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)
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 props and anchors
- external loads
- construction procedure
- construction quality
- others...
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
Empirical methods for evaluating movements

Settlements

I: sands and soft clays, standard construction quality
II: soft and very soft clays
III: soft and very soft clays reaching below excavation depth

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

(Peck, 1969)
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)

- 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)

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)

- 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

  
  - 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


\[ h < 0.6H \]

**System stiffness:** \( \frac{EI}{\gamma s^4} \) (Clough & O'Rourke, 1990)

- System stiffness does not appear to be a critical parameter in these cases
Empirical methods for evaluating movements


![Diagram showing excavation depth and system flexibility](image)

- Maximum lateral movement: $h < 0.6H$

- Flexibility number: $\frac{(s^5)}{(E_1)}$ (Addenbrooke et al., 2000)

- System flexibility does not appear to be a critical parameter in these cases
Empirical methods for evaluating movements


\[ h > 0.6H \]
Low FS

Maximum lateral movement
Empirical methods for evaluating movements


\[ h > 0.6H \]
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)
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)

  ![Graphs showing distribution of surface settlements for different soil types.](image)

  - Sands
  - Stiff to hard clays
  - Soft to medium clays
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

![Diagram showing Spandrel (cantilever) type and Concave type with symbols Ac and As]
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

![Graph showing wall deflection and distance from the wall](image)

- Concave type

*Note: The graph illustrates the relationship between wall deflection and distance from the wall, with measurements and calculations for different soil types and properties.*
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
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
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…
  - Simulation 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 allow the introduction of some nonlinearity
  - The subgrade modulus (a key parameter in this type of calculations) is a parameter with serious limitations
  - The global soil-interaction problem is not considered
  - The horizontal movements of the wall are computed, ground movements must be calculated separately
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
- They 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.)

**Specification for anchors:**
- Prestressed anchor force:
  1. Row: 768KN
  2. Row: 945KN
  3. Row: 980KN
- Distance of anchors:
  1. Row: 2.30m
  2. Row: 1.35m
  3. Row: 1.35m
- Cross section area: 15 cm²
- Young's modulus: \( E = 2.1 \times 10^8 \text{ kN/m}^2 \)

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

Westminster Palace, 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

- $R = 0.5$
- $R = 0.8$

Reference solution
$R_{\text{inter}} = 0.5$ (final stage)
$R_{\text{inter}} = 0.8$ $t_{\text{virt}} = 0.01$ (final stage)
$R_{\text{inter}} = 0.5$ (1. excavation stage)
$R_{\text{inter}} = 0.8$ $t_{\text{virt}} = 0.01$ (1. excavation stage)
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)

Horizontal wall displacements

Surface settlements
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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: \( \frac{(EI)}{(\gamma_w s^4)} \) (Clough & O’ Rourke, 1990)

Flexibility number: \( \frac{(s^5)}{(EI)} \) (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

![Diagram showing influence of system stiffness](image)

- System stiffness does not appear to be a dominant factor in these cases
Procedures for control and reduction of movements

- Influence of system stiffness

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

\[ h > 0.6H \]

Low FOS

**Maximum lateral movement**

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

Buen Pastor Cathedral, San Sebastián, Spain
Procedures for control and reduction of movements

- Early installation of bracing
  - top-down construction

![Graphs showing maximum lateral movement and maximum settlement](image)

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)

- 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
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
Procedures for control and reduction of movements

- Bracing below the maximum excavation depth
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 short and long term ground movements

**Sealing defects**

- Flow through wall flaw
- Flow along wall interface
- Flow beneath wall
- Flow from perched water

**Flow caused by dewatering**

**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

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(Bezuijen et al., 2009)
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Procedures for control and reduction of movements

Prat de Llobregat cut-and-cover tunnel
Los vecinos de El Prat afectados por el AVE amenazan con poner las obras.

Gloria de ligeras" y se han producido en edificios de planta baja construidos en los años 50, "de estructura muy simple y posiblemente de cimentación suelta". 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 fráctico, 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 las edificaciones previstas en el proyecto y la obra se seguirá mediante la observación "continua" de las viviendas existentes.

Incluso los que piden obras, como Barcelona, demuestran preocupación por la cimentación de las viviendas, con los vecinos de la calle Antonio García. También se menciona que la fábrica de refuerzo en concreto entre las viviendas tiene más riesgo de falla, y que el encargado del proyecto, con los vecinos del edificio del centro, ha de ser informado de las próximas obras.

Adif carece de un análisis más integral, y su competencia no se entiende para llevar a cabo las obras de reparación, y serán responsables de las mismas, pero se requiere de un análisis más a fondo para garantizar la seguridad de las viviendas.

En lo que respecta a las viviendas, se menciona que las obras de reparación han sido realizadas con un presupuesto muy bajo, y que no se ha tenido en cuenta la seguridad de las viviendas. Se menciona que los vecinos de El Prat han solicitado que se realicen obras de reparación en las viviendas que tienen daños por la construcción del AVE, y que se ha aceptado la solicitud de las viviendas.

Los vecinos de El Prat han hecho llegar cartas a la comisión de investigación, en las que se denuncia la falta de cimentación de las viviendas, y que el edificio del centro es vulnerable a las fallas estructurales. Se menciona que la cimentación de las viviendas no ha sido adecuada, y que se ha hecho con materiales de baja calidad.

Las fallas estructurales han sido ocasionadas por la construcción del AVE, y que se ha hecho sin tener en cuenta la seguridad de las viviendas. Se menciona que los vecinos de El Prat han solicitado que se realicen obras de reparación en las viviendas que tienen daños por la construcción del AVE, y que se ha aceptado la solicitud de las viviendas.

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Procedures for control and reduction of movements

Inclinometer

Computed settlements

Computed horizontal displacements
Procedures for control and reduction of movements
Procedures for control and reduction of movements

1. **Desplazamientos verticales de la superficie del terreno en calle M. Bertrand (pk 201+525)**
   - Project 0
   - No additional measures

2. **Desplazamientos horizontales de la superficie del terreno en calle M. Bertrand (pk 201+525)**

- **Computed settlements**
- **Computed horizontal displacements**
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

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

Computed settlements

Computed horizontal displacements
Procedures for control and reduction of movements

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

Desplazamientos verticales de la superficie del terreno en calle M. Bertrand (pk 201+525)

-0.035 -0.030 -0.025 -0.020 -0.015 -0.010 -0.005 0.000

Distancia al centro de la estructura del IB [m]

-0.035 -0.030 -0.025 -0.020 -0.015 -0.010 -0.005 0.000

Desplazamiento vertical [m]

Distancia al centro de la estructura del IB [m]

Compiuted horizontal displacements

Desplazamientos horizontales de la superficie del terreno en calle M. Bertrand (pk 201+525)

-0.035 -0.030 -0.025 -0.020 -0.015 -0.010 -0.005 0.000

Distancia al centro de la estructura del IB [m]

-0.035 -0.030 -0.025 -0.020 -0.015 -0.010 -0.005 0.000

Desplazamiento horizontal [m]

Distancia al centro de la estructura del IB [m]

Procedures for control and reduction of movements

- 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

- 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
Procedures for control and reduction of movements

- 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
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
Observations and model calibration. Ground inclinometers

Procedures for control and reduction of movements

- 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

Displacements from phase 7 to phase 16

Angular distortion (‰)

Horizontal strain (‰)

Negligible

Very slight

Slight

Moderate

Severe to very severe

Excavation of the second tunnel
Procedures for control and reduction of movements

- Estimation of potential damage

Displacements from phase 0 to phase 16

- Angular distortion (‰)
- Horizontal strain (‰)

Severe to very severe

Moderate

Slight

Negligible

Very slight

Negligible

Estimated potential damage

Procedures for control and reduction of movements
Procedures for control and reduction of movements

Construction of tunnel UIC
Procedures for control and reduction of movements
Procedures for control and reduction of movements

- Observations Maragall St.

Horizontal displacements

- d=7m
- d=32m
- d=55m
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A case history

Excavations with large movements: announcing failure?

Conclusions
Excavations with large movements: announcing failure?

- **Diagonal Mar**
  - Surface: 40,000 m²
  - Excavation depth: 20 m
  - Excavation volume: 800,000 m³
  - 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?

- Cantilever excavation to -4.50 m
- Anchor head
- -4.50 m
- -7.50 m
- -9.00 m
- Excavation with 1 anchor

Wall horizontal displacements
Excavations with large movements: announcing failure?

Diagonal Mar: numerical model

- Sands (upper aquifer)
- Silty fine sands (intermediate layer)
- Gravel (lower aquifer)
- Still clayey silt

Symmetry axis: 60 m
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

Horizontal displacements contours

Cantilever wall

Anchored wall
Surface crack 35 m away from the wall

Excavations with large movements: announcing failure?

- Diagonal Mar: field observations
Excavations with large movements: announcing failure?

- Diagonal Mar
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

\[
\frac{\delta_{hm}}{H} = 0.5\% \\
\frac{\delta_{hm}}{H} = 0.2\%
\]
### Excavations with large movements: announcing failure?

- **Diagonal Mar**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Safety factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.68</td>
</tr>
<tr>
<td>8</td>
<td>3.09</td>
</tr>
<tr>
<td>16</td>
<td>&gt;1.88</td>
</tr>
<tr>
<td>19</td>
<td>1.99</td>
</tr>
<tr>
<td>21</td>
<td>2.34</td>
</tr>
</tbody>
</table>

**Cantilever excavation to -4.50 m. SF = 1.68**

**Maximum excavation. SF = 1.99**
Excavations with large movements: announcing failure?

- Diagonal Mar
Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore
Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore
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Excavations with large movements: announcing failure?

- Nicoll Highway excavation, Singapore
Excavations with large movements: announcing failure?

Nicoll Highway excavation, Singapore

Strain Gauge Reading for SG335 from 19/4/2004 to 20/4/2004 @ Type M3 DWall

- PC3351 Total force
- PC3352 Total force
- PC3353 Total force
- PC3354 Total force
- PC3355 Total force
- SG3355 Total force
- SG3357 Total force
- SG3358 Total force
- SG3359 Total force

Time (Hour)
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 their 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.