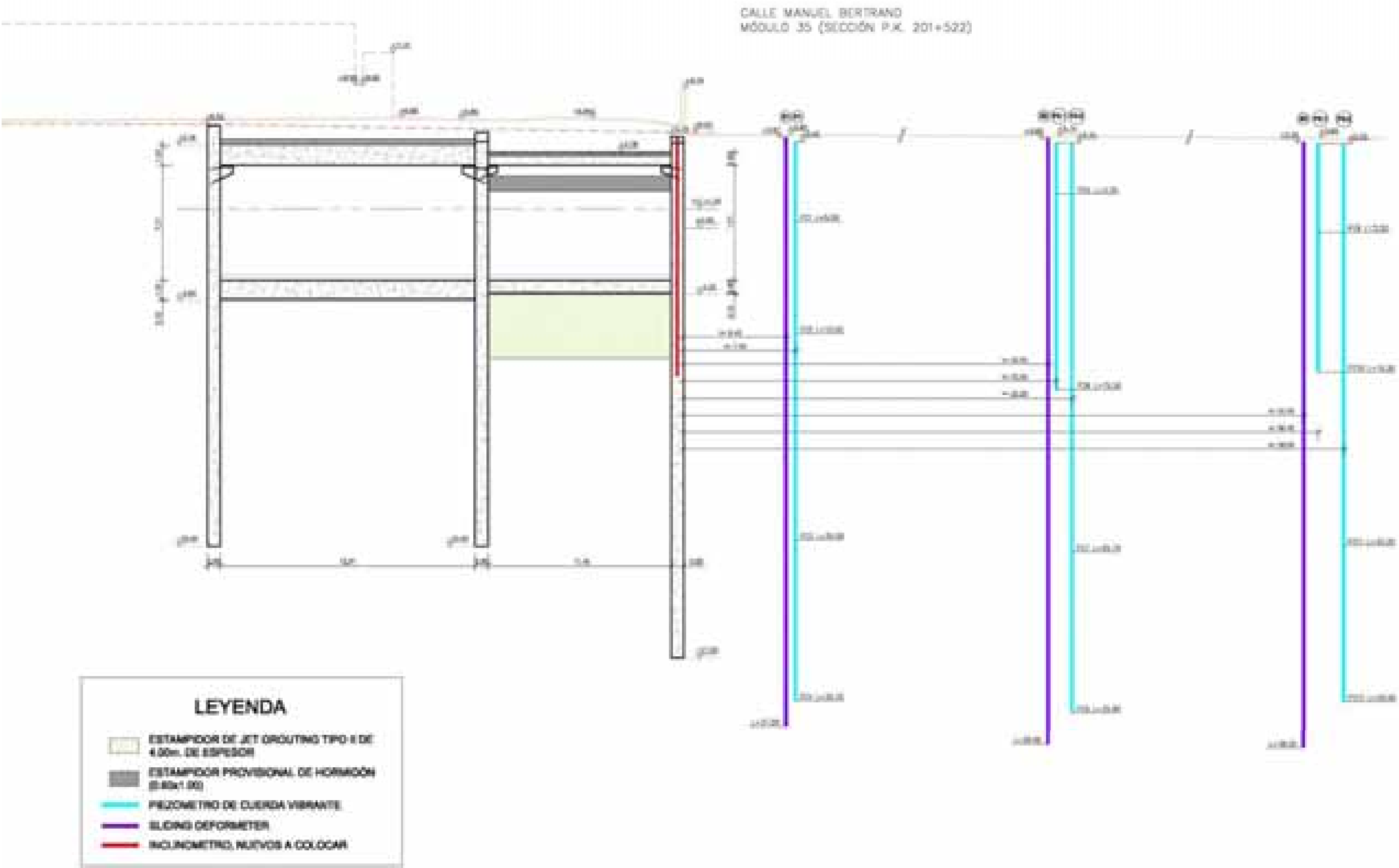


Jet-grouting

Excavation from top to bottom slab

Total excavation

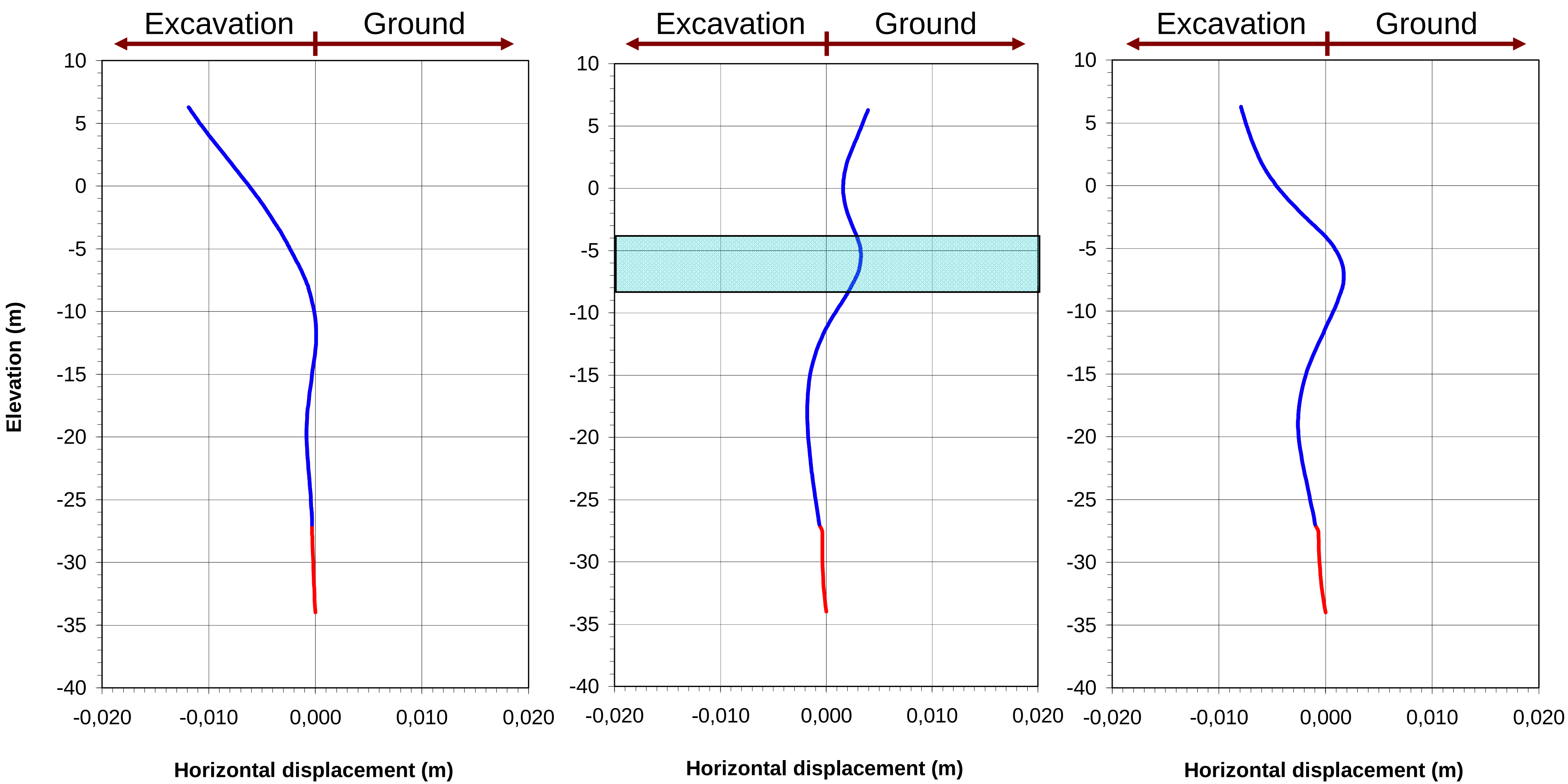
Procedures for control and reduction of movements



Maragall St. section

Procedures for control and reduction of movements

- Predictions of the calibrated model. Wall inclinometer



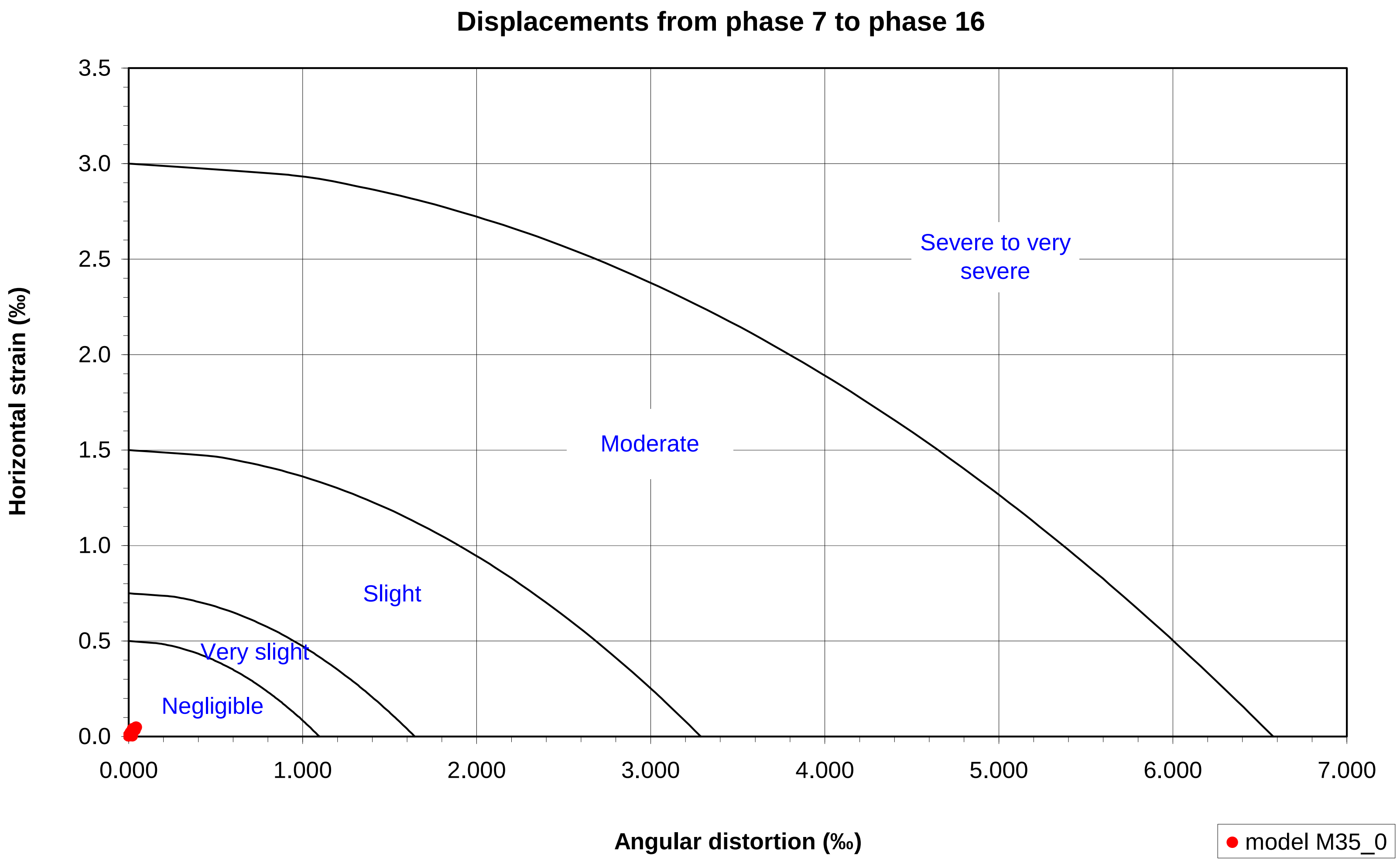
Excavation of first tunnel

Excavation of second tunnel

Total excavation

Procedures for control and reduction of movements

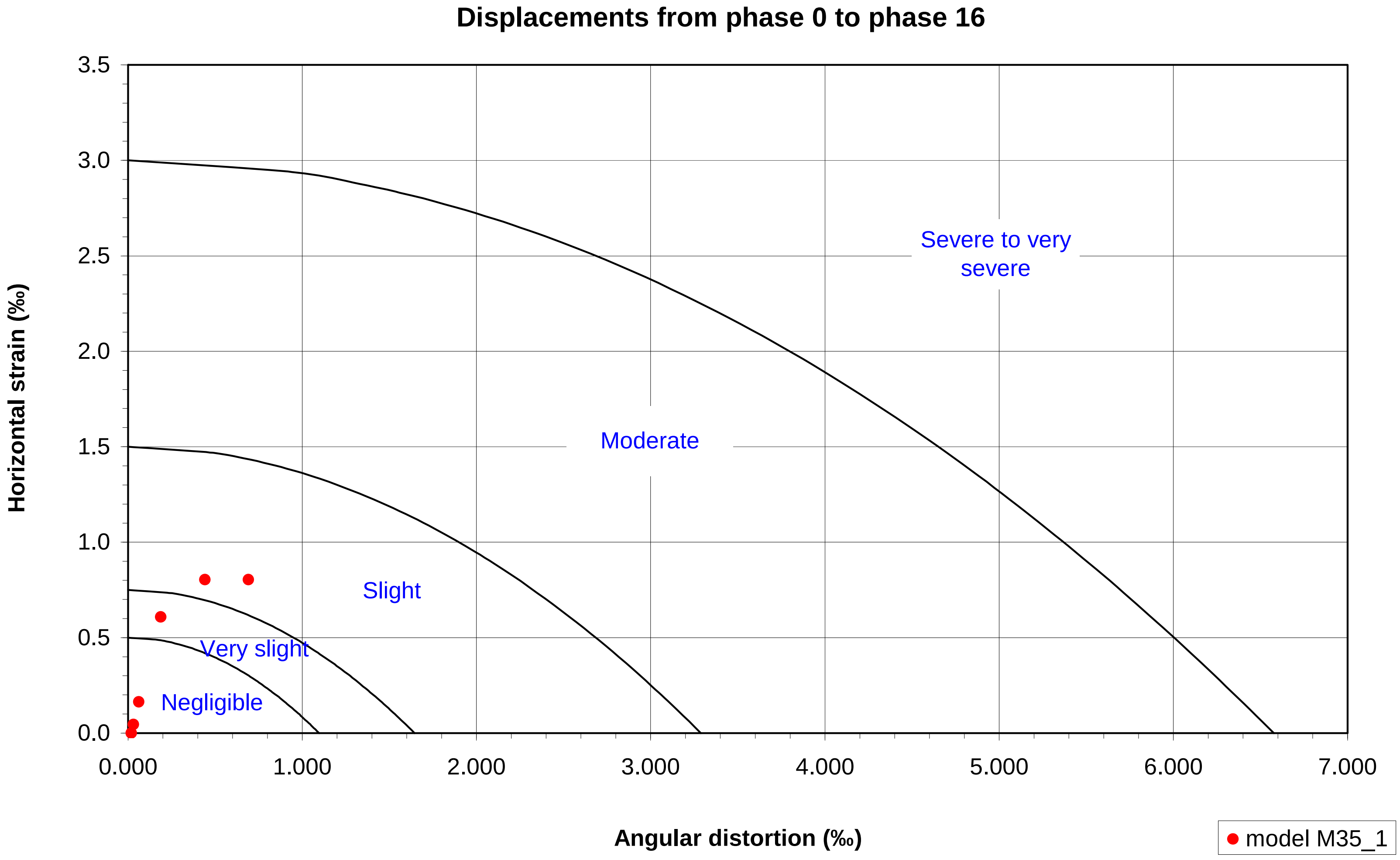
❑ Estimation of potential damage



Excavation of the second tunnel

Procedures for control and reduction of movements

❑ Estimation of potential damage



Total excavation

Procedures for control and reduction of movements

Construction of tunnel UIC

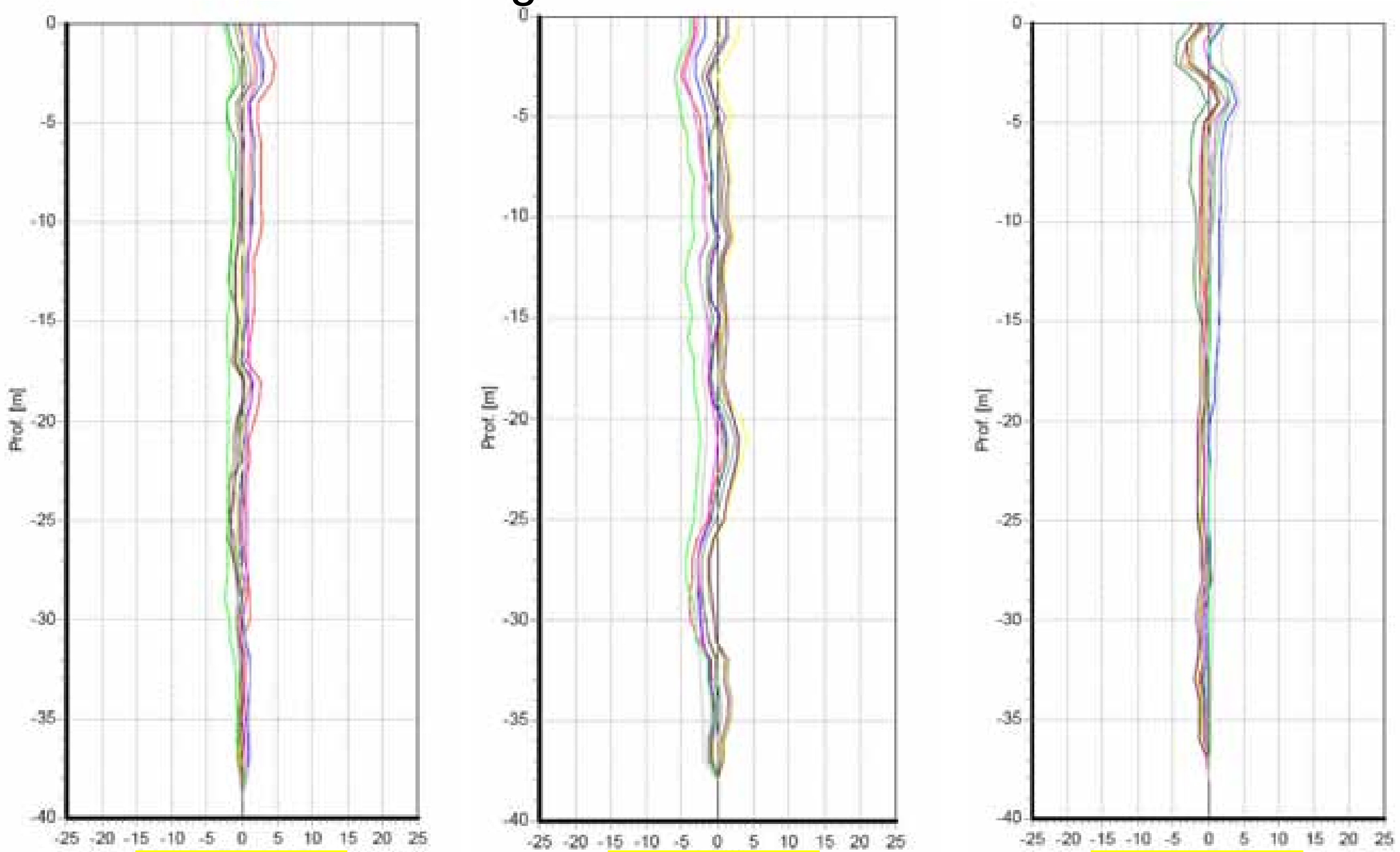
Procedures for control and reduction of movements

7-06-2007

15-10-2007

Procedures for control and reduction of movements

❑ Observations Maragall St.



d=7m

d=32m

d=55m

Horizontal displacements

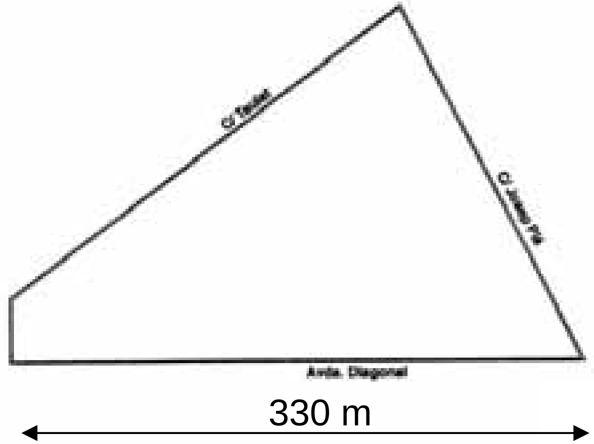
Esquema de la presentación

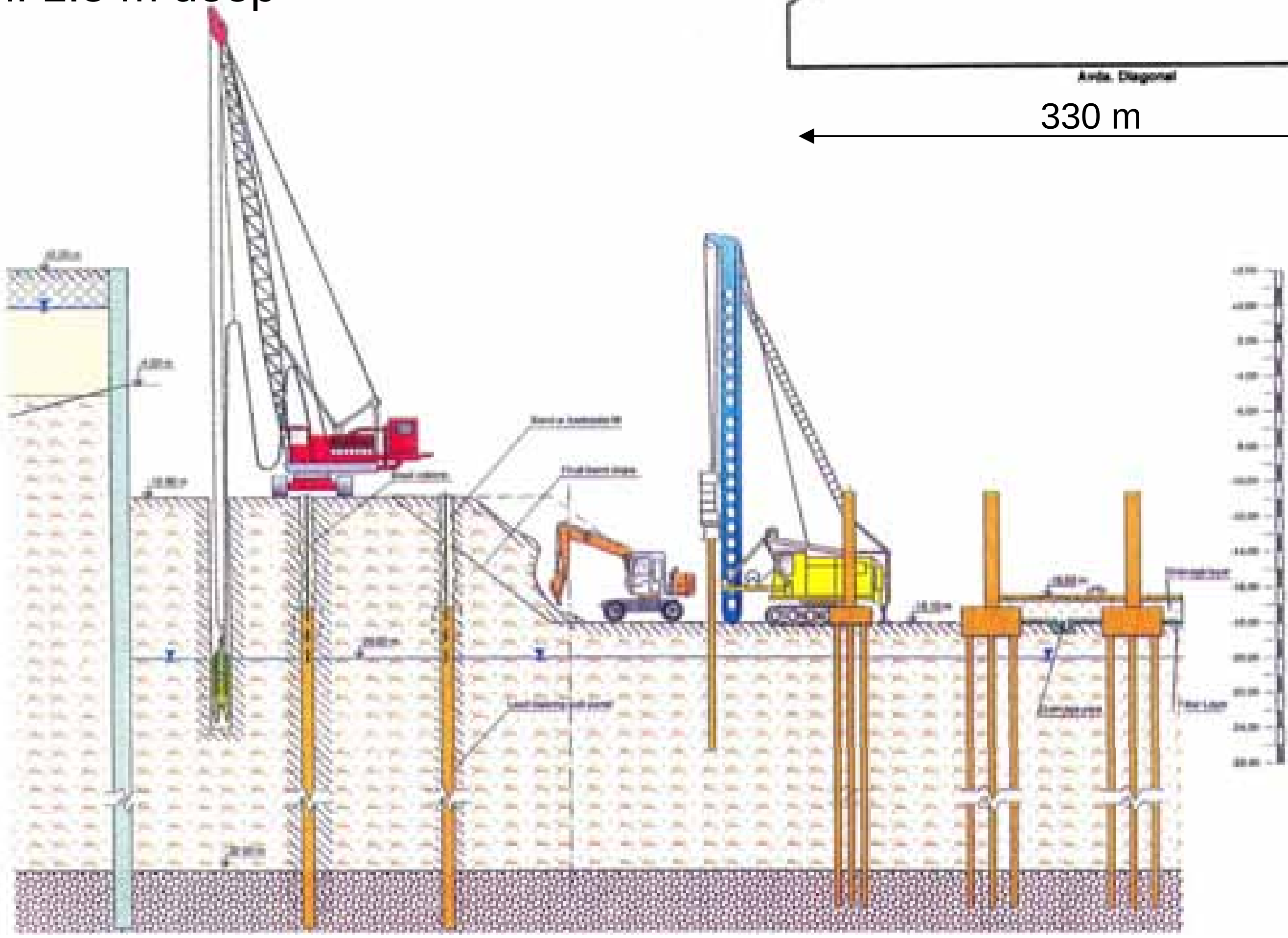
- Introduction. Generation of ground movements by deep excavations
- Empirical methods for estimating ground movements
- Methods for calculating ground movements
- Procedures for control and reduction of movements
- A case history
- Excavations with large movements: announcing failure?
- Conclusions

Excavations with large movements: announcing failure?

❑ Diagonal Mar

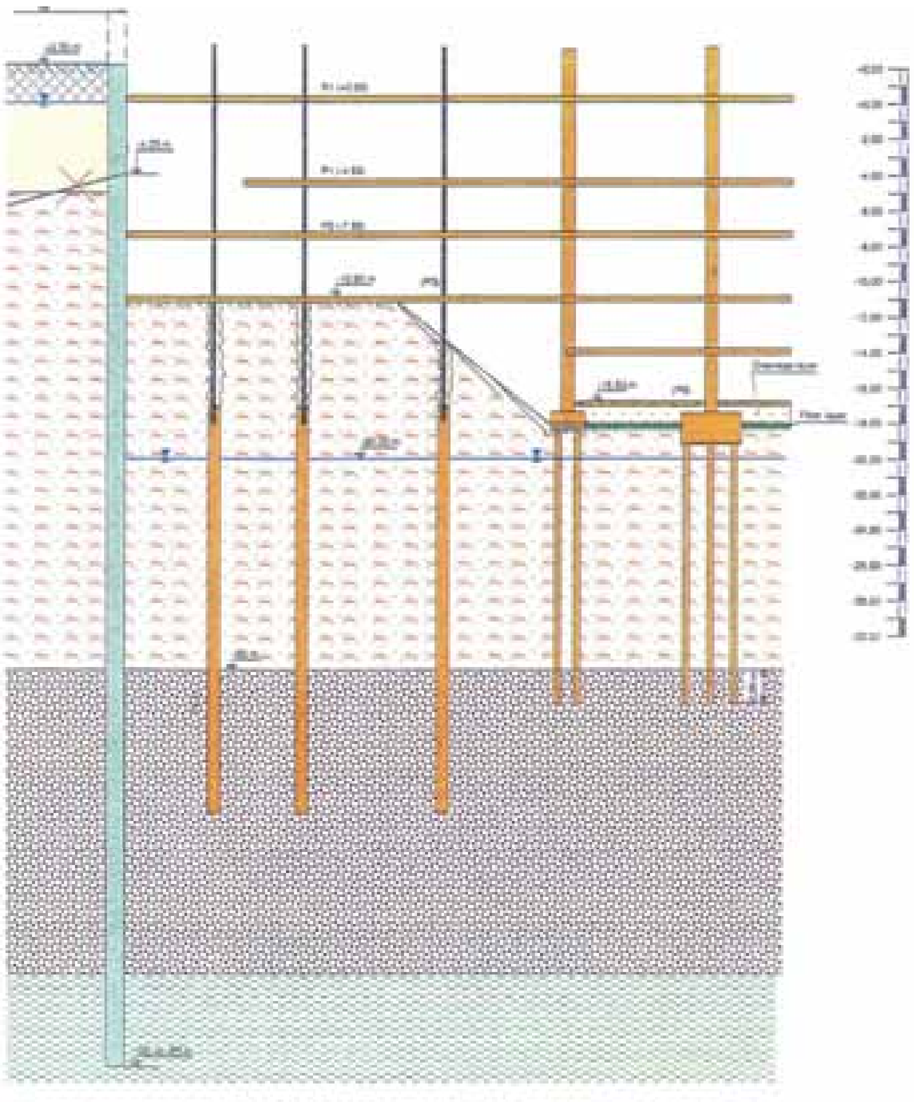
- Surface: 40,000 m^2
- Excavation depth: 20 m
- Excavation volume: 800,000 m^3
- Water level: 1.5 m deep

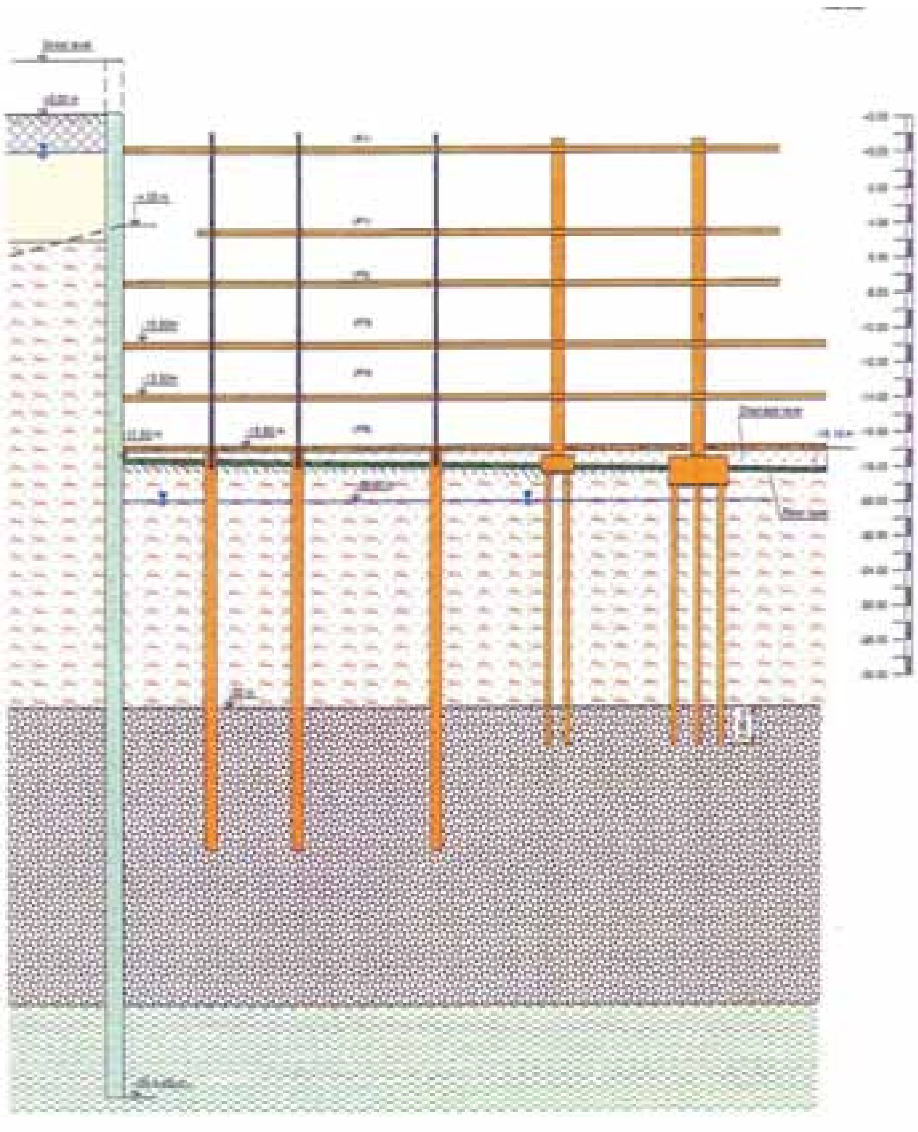




Excavations with large movements: announcing failure?

- Diagonal Mar



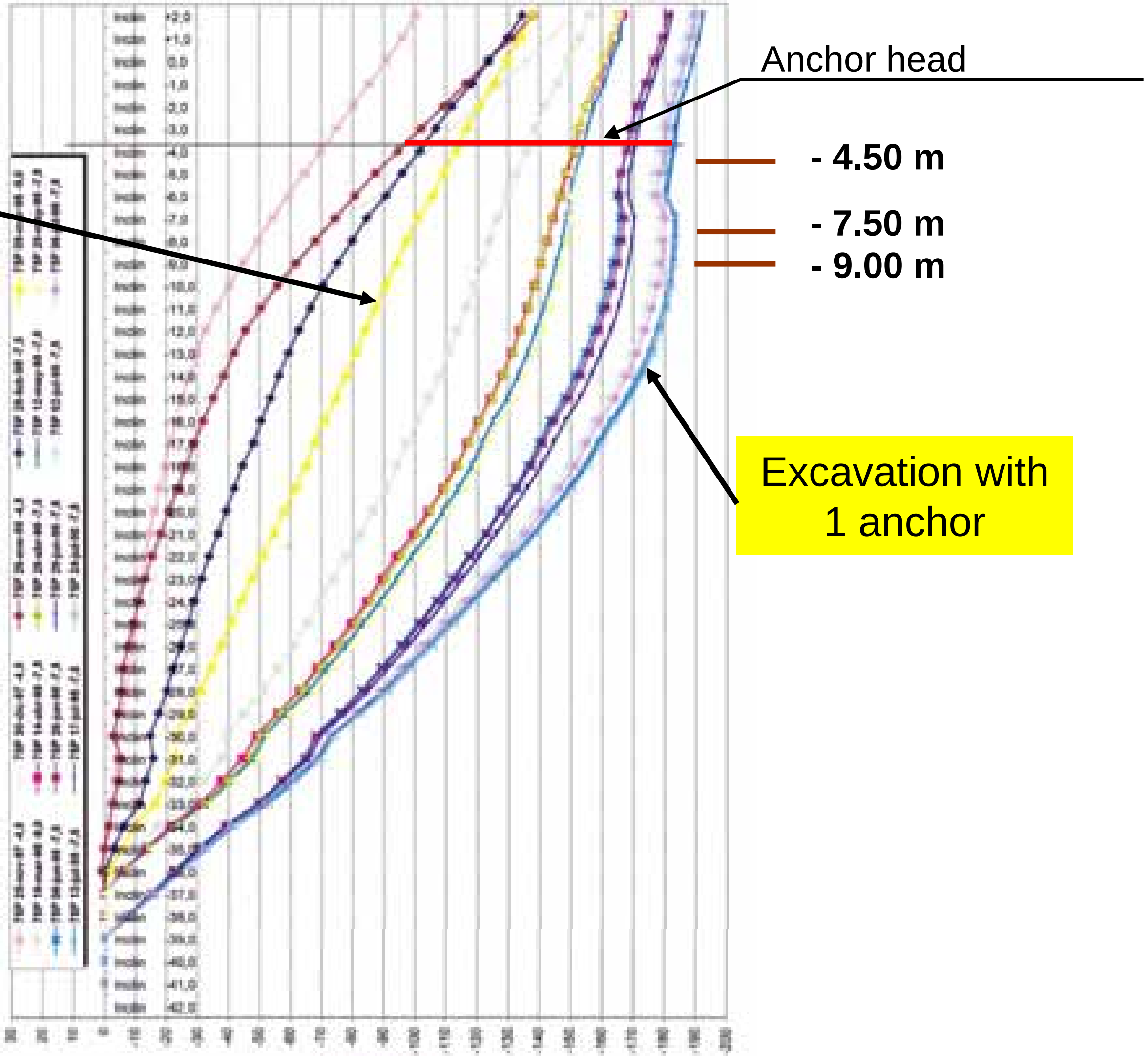


Excavations with large movements: announcing failure?

- Diagonal Mar

Excavations with large movements: announcing failure?

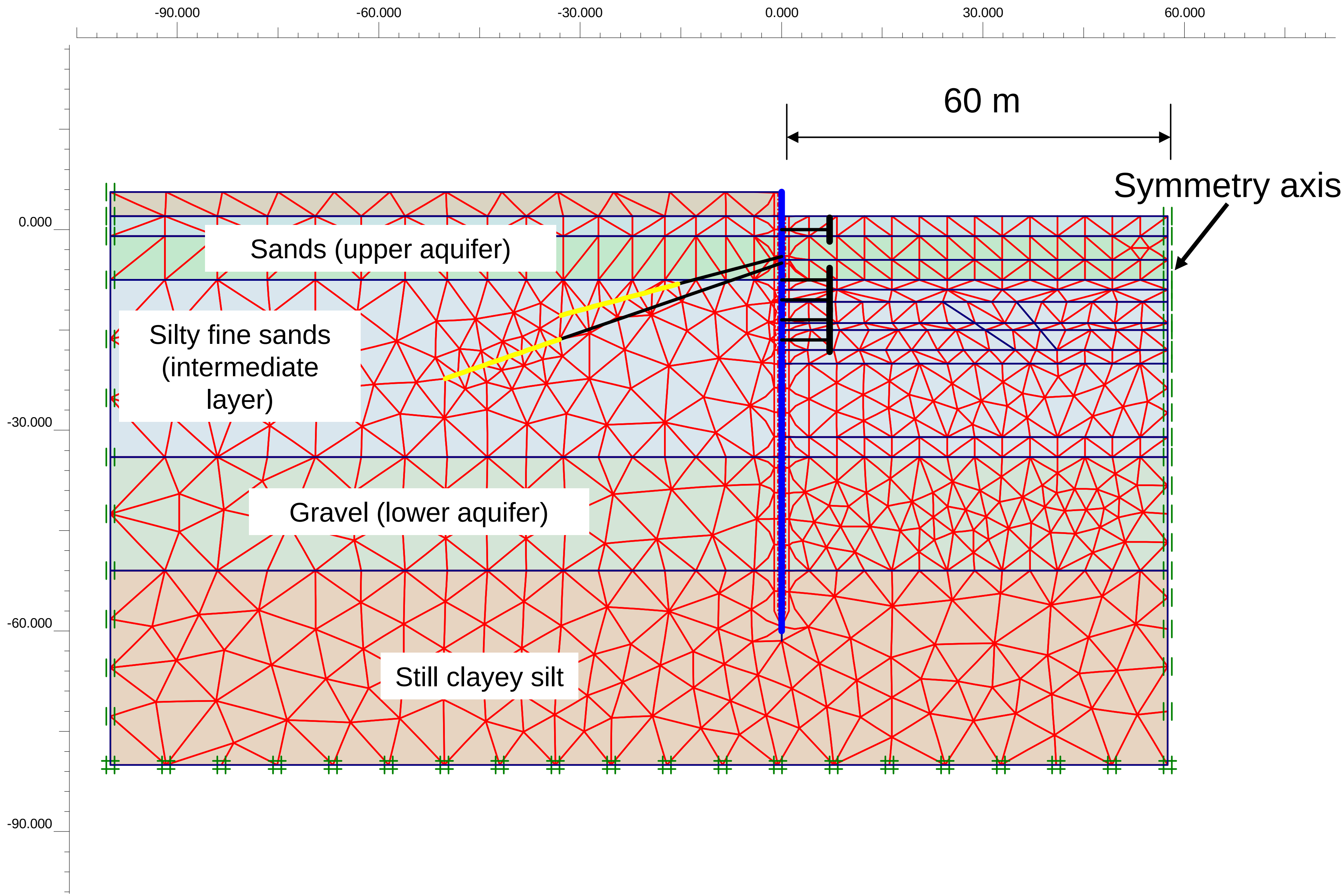
- Diagonal Mar



Wall horizontal displacements

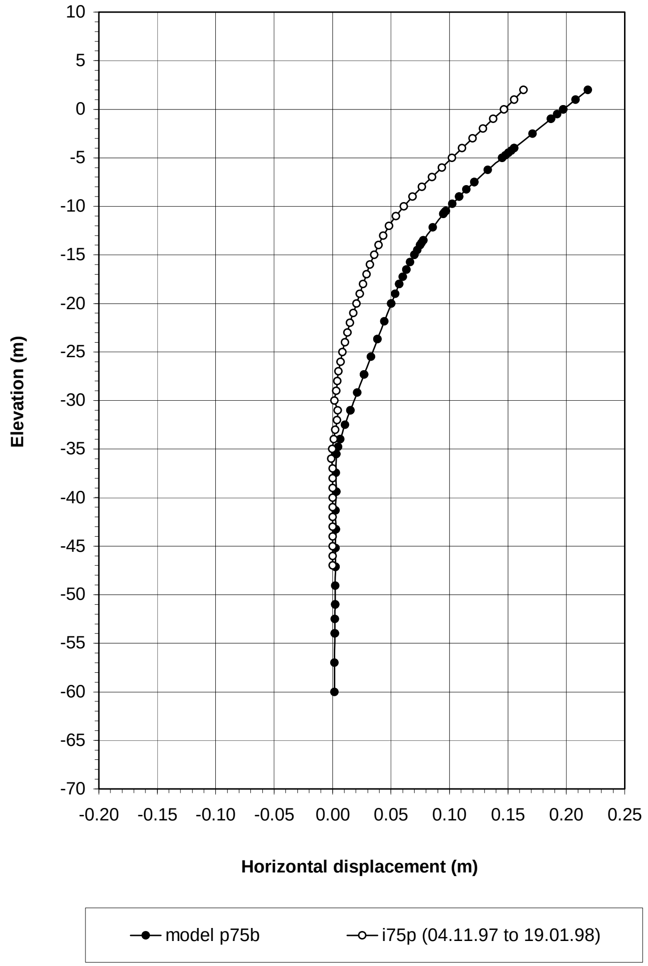
Excavations with large movements: announcing failure?

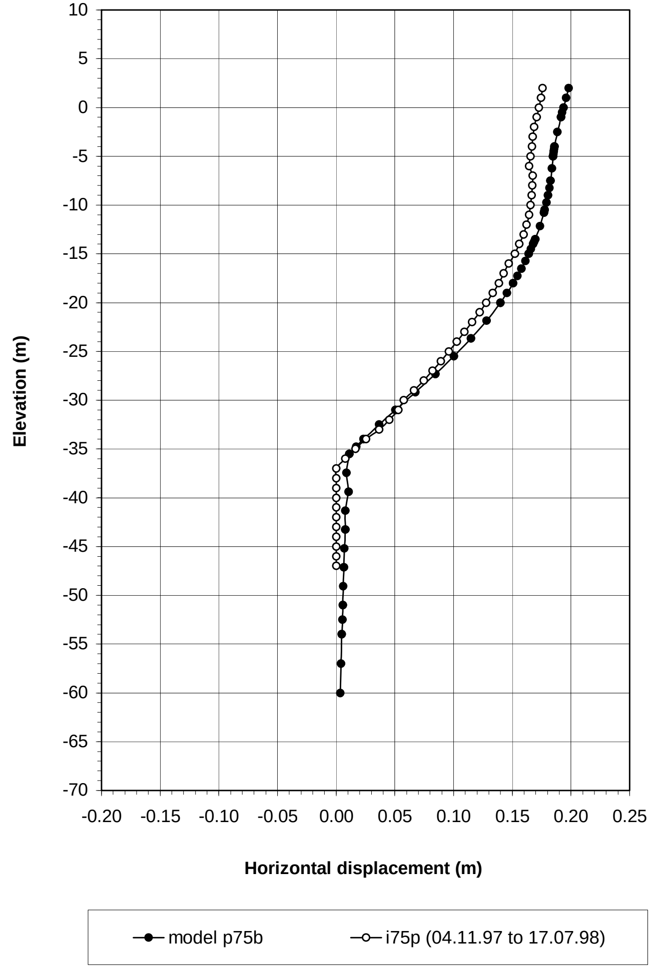
- Diagonal Mar: numerical model



Excavations with large movements: announcing failure?

- Diagonal Mar: calculations and observations





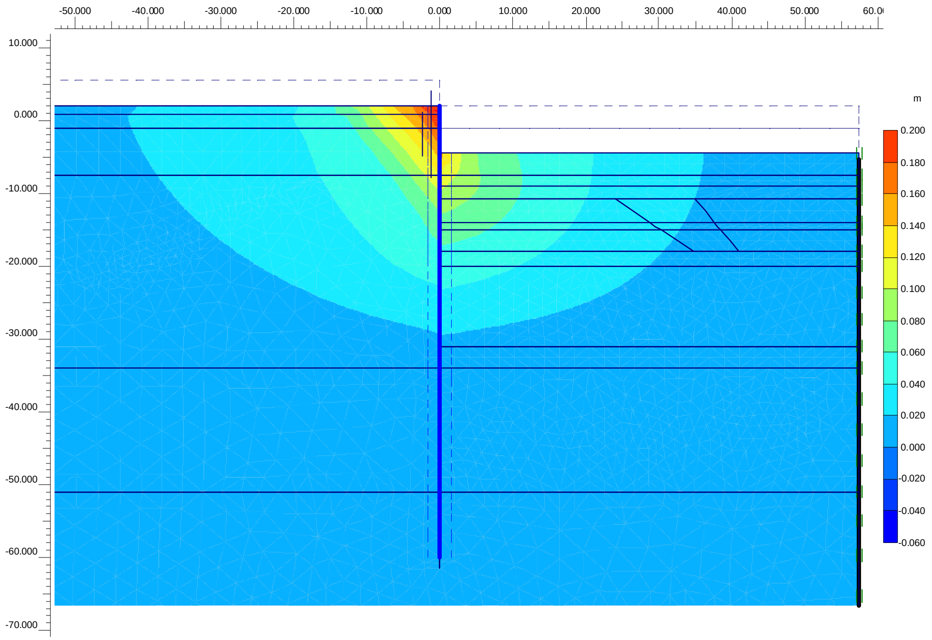
Cantilever excavation to -4.50 m

Anchored excavation to -7.50 m

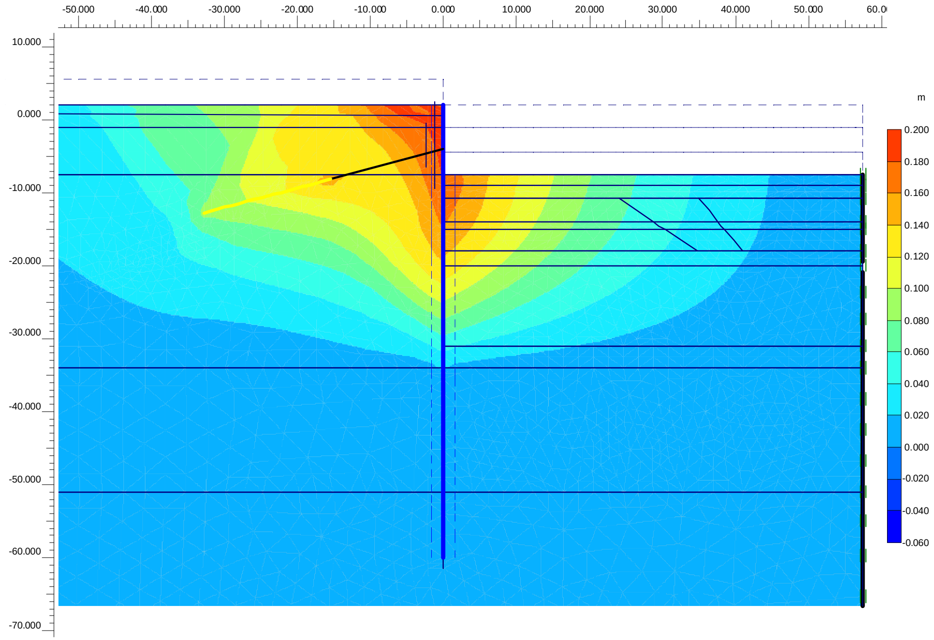
Horizontal wall displacements

Excavations with large movements: announcing failure?

- Diagonal Mar: numerical model



Cantilever wall



Anchored wall

Horizontal displacements contours

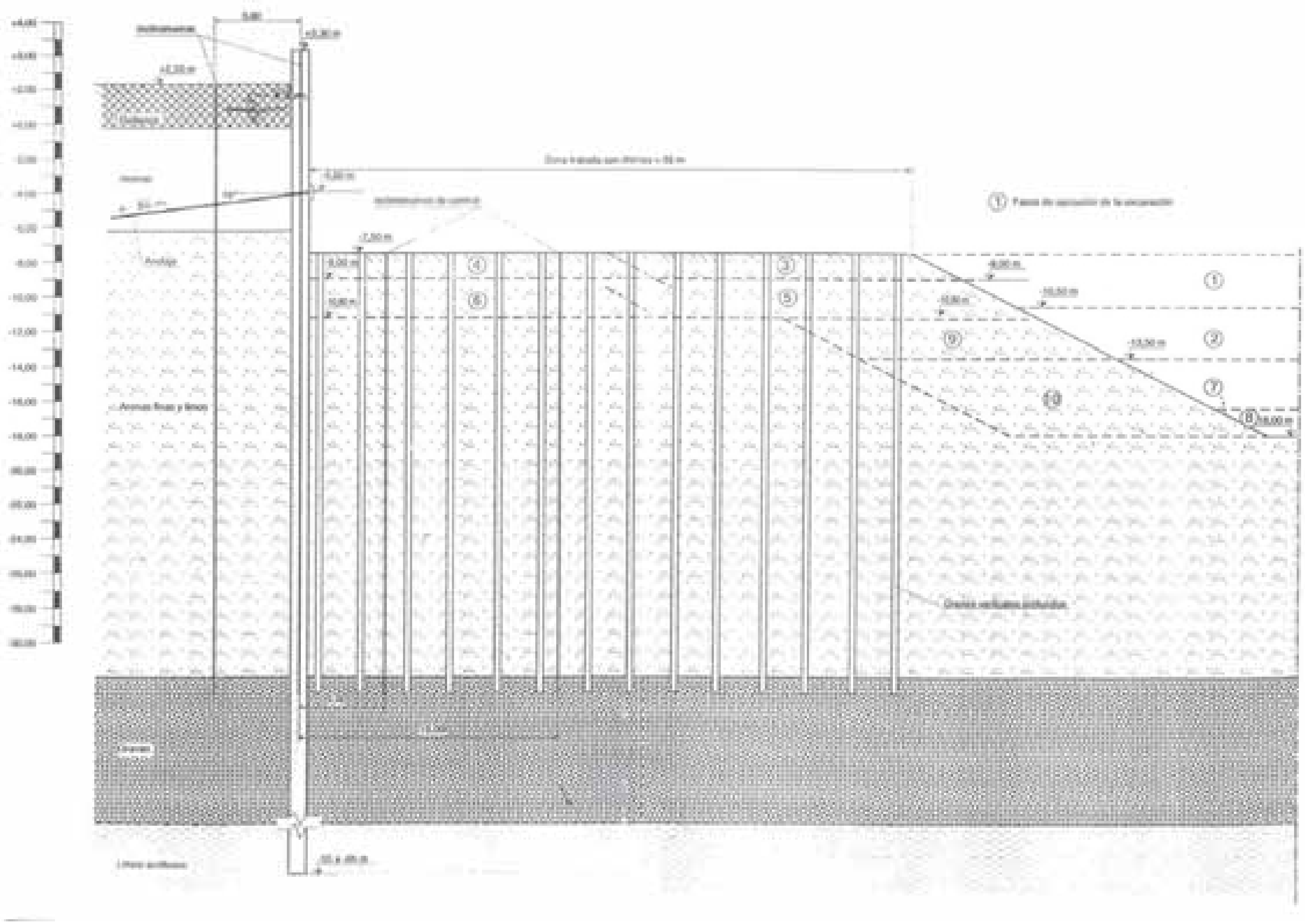
Excavations with large movements: announcing failure?

- Diagonal Mar: field observations

Surface crack 35 m away from the wall

Excavations with large movements: announcing failure?

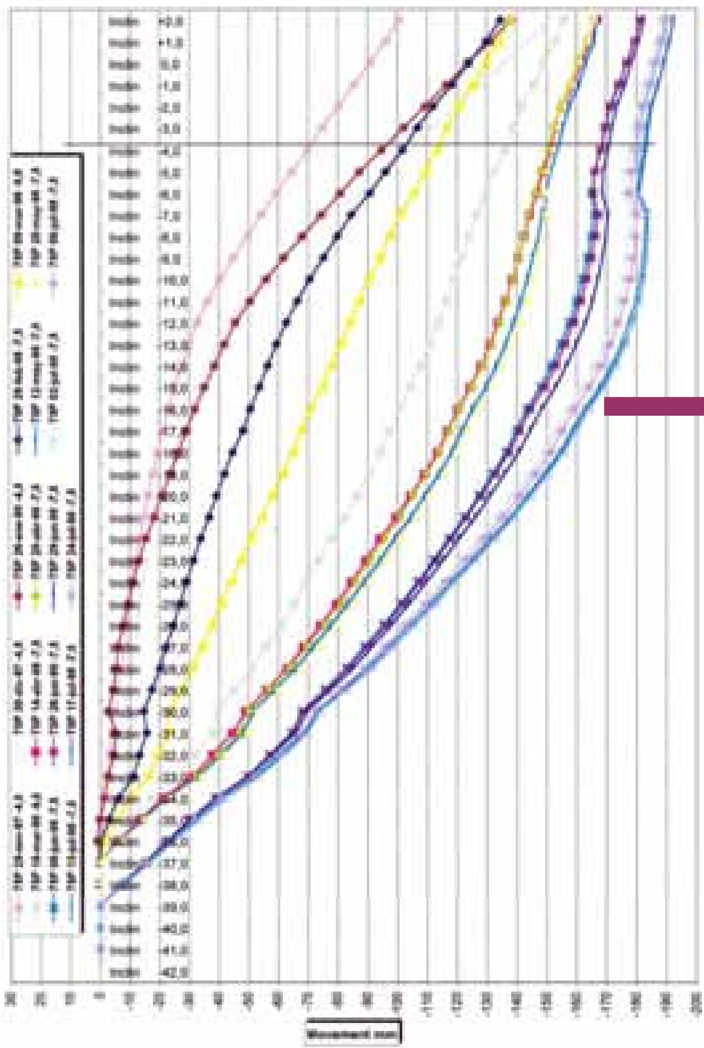
- Diagonal Mar

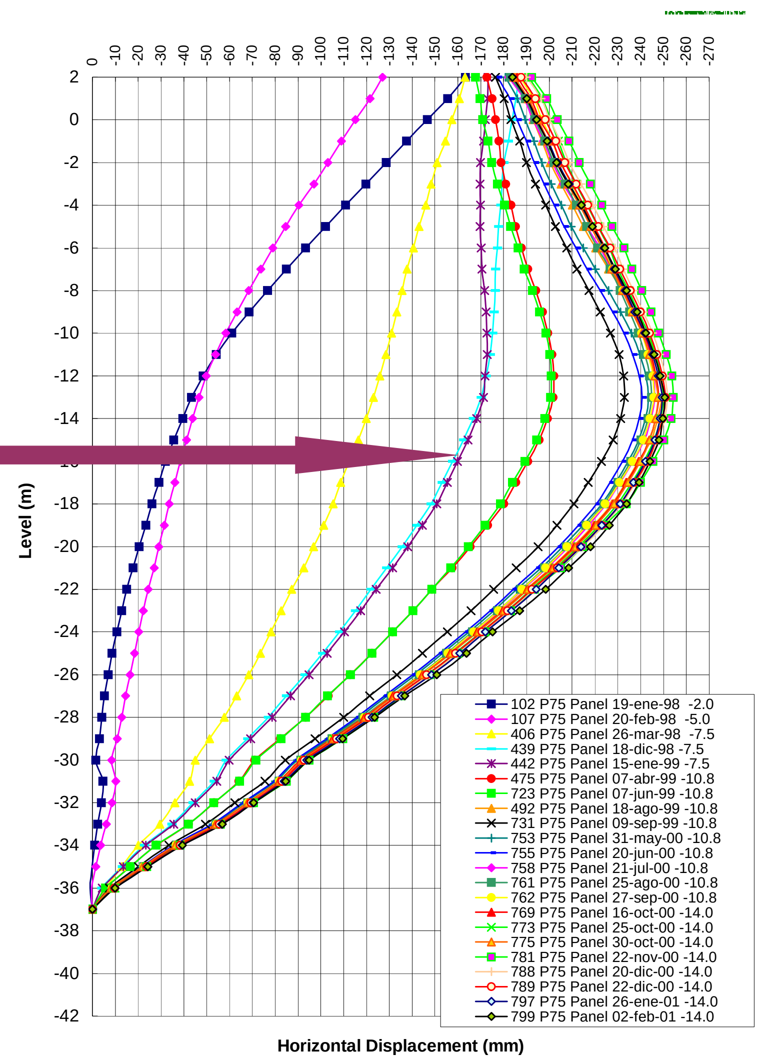


Excavation trial

Excavations with large movements: announcing failure?

- Diagonal Mar

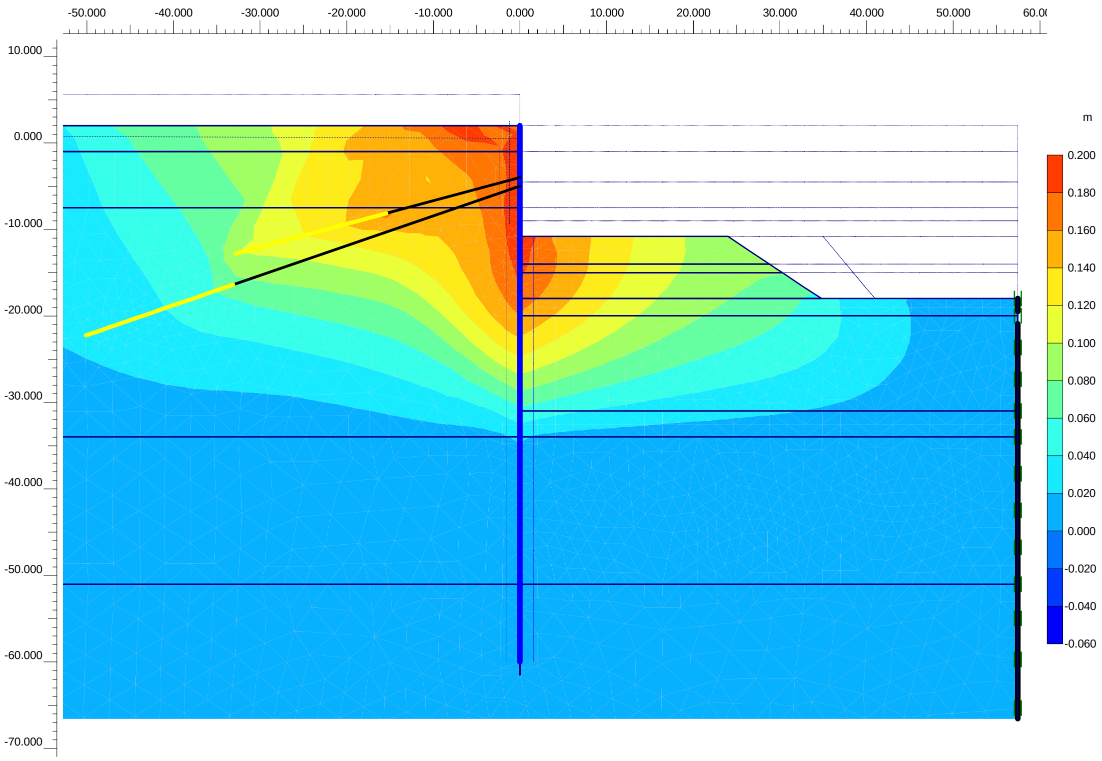


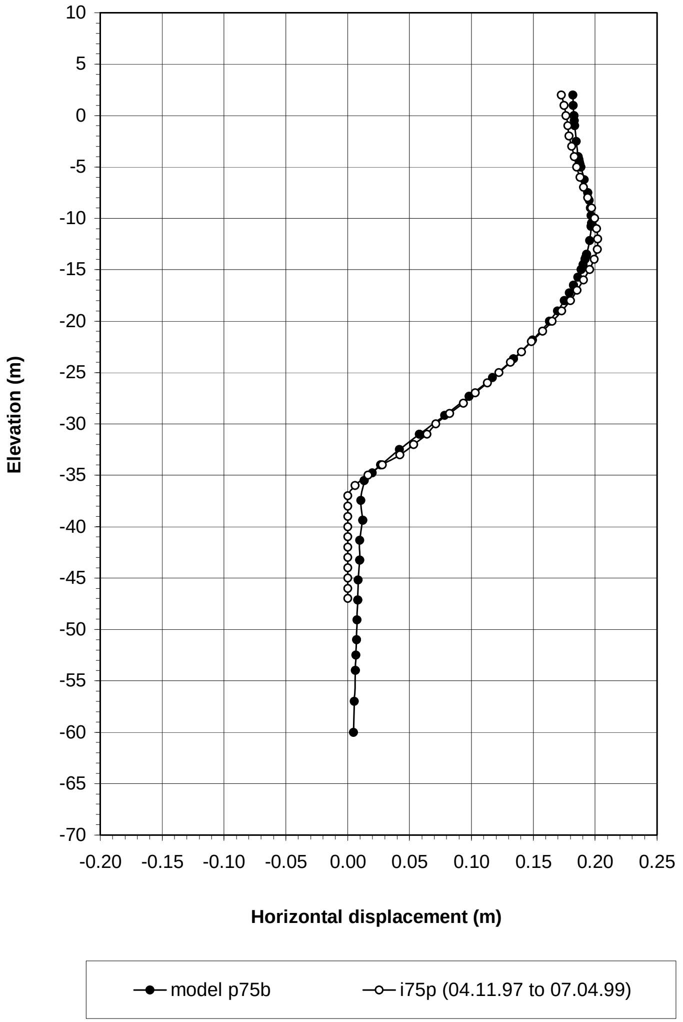


Excavation trial

Excavations with large movements: announcing failure?

- Diagonal Mar: observations and calculations

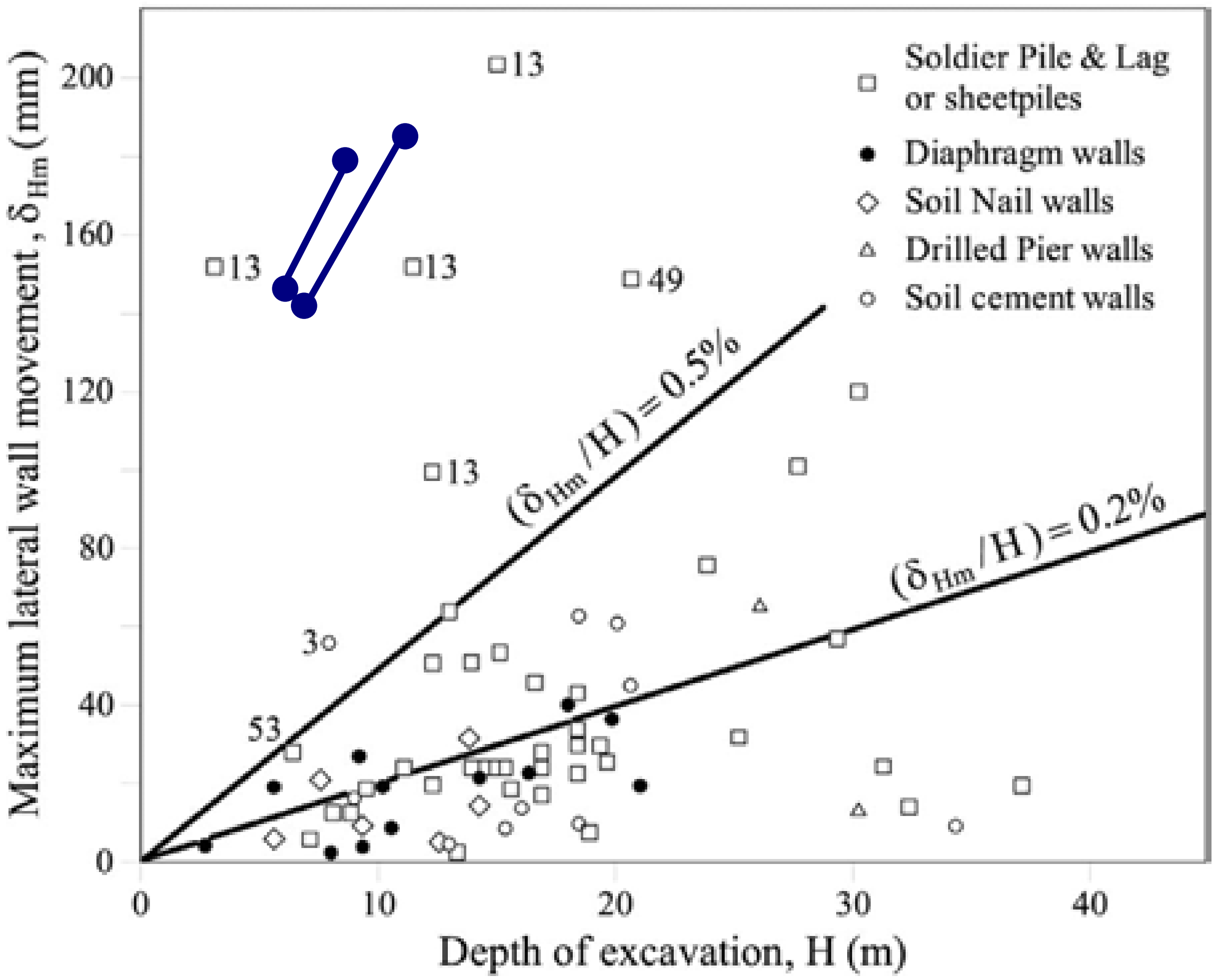




Anchored excavation to -18.0 m. Horizontal displacements

Excavations with large movements: announcing failure?

- Diagonal Mar

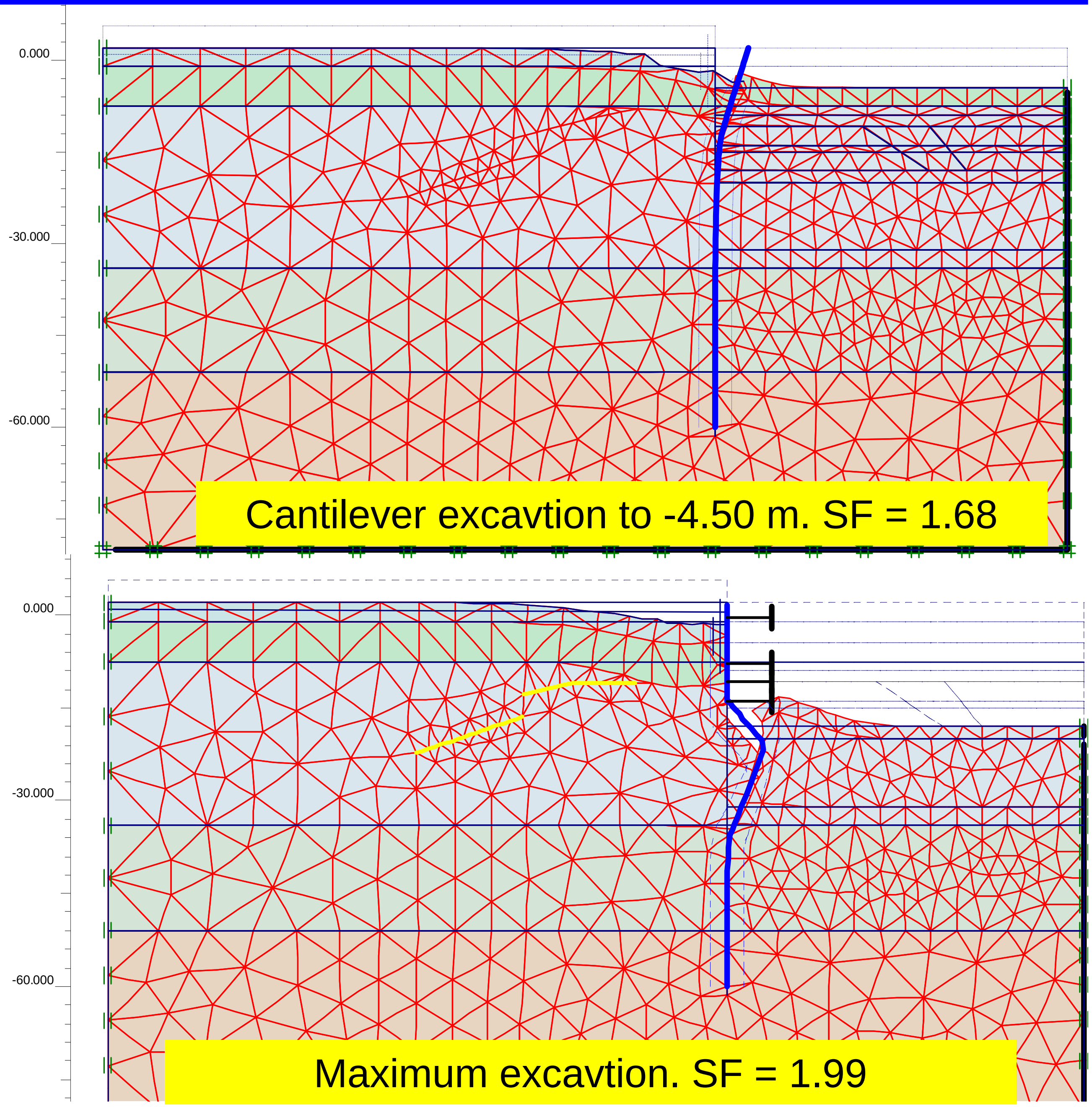


Maximum lateral wall displacements

Excavations with large movements: announcing failure?

- Diagonal Mar

Phase	Safety factors
2	1.68
8	3.09
16	>1.88
19	1.99
21	2.34



Excavations with large movements: announcing failure?

- Diagonal Mar

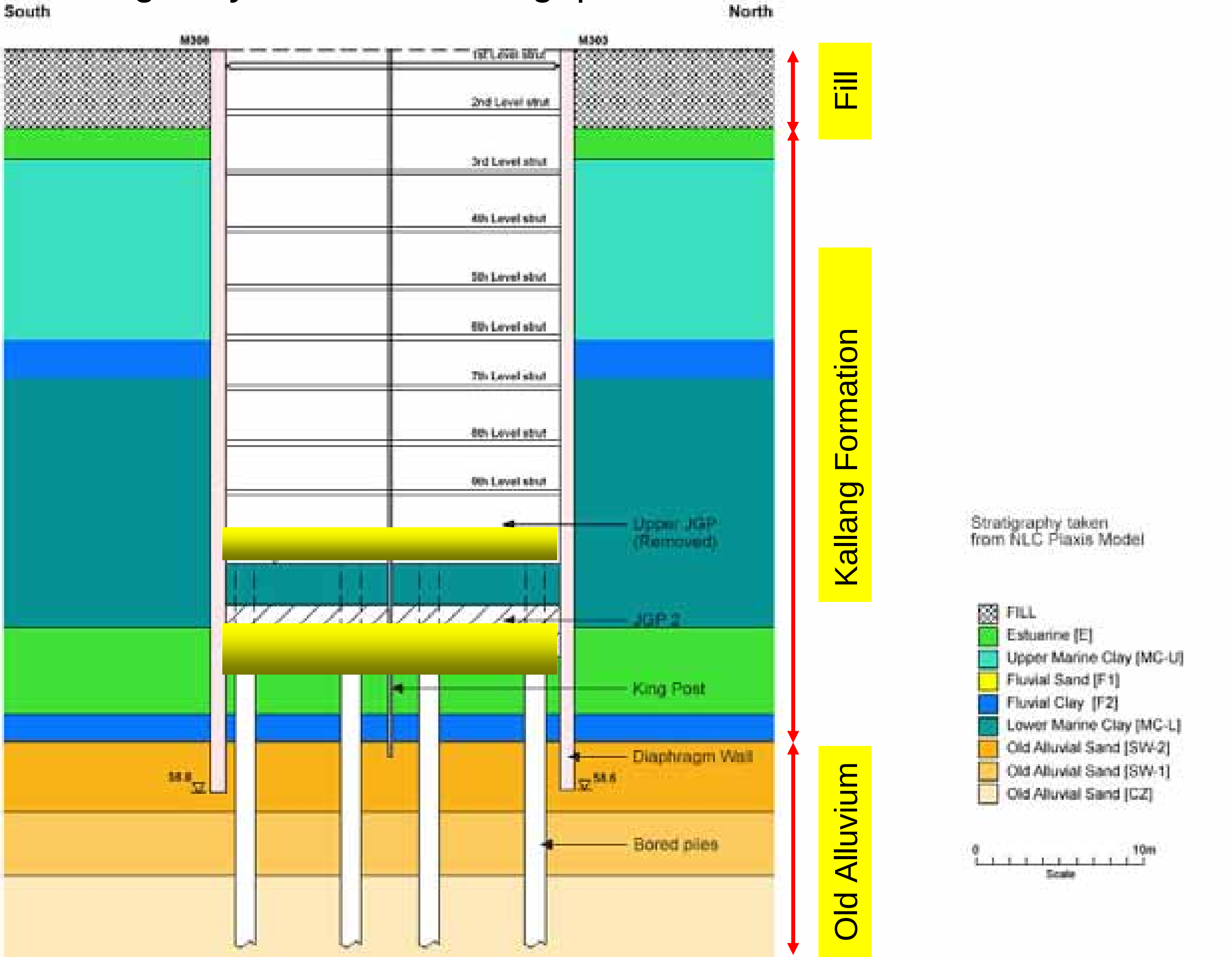
Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore

20/4/04

Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore

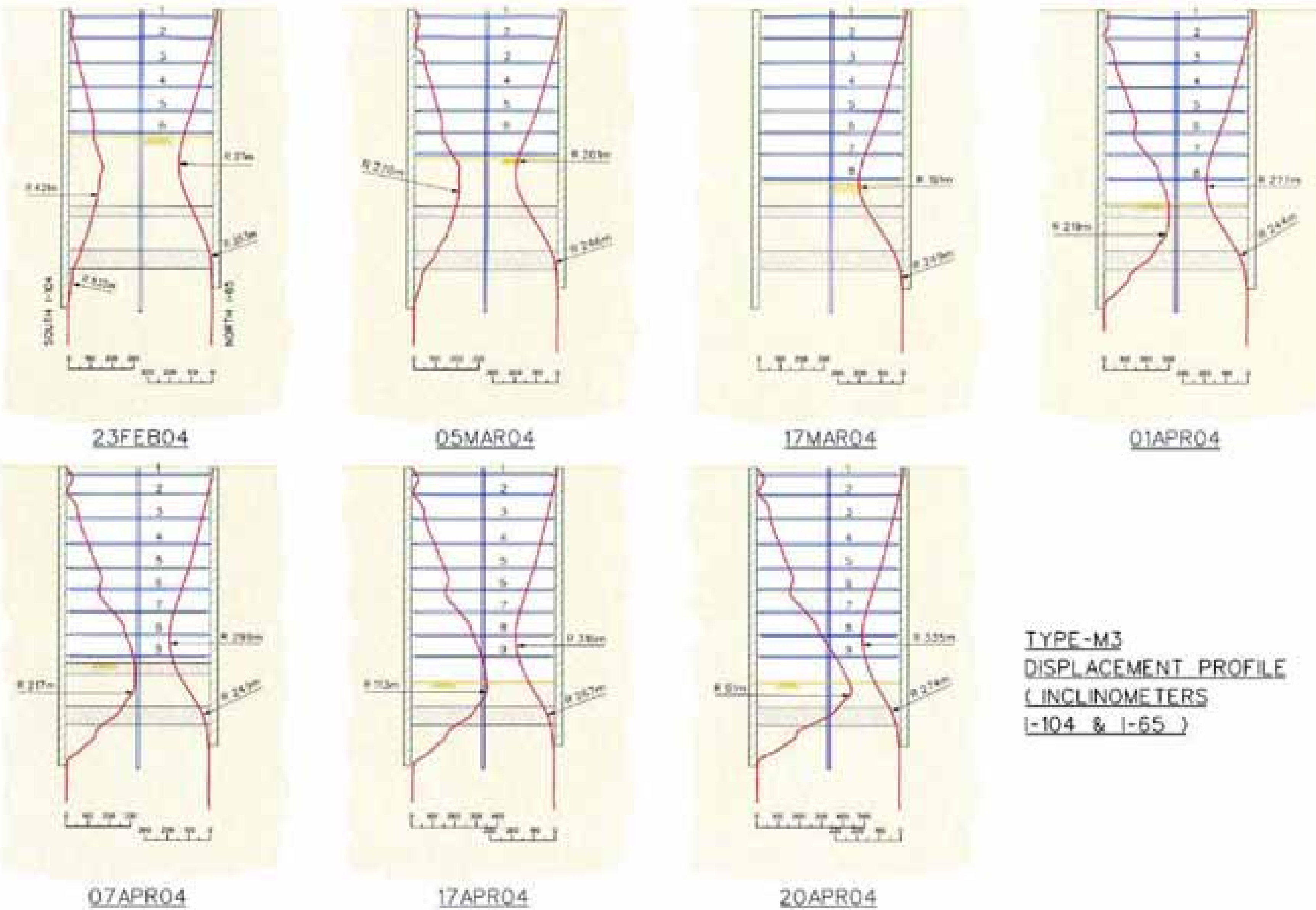


Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore

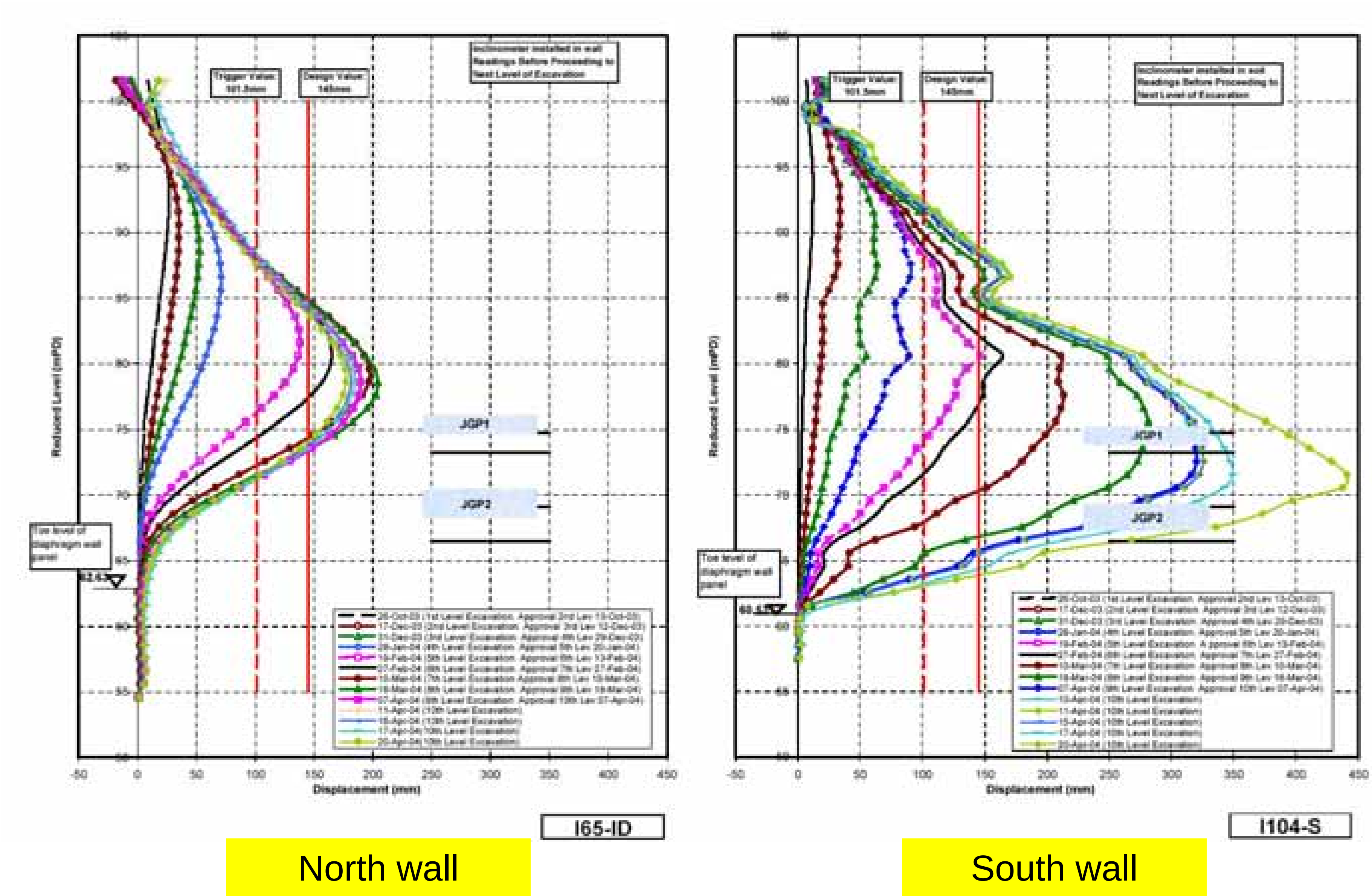
Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore



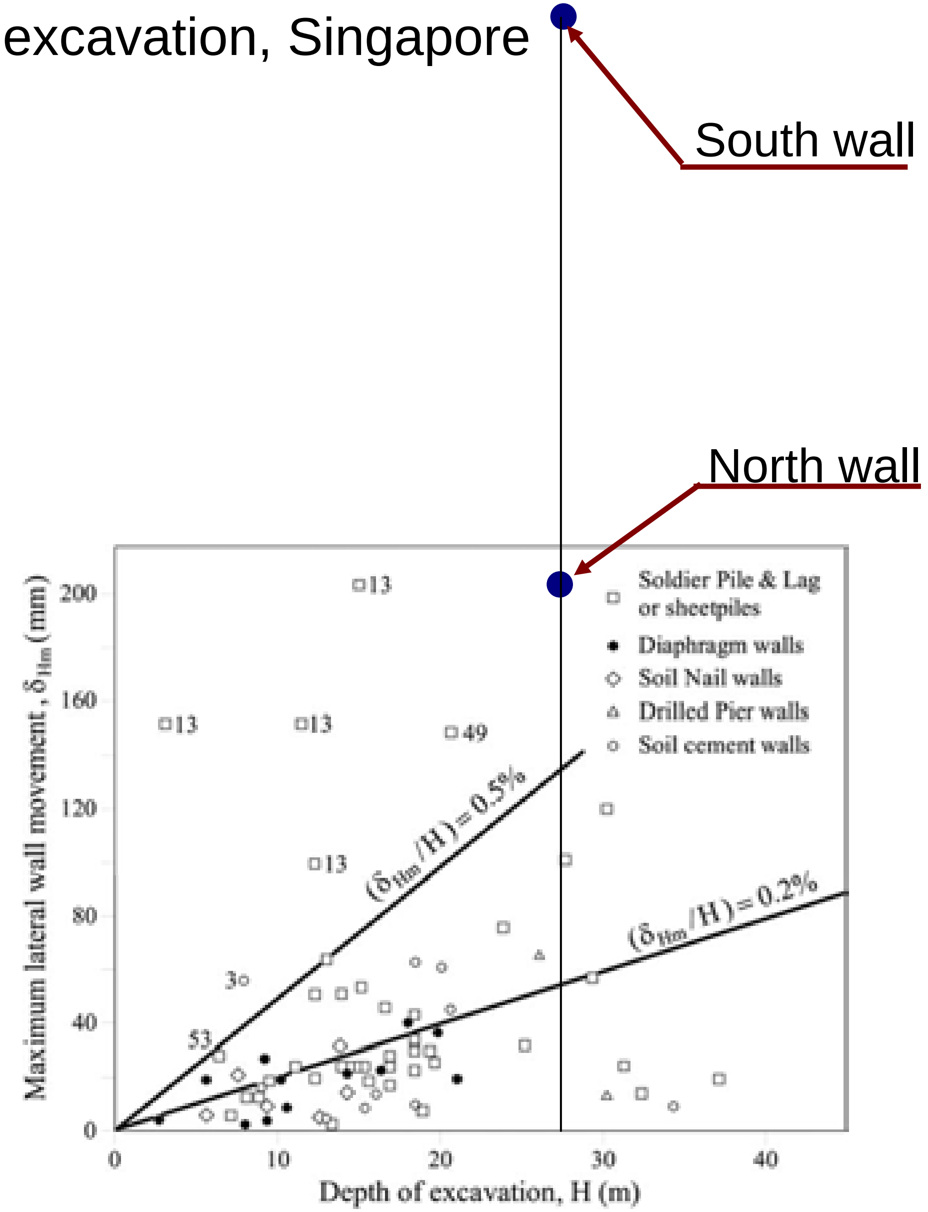
Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore



Excavations with large movements: announcing failure?

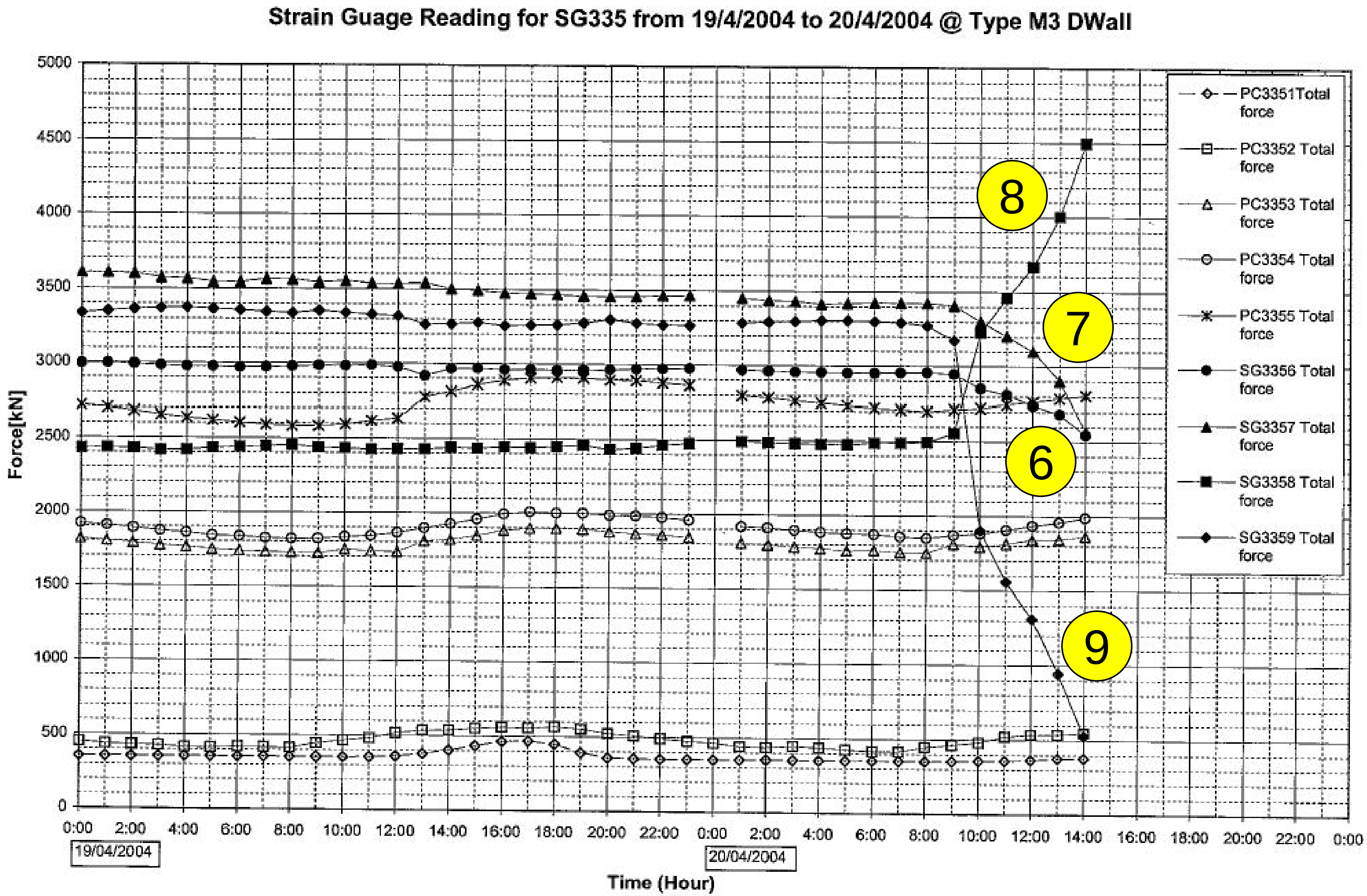
- Nicoll Highway excavation, Singapore



Maximum lateral wall displacements

Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore



Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore

Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore

Strut 338-9 north wall

Strut 335-9 south wall

Summary & conclusions

- Performing a deep excavation inevitably produces movements in the retaining walls and surrounding ground. The tolerance concerning acceptable deformation levels (in urban conditions) has reduced significantly in recent years
- The mechanisms of excavation-induced deformations are well identified. Horizontal movements are mainly tension ones, more unfavourable than in the tunnelling case
- There exists a wide documented experience providing useful information to estimate excavation-induced ground movements and heir possible effects on nearby structures
- Numerical analyses of excavations are becoming widespread. Those methods provide a more complete perspective of the problem but must be validated and calibrated if used for prediction purposes.
- There is a large range of construction procedures to reduce the excavation-induced ground movements to the required levels.
- Although it is advisable to try to prevent large deformations of the retaining walls, they are not necessarily signs of impending failure.